Title

The effect of atelectasis and lateral positioning on the regional distribution of pulmonary blood flow in dogs

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Publication Date

1982

Peer reviewed|Thesis/dissertation

The Effect of Atelectasis and Lateral Positioning on the Regional Distribution of Pulmonary Blood Flow in Dogs

by

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Nursing

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

San Francisco

Date University Librarian

Degree Conferred: . . . . . .

"A man would do nothing if he
waited until he could do it so
well that no one could find
fault with what he had done."

-Cardinal Newman

"...learning still has a long way to go, and not even the most complete explanation is likely to detract from the wonder of the journey. For a miracle explained is no less a miracle."

Sharon Begley with
John Carly
Newsweek
January 11, 1982

ABSTRACT

The effects which lobar atelectasis and lateral positioning have on the regional distribution of pulmonary blood flow were studied in five dogs with intact chests. With the animals in the supine position, atelectasis was created in the left lower lobe (LLL) by endobronchial occlusion and allowed to stabilize for two hours before the dogs were turned into the left lateral decubitus position. Regional distribution of perfusion was measured directly by injection of differentially-labeled radioactive microspheres and indirectly by use of the shunt equation. Atelectasis resulted in a fall in LLL perfusion from a mean ± standard deviation of 29.3 ± 1.2% to 20.7 ± 6.2% of cardiac output ($p < .001$) when measured 2 hours after occlusion, with an increase in shunt from 13.5 ± 4.4% to 26.1 ± 7.4% measured 15 minutes after occlusion ($p < .001$). Following the initial increase, the shunt fell gradually at an average rate of 1.0% every 22 minutes. This rate of fall did not change significantly when the animal was turned, despite the fact that 15 minutes after turning, mean perfusion to the LLL had decreased to 11.7 ± 7.9% of cardiac output ($p < .001$). The fact that shunt did not decrease more with the post-turning decrease in perfusion to the LLL suggests that this lobe was not the only region of the lung contributing to shunt. Findings from this study could be generalized to suggest that patients with unilateral atelectasis might have less shunting of blood through the collapsed tissue if positioned with that tissue dependent. This is in apparent contradiction to previous literature which, using blood gases as an indirect measure of the distribution of perfusion in the lungs, found decreased oxygenation when the atelectatic area was dependent. The importance of the present study is that it challenges, using direct measures of pulmonary blood flow, the assumption that the oxygenation decreased because flow through the atelectatic region was enhanced. Further research is suggested to clarify whether the discrepancies between the findings of this study and those previously reported in the literature can be explained solely on the basis of differences in the models and methods used. Until these discrepancies are resolved, selection of position for patients with atelectasis should be done on an individual basis. These patients should not be assumed to respond to positioning in the same way as do patients with other types of lung disease; they should be observed closely for signs of hypoxemia when any new position is assumed.

ACKNOWLEDGEMENTS

This research would not have been possible without the help of many people to whom I am very grateful. I am especially indebted to mentor, Dr. Charles Fisher, Jr. for his support and guidance throughout the entire course of the project. I am grateful for the many patient hours he spent helping me learn to think as a scientist. I consider myself very fortunate to have worked under his thundering velvet supervision: his intolerance of poor science drove me to excel toward goals I only believed possible because of his encouragement and his belief that I could achieve them. His generous financial support, which made this project possible, is greatly appreciated. I consider myself very fortunate to have worked with Dr. Virginia Carrieri and Dr. Nancy Stotts who have clearly illustrated for me the role for research in nursing. Their critical reviews of preliminary drafts of this manuscript sharpened my thinking and helped me learn to express those thoughts in writing.

I am also grateful to:

William Walby for teaching me many of the experimental techniques and and his invaluable surgical assistance in the laboratory.
Dr. Tom Iberti for his assistance in the laboratory, his humor and his creative problem-solving skills.
Mark Hudas and Dr. Garrett Foulke for assisting with the data analysis.
Hal Pullum and the Department of Medical Illustrations at the University of California Davis Medical Center (UCDMC) for preparing the figures and graphs.
The Department of Surgery at UCDMC for the use of the blood gas analyzer and Ms. Claudia Jo Weber for her assistance with its use.
The Department of Nuclear Medicine at UCDMC for the use of their gamma well counter.
The Department of Cardiology at UCDMC for the loan of the fluroscope.
Dr. Lester Schwartz and the California Center for Primate Research at the University of California Davis campus for the loan of the fiberoptic bronchoscope.
Mrs. Nancy Davitt for typing the manuscript.
The American Lung Association for the Pulmonary Nurse Fellowship.
My family and friends, especially with regard to my parents, Lois and Ken Bacon, and my husband, Barry, for their constant encouragement and support.

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THE STUDY PROBLEM

Background

Atelectasis, defined as the complete loss of alveolar air space, is frequently seen in critically ill patients. These patients are often immobile and depend on the nursing staff for turning and positioning. Unfortunately, the scientific basis for turning and positioning in the presence of atelectasis is incomplete. It should be developed as an integral part of nursing research.

The purpose of ventilation, the flow of air in and out of the lung, is to provide gas exchange between the atmosphere and the alveoli. The volume of ventilation going to a region of lung tissue will determine, in part, the volume and composition of gases in those alveoli. Soluble gases in the alveoli diffuse across the alveolar-capillary membrane and establish equilibrium with the blood. The distribution of partial pressure of gases in the venous blood returning from the body and in the alveoli favors the net movement of gas from the alveoli into the blood. Unless there is a constant replenishing of the alveolar volume by adequate ventilation, the gases will eventually be absorbed, resulting in atelectasis.

When the alveoli are filled primarily with a relatively insoluble gas, such as nitrogen (N_2) while breathing room air, the process of absorption atelectasis may take hours to several days. The relative insolubility of N_2 inhibits its diffusion across the alveolar-capillary membrane, thus

maintaining alveolar volume. Hospitalized patients, however, often breath more soluble gases, such as nitrous oxide (N_2O) in surgery or an increased fraction of inspired oxygen (FiO_2) in critical care areas. Because these latter gases are so soluble, they diffuse readily from the alveoli into the blood, accelerating the process of absorption atelectasis.

There are many causes of atelectasis in hospitalized patients. Any condition which limits ventilation to a part of the lung predisposes that area to develop atelectasis. Ventilation may be obstructed regionally by such things as bronchospasm, retained secretions, cellular debris, foreign bodies, tumors, swollen airway tissue or loss of the supporting tissue matrix which surrounds the airway. Ventilation may also be hindered in a more generalized manner. For example, this may occur when breathing deeply causes pain, when the respiratory center is depressed or when expansion of the chest wall is restricted.

In normal physiological circumstances there is a matching of ventilactions ($\dot{V}$) and perfusion ($\dot{Q}$) in the lung. This facilitates transfer of metabolic waste products such as carbon dioxide (CO_2) from the blood into the alveoli to be ventilated out. It also facilitates the movement of oxygen (O_2) from the alveoli into the blood to be distributed to the body's tissues. For desaturated venous blood to become fully saturated with oxygen, the distribution of perfusion must be well matched by the distribution of ventilation.

When regional ventilation is diminished or has ceased, as in atelectasis, mechanisms are thought to be activated which tend to reduce perfusion to that area. There is general agreement that pulmonary blood flow

(PBF) to chronically atelectatic tissue is decreased. In the presence of acute atelectasis, however, there is considerable controversy regarding how effectively and by what mechanism(s) PBF can be reduced (see Table 1).

The decrease in perfusion to areas of the lung which are ventilating poorly or not at all minimizes the amount of blood flowing past alveoli which can neither accept CO_2 nor provide O_2. To the extent that the distribution of PBF continues to provide perfusion to the atelectatic region, desaturated venous blood will be added to the oxygenated arterial blood. This is known as a right to left intrapulmonary shunt. It results in systemic hypoxemia.

Clinical attempts to alleviate systemic hypoxemia usually include increasing the FiO_2, which increases the oxygen tension in the ventilated alveoli. Since shunted blood does not perfuse the ventilated alveoli, hypoxemia may persist despite the use of an increased FiO_2. However, a high concentration of oxygen usually is able to slightly improve the partial pressure of arterial oxygen (PaO_2) in the presence of shunt. This is because the high alveolar oxygen tension in the ventilating alveoli provides a small amount of additional dissolved O_2 to the surrounding capillaries.

The prolonged use of a high FiO_2 is not without risk. It is well known to result in toxic damage to the lung tissue. A recent review on oxygen toxicity of the lung is provided by Deneke and Fanburg (1980). This toxic damage may further impair gas exchange, thereby resulting in the need for more oxygen, which in turn may further the toxic damage.

Once this cycle begins it is difficult to break. It is far better to prevent the cycle from starting. Thus, clinical goals should include maintaining adequate PaO_2 on the lowest FiO_2 possible and preventing conditions such as atelectasis which may result in intrapulmonary shunting.

In the practice of nursing, frequent turning of the patient has long been emphasized as being essential for preventing atelectasis. Intuitively, turning must lead to improved draining of the tracheobronchial tree. Absorption atelectasis is prevented because pooled secretions are not allowed to obstruct ventilation.

Much research has been done on the effect atelectasis has on the distribution of PBF, or on its subsequent effects on arterial blood gases. Less is known, however, about the effect of positioning on the regional distribution of PBF and on shunt when atelectasis is already present. Recently, a few studies have appeared in the literature which demonstrated that in a variety of different unilateral lung diseases, positioning with the diseased area dependent resulted in immediate deterioration of PaO_2 (Falke, Pontoppidan, Kumar, Leith, Geffin & Lauer, 1972; Remolina, Khan, Santiago & Edelman, 1981; Schimmel, Civetta & Kirby, 1977; Zack, Pontopoddian & Kazemi, 1974). With the diseased lung dependent, its blood flow may be enhanced. This could lead to an increased shunt.

When the distribution of PBF and thus shunting through diseased lung tissue can be significantly altered simply by turning the patient, it becomes crucial to use this knowledge in carefully positioning patients to achieve adequate arterial oxygenation with the use of a minimal FiO_2

An arbitrary system of frequently turning without considering choice of position does not provide optimal care for the critically ill patient with pulmonary disease.

Purpose

The purpose of this study was to examine the effects of lobar atelectasis and positioning on the regional distribution of PBF and on intrapulmonary shunt.

Research Questions

The following research questions were addressed in this study:

1. What is the effect of lobar atelectasis on the regional distribution of PBF?
2. What is the effect of lobar atelectasis on intrapulmonary shunt?
3. Does shunt change over the 2 hours following the onset of atelectasis?
4. What is the effect of lateral positioning with the atelectatic lobe dependent on the regional distribution of PBF?
5. What is the effect of lateral positioning with the atelectatic lobe dependent on intrapulmonary shunt?
6. Does intrapulmonary shunt change with time if lateral positioning is maintained?

Hypotheses

Six theoretical hypotheses were proposed prior to the execution of the experiment. It was hypothesized that:

1. Lobar atelectasis would result in a significant decrease in perfusion to the collapsed lobe.
2. Lobar atelectasis would result in a significant increase in intrapulmonary shunt.
3. The expected high post-atelectasis shunt would decrease over time stabilizing by the second hour somewhere still above the pre-atelectasis control value.
4. Lateral positioning with the atelectatic lobe dependent would result in a significant increase in perfusion to that lobe.
5. Lateral positioning with the atelectatic lobe dependent would result in a significant increase in intrapulmonary shunt.
6. Intrapulmonary shunt would be less at 1 hour post-turning than at 15 minutes post-turning.

Chapter 2

REVIEW OF RELEVANT LITERATURE

Ideal gas exchange in the lung is dependent upon matching of ventilation and perfusion: a $\dot{V}/\dot{Q}$ ratio close to 1. Ventilation in excess of perfusion results in a high $\dot{V}/\dot{Q}$ ratio. The excess ventilation is wasted; it is known as dead space ventilation. Perfusion in excess of ventilation causes a low $\dot{V}/\dot{Q}$ ratio and results in hypoxemia as desaturated venous blood is added to the systemic arterial circulation. Neither ventilation nor perfusion are distributed homogeneously in the lung. Therefore, it is essential that they be matched at the local level. An area receiving a large amount of perfusion needs also to receive a large amount of ventilation and vice-versa. Fortunately the pressures and resistances involved in determining the normal distribution of ventilation and perfusion operate to keep them well matched throughout the lung.

In order to predict the effect which position will have on the regional distribution of PBF and on shunt in atelectasis, it is necessary to understand the factors which influence the distribution of $\dot{V}$ and $\dot{Q}$. Both air flow and blood flow follow the path of least resistance. Flow (f) is proportional to the pressure drop along the system (ΔP) and inversely proportional to the resistance (R):

$$f = \frac{\Delta P}{R}$$

Body position influences the $\dot{V}/\dot{Q}$ ratio throughout the lung by changing the pressures and resistances which control the flow of air and blood; atelectasis influences the $\dot{V}/\dot{Q}$ ratio in a similar manner. An area of atelectasis alters pressures and resistances for the flow of air and blood not only locally in the collapsed tissue but also throughout the remaining

healthy lung. The influence of body position on $\dot{V}/\dot{Q}$ matching in the presence of atelectasis is dependent not only on conditions in the atelectatic tissue itself but on conditions present throughout the lung. The ability to turn and correctly position patients for maximal gas exchange with minimal complications requires then, an understanding of the effect of position on the distribution of $\dot{V}$ and $\dot{Q}$ in both normal and diseased lung tissue.

DISTRIBUTION OF VENTILATION

Ventilation ($\dot{V}$) refers to the movement of gases in and out of the lung. Rarely, however, is ventilation assessed by actually measuring the volume of gas being exchanged. In practice, it is more frequently the adequacy of $\dot{V}$ which is of interest, and this is assessed by examining the effect which it has on arterial blood gases.

Cellular metabolism produces CO_2 as a waste product. This gas is carried in the venous blood to the lungs. If there is good matching of $\dot{V}$ and $\dot{Q}$, the CO_2 arrives at a ventilating alveoli. Since CO_2 is highly diffusible it rapidly reaches equilibrium with alveolar gases across the alveolar-capillary membrane. Thus, the end-capillary CO_2 can be considered equal to the alveolar CO_2 (P_ACO_2).

There is essentially no CO_2 present in ambient air, so ventilation serves only to remove CO_2 from the alveoli, it does not replenish it. Since all the expired CO_2 comes from the alveoli, alveolar ventilation ($\dot{V}_A$) can be measured by dividing the CO_2 exhaled ($\dot{V}CO_2$) by the alveolar concentration of this gas:

$$\dot{V}_A = \dot{V}CO_2/P_ACO_2 \times K$$

where K is a constant (West, 1979, p. 17). When ventilation is excessive, CO_2 is washed from the alveoli. When P_ACO_2 drops, the end-capillary CO_2 also drops, since they are in equilibrium. Conversely, when ventilation is insufficient, P_ACO_2 rises, which results in an elevated end-capillary CO_2 as well.

The end-capillary blood draining from each alveolus mixes together to form the arterial blood. The level of CO_2 in the arterial blood ($PaCO_2$) serves as a measure of overall ventilation in the lung. It is a mixture of all blood draining from all alveoli. Not all the capillaries contribute the same amount of CO_2 to the arterial blood. This is because they drain from alveoli which are ventilated to different degrees. Ventilation does not occur in a homogeneous manner.

The distribution of ventilation in the lung depends upon regional differences in the pressures and resistances which are involved in breathing. It is influenced by body position and it is influenced by lung disease.

PRESSURES AND RESISTANCES INVOLVED IN VENTILATION

The lung is surrounded by two membranes known as pleura. The visceral pleura adheres to the lung, while the parietal pleura adheres to the chest wall. The pleura slide along one another during breathing, lubricated by a very small amount of fluid, thus the area between the pleura is not an actual space, but only a potential one. The pressure which exists in this potential space is known as the intrapleural pressure (Ppl).

Since the intrapleural space is a closed area, any tendency for the chest wall or lung to pull away from the other results in a negative intrapleural pressure. The chest wall and lung are both elastic structures; they each have a size at which the elastic tissue is in a relaxed state. For the chest wall this size is larger than is the relaxation size for the lung. Thus, under normal conditions of breathing, the chest wall has a tendency to spring out to its relaxed state and the lung has a tendency to collapse to its relaxed state. This creates a relative vacuum in the intrapleural space. Thus, the normal Ppl is negative (see Figure 1). The lung volume at which the tendency of the chest to spring out is exactly balanced by the tendency of the lung to collapse is known as the functional residual capacity (FRC).

In addition to the elastic properties which make the lung tend to reduce its volume, the lung also has surface tension properties which act in the same direction. Surface tension arises in the lung because of the liquid film lining the alveoli. The attraction of the liquid molecules for each other is much greater than the attraction between the gas and liquid molecules. The result is that the liquid surface area becomes as small as possible. This would rapidly result in collapse of alveoli were it not for the presence of a surface tension reducing substance known as surfactant.

On inspiration, muscular force is exerted to expand the chest wall. As the chest wall pulls away from the lung, its expansion is resisted by the retractive forces of the lung. This resistance determines how much force must be used to overcome lung elasticity and surface tension. The movement

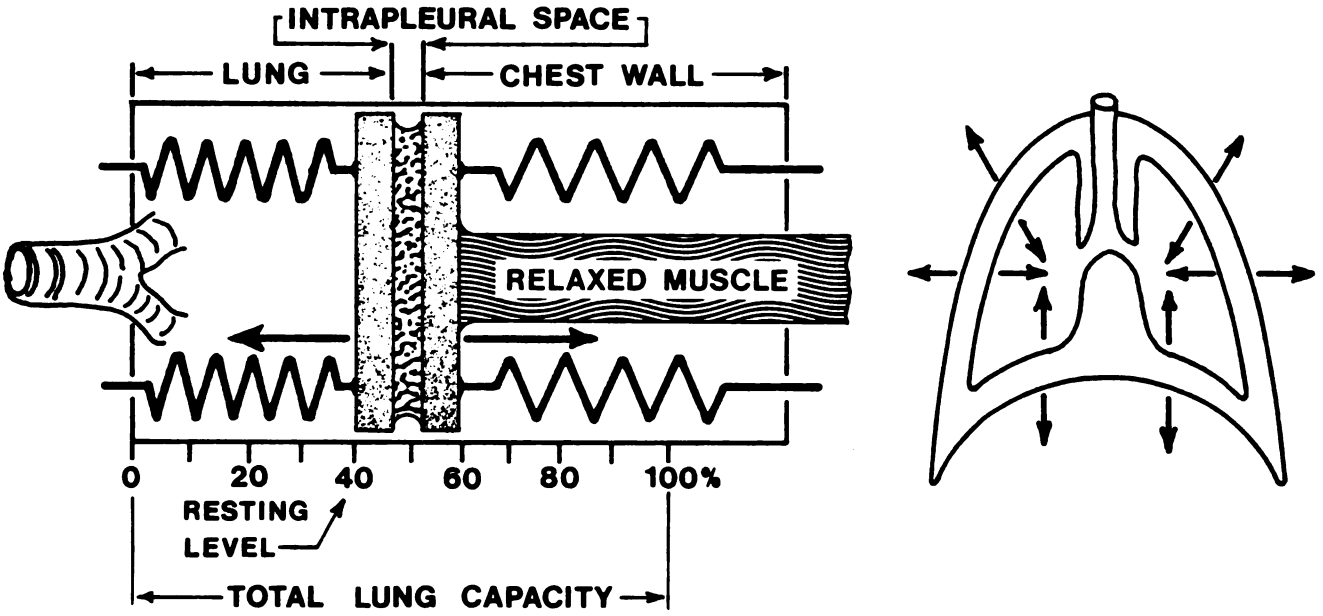

Figure 1. Elastic Forces in the Thorax. A mechanical correlation (left) and diagram of the thorax (right) illustrate the opposing elastic forces of the lung and chest wall at rest. (Adapted from Cherniack, Cherniack & Naimark, 1972).

of the chest wall away from the lung causes the Ppl to fall. The difference in pressure between the inner and outer surface of the lung measures the net force tending to expand or deflate the lung. This is known as the transpulmonary pressure (P_L) and is the difference between the pressure in the alveoli (Palv) and that in the intrapleural space:

$$P_L = Palv - Ppl$$

If the alveoli were in free communication with the airway opening, the only resistance to inspiration would be the elastic and surface tension properties of the lung. In reality, the alveoli are connected to the airway opening through many generations of bronchial branching. Thus, resistance in the airway adds to the pressure which must be generated to create inspiration (see Figure 2). Airway resistance is reflected in the pressure difference between the airway opening (Pao) and the alveoli: (Pao-Palv).

Narrowing of airways can be caused in 3 ways: intraluminal obstruction, thickening of the airway wall or external compression (see Figure 3). Intraluminal obstruction may be caused by excessive mucus, debris or foreign bodies. The airway tissue itself can narrow the airway when it is edematous or hypertrophied or when the circular muscle contracts. External compression is the third cause of increased airway resistance. Peribronchial edema and atelectasis are conditions which compress the airways from without, as is any condition which minimizes the support provided to the airways by the surrounding tissue. The airways are surrounded by the elastic tissue of the lung. Stretching of the lung parenchyma exerts radial tractions on the airways, a tethering effect which increases their diameter. The loss of elastic tissue such as is seen in aging and emphysema results in

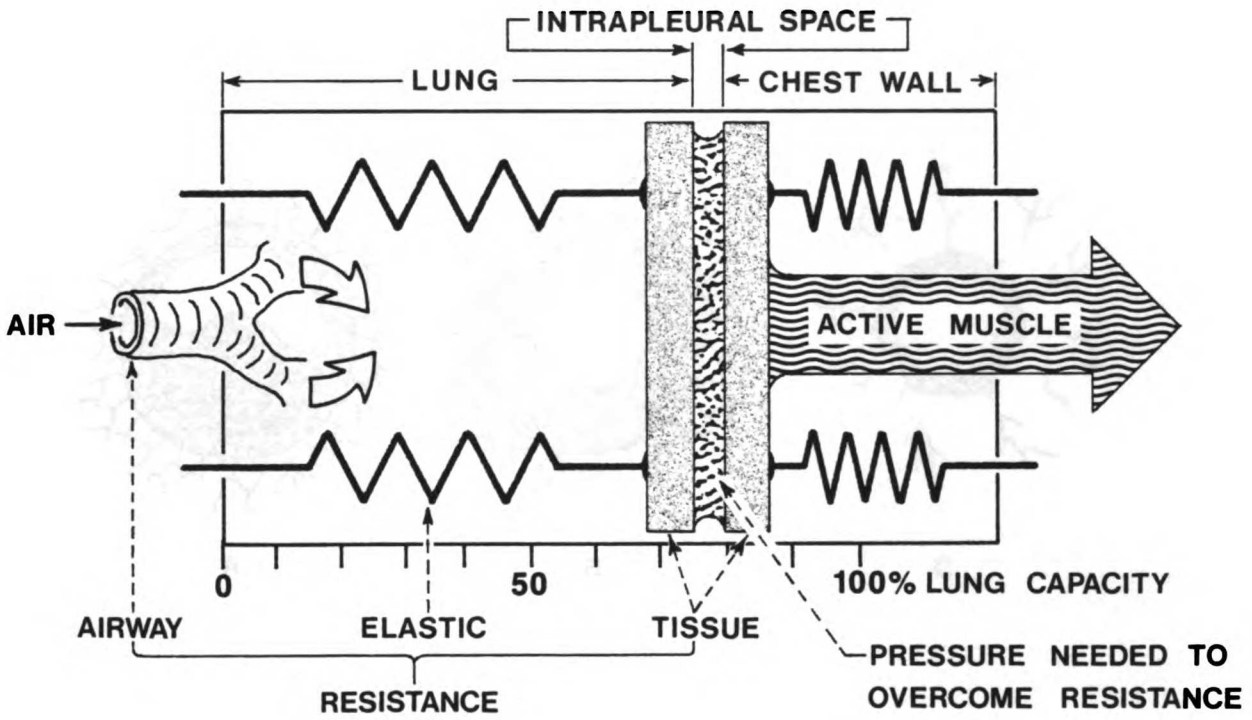

Figure 2. Resistance to Breathing. Active muscular contraction generates the pressure required to overcome elastic and non-elastic (airway and tissue) resistance to airflow. (Adapted from Cherniack, et al. 1972).

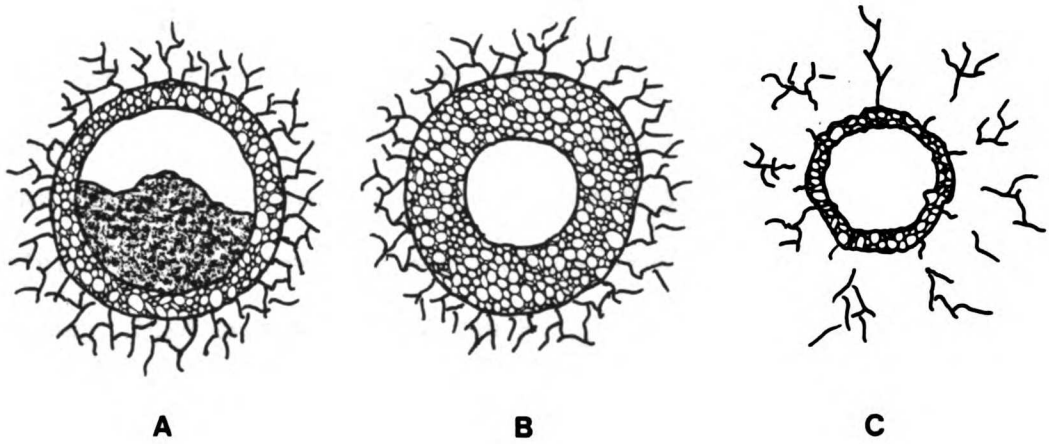

Figure 3. Types of Airway Resistance. Narrowing of airways can be caused by intraluminal obstruction (A), thickening of the airway wall (B), or external compression (C). (Adapted from West, 1977).

decreased tethering and increased airway resistance.

The larger the lung volume the more the elastic tissue is stretched and the larger the airways. On forced, complete exhalation, the chest wall contracts down and the lung volume is compressed. At this residual volume, the compressed elastic tissue has a tendency to return to its relaxed state at FRC. As the lung tends to enlarge toward FRC, Ppl is made positive. When surrounded by positive pressure and not subject to tethering from the surrounding tissue, airways close, trapping the residual volume in the lungs. When lung volume is very low or when there is diminished radial traction because lung tissue has been lost, the airways may close even without a forced exhalation.

The types of resistance which must be overcome during ventilation can be conveniently divided into two types: elastic and non-elastic. Elastic resistance is created by both the lung and the chest wall and is reflected in the transpulmonary pressure. Non-elastic resistance is created by the airways and viscous structures which are deformed or displaced during breathing such as the abdominal wall and the abdominal contents. Since more than 90% of non-elastic resistance is created by the airways it is fairly accurate to consider non-elastic resistance to be reflected in the pressure drop: Pao-Palv. Exceptions to this would be in conditions where excessive tissue must be displaced, as in obesity. Non-elastic resistance is only encountered while the volume of the lung is in the process of changing, that is, during air flow. Elastic resistance differs from this

in that it is dependent on lung volume, not on air flow.

The amount of pressure which must be generated to overcome resistance and allow air flow into the lungs reflects the compliance of the respiratory system. Compliance is a measure of the ease with which air can flow into the lungs; it is defined as the change in volume divided by the change in pressure. There are two types of compliance which correspond to the two types of resistance: static compliance and dynamic compliance.

Static compliance reflects the elastic properties of the lung and chest wall. It is measured under conditions of no air flow, when Pao-Palv is zero. Since stretched elastic tissue has a tendency to relax, deflating the lung to FRC, a certain amount of pressure is required just to keep the lungs inflated. When compliance is reduced, an elevated Pao is required to hold the lungs at any given volume over FRC. In restrictive lung disease, when the chest cavity cannot enlarge well due to chest wall or diaphragmatic problems, the Palv-Ppl difference will be small. When the alveoli are diseased and resist expansion, the Pao-Palv difference will be small. In either situation air flow will be limited. A large pressure change would be required to hold the lungs inflated at any given volume change; this is a poorly compliant lung. Dynamic compliance differs from static compliance in that it reflects the total pressure required to inflate the lungs. It is measured during air flow and reflects not only the elastic resistance of the lung and thoracic cage but also the non-elastic resistance.

POSITIONING AND THE DISTRIBUTION OF VENTILATION

The non-uniform distribution of $\dot{V}$ has been recognized for some time

(Fowler, Cornish & Kety, 1952). In spontaneously breathing subjects with healthy lungs $\dot{V}$ occurs preferentially in dependent regions. This occurs regardless of body position and has been documented in the seated versus supine positions (Bryan, Bentivogglio, Beerel, MacLeish, Zidulka & Bates, 1964) and in a comparison of the prone, right lateral, left lateral and supine positions (Kaneko, Milic-Emili, Dolovich & Bates, 1966). There are several factors which may contribute to the non-homogeneous pattern of ventilation seen even in healthy lungs. Regional variation in $\dot{V}$ has been attributed to differences in Ppl (Banchero, Rutishauser, Tsakiris & Wood, 1966; Rutishauser, Banchero, Tsakiris, Edmundowicz & Wood, 1966; Zardini & West, 1966) as well as to lung volume (West, 1979, p. 97).

Intrapleural pressure is not the same at all points within the chest. It is more negative in the non-dependent regions than it is in the dependent regions. This can be attributed to the force of gravity on the lung. The lung has a certain amount of weight as it hangs within the thorax. In the non-dependent lung regions the effect of gravity on the lung's weight adds to the elastic recoil of the lung, both tending to pull the lung away from the chest wall. In the dependent lung regions the effect of gravity is to push the lung toward the chest wall, opposing the lung's natural recoil. Thus, at the top of the lung, where the effect of gravity works in conjunction with the elastic nature of the lung, the Ppl is more negative than it is at the bottom of the lung where the force of gravity and the elastic recoil of the lung work in opposite directions. (see Figure 4).

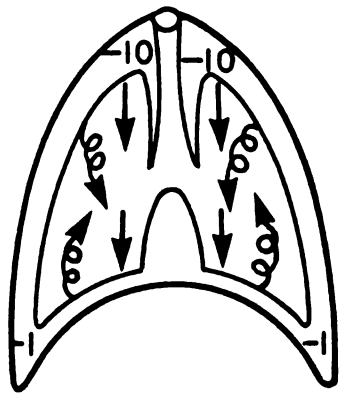

Figure 4. Influence of Gravity and Elastic Recoil on Intrapleural Pressure. At the top of the lungs where gravity (straight line) and elastic recoil (curled line) both tend to pull the lung away from the chest wall, intrapleural pressure is more negative than it is at the bottom of the lung where elastic recoil is opposed by gravity.

Because of the regional gradient for intrapleural pressure, different parts of the lung will be expanded to different degrees at any given lung volume. During conditions of no air flow when the glottis is open, the alveoli are connected through an open system to the atmosphere. The pressure in the alveoli throughout the lung is equal to atmospheric pressure (P_B). Since the Ppl is more negative at the top of the lung it follows that the P_L is greatest in this area. This keeps the non-dependent lung parenchyma expanded more fully than the dependent parenchyma which is exposed to less negative Ppl and thus has a lower P_L.

The relationship between the change in lung volume seen with any given change in pleural pressure allows the construction of a pressure-volume (P-V) curve for the lung (see Figure 5). Because of the regional gradient seen in alveolar volume, different parts of the lung lie on different parts of the curve at any given total lung volume. The relatively large alveoli in the non-dependent lung regions lie high on the curve; the smaller alveoli in dependent regions lie lower on the curve. The slope of the P-V curve measures pulmonary compliance. When compliance is high, a small change in pressure results in a large change in volume and the slope is steep. When compliance is low, a small change in pressure results in only a small change in volume and the curve is relatively flat.

As the chest wall expands and air flows into the lungs, it will flow preferentially to the areas of greatest compliance. At normal lung volumes the relatively large, non-dependent alveoli lie on a part of the curve which is not as steep as the part of the curve where the smaller dependent

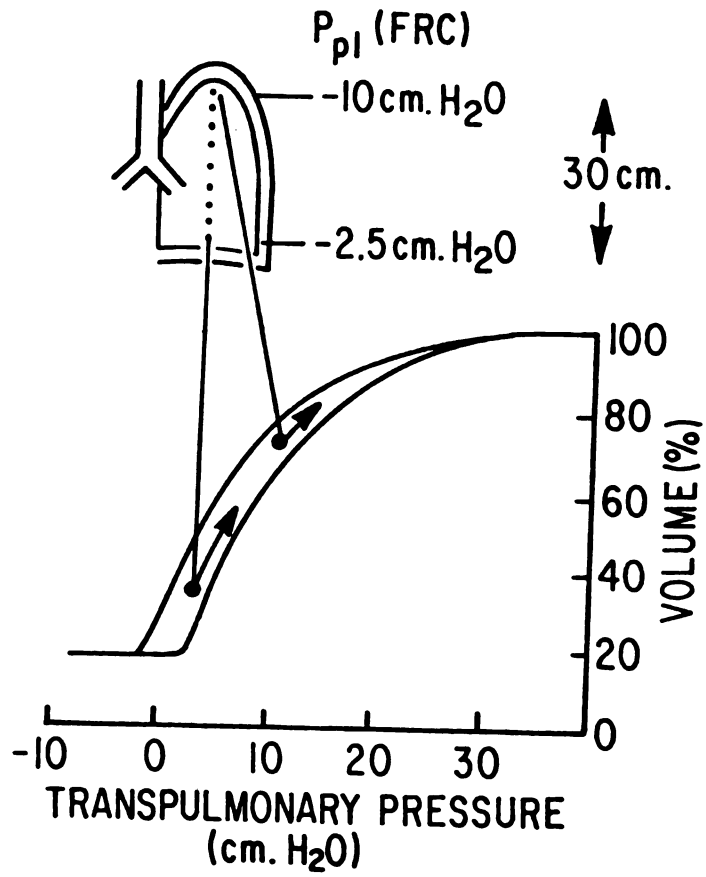

Figure 5. Pressure-Volume Curve of the Lung at Normal Lung Volumes. At functional residual capacity (FRC), intrapleural pressure is more negative at the apex than at the base of the lung. The alveoli at the apex are thus larger than those at the base and lie higher on the curve. Inspiration from FRC results in a greater change in the volume of the basal alveoli than of those at the apex where the curve is less steep. (Redrawn from West, 1977.)

alveoli are located. Thus, at normal lung volumes, such as FRC, ventilation occurs preferentially to the dependent regions of the lung. At high lung volumes, when the alveoli are all very large and lie high up on the P-V curve, there is little difference in their compliance and ventilation will be distributed in a more homogeneous manner (see Figure 6).

At low lung volumes the distribution of ventilation may be complicated by airway resistance in the form of airway closure. Airway closure is seen primarily in the dependent lung zones where Ppl is less negative, the alveoli are smaller and there is less radial traction on the airways. The lung volume at which airways close is called the closing volume (CV). When CV is greater than the normal resting volume (FRC) some of the airways close before exhalation is completed. A large pressure gradient must then be generated with the next inspiration to reopen the closed airways before the distal alveoli can be ventilated. The compliance of this distal region is low because of airway resistance and ventilation will occur preferentially to other areas of the lung (see Figure 7).

When CV exceeds FRC, gas exchange has been found to decrease (Craig, Wahba, Don, Couture & Becklake, 1971; Rea, Withy, Seelye & Harris, 1977). This phenomenon has been attributed to gas trapped in regions of the lung which continue to be perfused (Don, Craig, Wahba, & Couture, 1971). The situation is analogous to that described earlier when a bronchus obstructs. If the airway remains closed but the distal alveoli continue to be perfused, gas exchange will deteriorate.

The relationship between CV and FRC is influenced by both position and

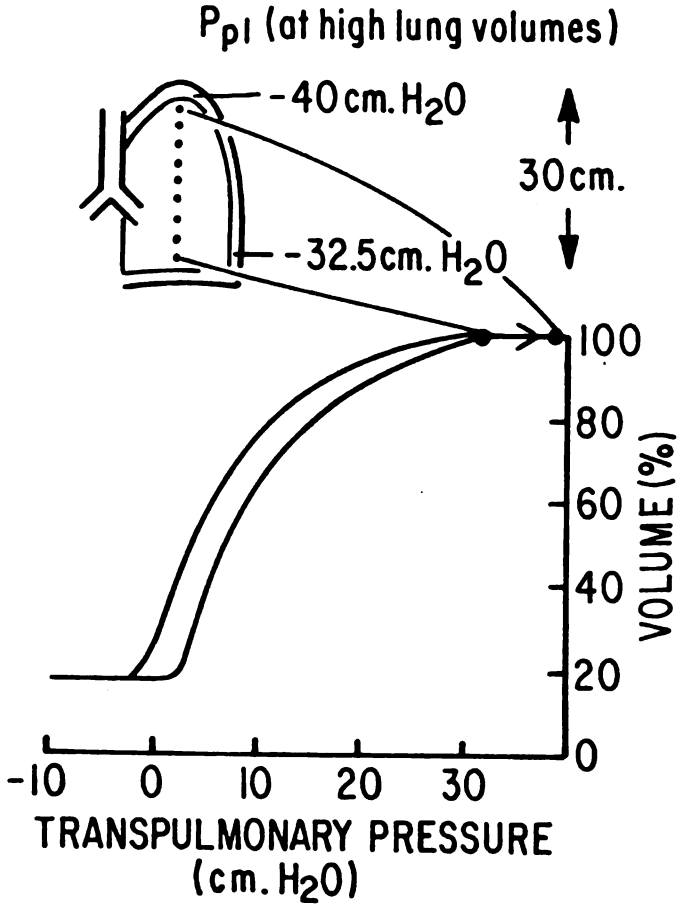

Figure 6. Pressure-Volume Curve of the Lung at High Lung Volumes. The alveoli are all very large and lie on a fairly flat section of the curve. Inspiration is distributed in a relatively homogenous manner. (Redrawn from West, 1977.)

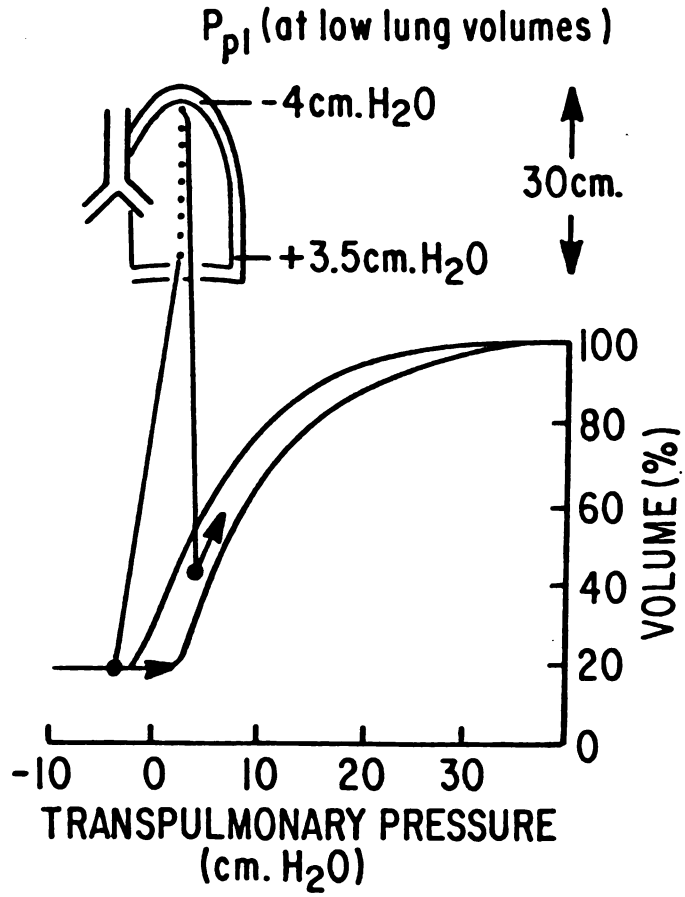

Figure 7. Pressure-Volume Curve of the Lung at Low Lung Volumes. At low lung volumes the distribution of ventilation to basal regions may be limited by closure of airways. A larger than normal pressure gradient must be generated to re-open the airways before the distal alveoli can be ventilated. (Redrawn from West, 1977.)

age. FRC has been shown to decrease when going from the seated to the supine position, while CV remains essentially unchanged (LeBlanc, Ruff & Milic-Emili, 1970). Younger subjects (less than 35 years old, Don, et al., 1971; less than 44 years old, LeBlanc, et al., 1970), tend to have a CV which is less than FRC in both supine and sitting positions, and thus have adequate gas exchange in either situation. Above this age, and up to about age 65, CV tends to be above FRC when supine, but when seated the increase in FRC results in improved gas exchange. LeBlanc et al.(1970) have demonstrated a tendency for CV to move above FRC in the over 65 age group even when sitting, accounting for the lower PaO_2 seen in this group regardless of position. The decrease in elastic tissue seen with aging may be responsible for this increase in CV, as the tethering effect on the airways is decreased.

Positioning influences the distribution of ventilation to spontaneously breathing subjects by altering the pressures and resistances which affect the respiratory system's elastic qualities as well as the airway component of the non-elastic qualities. In some situations, positioning can affect the distribution of ventilation by altering the tissue component of the respiratory system's non-elastic qualities. Although displacing the thorax and abdominal tissue normally accounts only for about 10% of non-elastic resistance to air flow, it becomes a more important factor in the distribution of $\dot{V}$ to a patient on a positive-pressure ventilator. These patients do not have a significant respiratory change in Ppl. The total difference in the regional gradient of Ppl is minimal compared to the pressures usually required by the ventilator to deliver the tidal volume.

In this situation, displacing the diaphragm becomes crucial in the distribution of ventilation. Since the positional effect of gravity on intra-abdominal contents makes the diaphragm easier to move in non-dependent regions, ventilation occurs preferentially to non-dependent lung zones. This distribution of ventilation is distinctly different from that seen in a spontaneously breathing subject.

ATELECTASIS AND THE DISTRIBUTION OF VENTILATION

The development of atelectasis can be expected to effect ventilation in both the collapsed tissue and the remaining aerated tissue. Since atelectasis is defined as the complete loss of alveolar air space, it follows that no ventilation whatsoever occurs there. Poorly compliant alveoli and closed airways are probably the cause of this. The pressure in a collapsed region of the lung is thought to be close to the Ppl (Finley, Hill & Bonica, 1963; Morgan & Guntheroth, 1970). Thus, atelectatic alveoli, being filled with a similar pressure as that which surrounds them, do not develop a P_L difference which would allow air to flow in.

To re-ventilate an area of atelectasis, a larger than normal pressure gradient must be developed. Patients are encouraged to take deep breaths, making Ppl more negative, or are given positive pressure ventilation, making airway pressure more positive. Factors which facilitate more negative Ppl immediately surrounding the collapsed region are utilized: post-operative patients with dependent atelectasis are encouraged to sit up or stand and ambulate; bedridden patients are turned with the collapsed lung up.

In addition to the alterations in ventilation seen in the collapsed tissue, atelectasis may also result in altered ventilation in the rest of the spontaneously breathing lung. Niden (1964) reported that atelectasis resulted in a two to four fold increase in respiratory minute volume due to an increase in rate, tidal volume or both. Morgan and Guntheroth (1970) noted that atelectasis resulted in an increased depth of respiration without a change in the respiratory rate. Finley et al. (1963) also reported hyperpnea following one lung atelectasis, although they based this judgment on changes in Ppl, and did not report control Ppl values.

DISTRIBUTION OF PERFUSION

As with the distribution of $\dot{V}$, the distribution of $\dot{Q}$ will follow the path of least resistance. Blood flow is proportional to the change in pressure across the vascular bed and inversely proportional to vascular resistance. It is influenced by body position and disease.

PRESSURES AND RESISTANCES INVOLVED IN PERFUSION

The caliber, and thus, the resistance of blood vessels depends upon the balance between the pressures inside and outside the vessel wall. This pressure difference across the wall is referred to as the transmural pressure. Due to the parallel arrangement of vessels in the pulmonary circulation the pressures within the vessels tends to be low.

The pressure outside pulmonary vessels varies in different parts of the circulatory system (see Figure 8). Capillaries are virtually surrounded by alveoli and have very thin walls which provide little support, so they are liable to collapse or distend depending on the

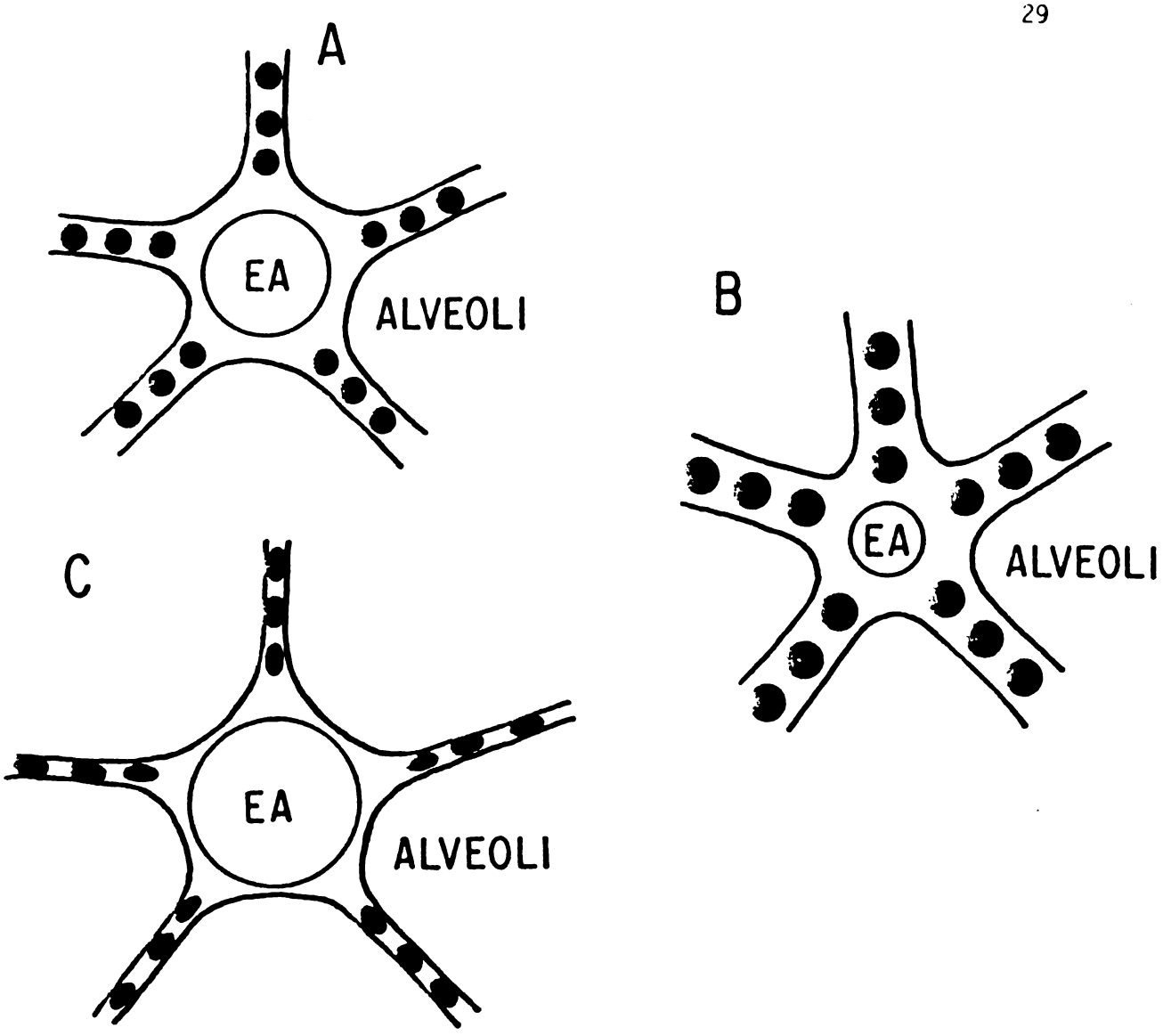

Figure 8. Influence of Surrounding Pressure on Resistance in Alveolar and Extra-alveolar Vessels. At normal lung volumes (A), resistance is moderate both in the alveolar vessels (dark circles or ovals) which are surrounded by alveoli and in the extra-alveolar vessels (EA) which are surrounded by interstitial space. At low lung volumes (B), alveoli are small and do not compress the alveolar vessels, thus the resistance of these vessels is low. The interstitial space is compressed at low lung voluems resulting in high resistance of the extra-alveolar vessels. At high lung volumes (C), alveoli are large and compress the alveolar vessels thus increasing their resistance. Interstitial pressure is low because of stretched elastic tissue. This expands the extra-alveolar vessels and lowers their resistance.

pressure which surrounds them. As the alveoli expand during inspiration, the transmural pressure changes with the tendency toward vessel collapse. In contrast to the capillaries, the walls of pulmonary arteries and veins contain smooth muscle and elastic tissue which tend to resist distension. These vessels are imbedded in the interstitial space of the lung parenchyma and their walls are tethered by elastic fibers in a similar manner to the tethering of airways already discussed. As the lung volume increases during inspiration and the elastic tissue is stretched, transmural pressure is altered and the vessel diameter enlarges.

The capillaries in the pulmonary circulation behave so differently from the arteries and veins that they are often referred to as alveolar vessels to distinguish them from the arteries and veins which are called extra-alveolar vessels. The caliber of the alveolar vessels is determined by the relationship between capillary hydrostatic pressure and the alveolar pressure. The caliber of the extra-alveolar vessels is determined by the relationship between the hydrostatic pressure in the artery or vein and the amount of tethering present at any given lung volume.

The total pulmonary vascular resistance (PVR) is composed of the resistance encountered in both the alveolar and the extra-alveolar vessels. The relationship between lung volume and total PVR forms a "U" shaped curve (see Figure 9). At physiologic lung volumes, resistance is low; however, resistance can increase by either increasing or decreasing volume. At low lung volumes the alveolar vessels are large but the extra-alveolar vessels are small. PVR is increased because of resistance in the extra-

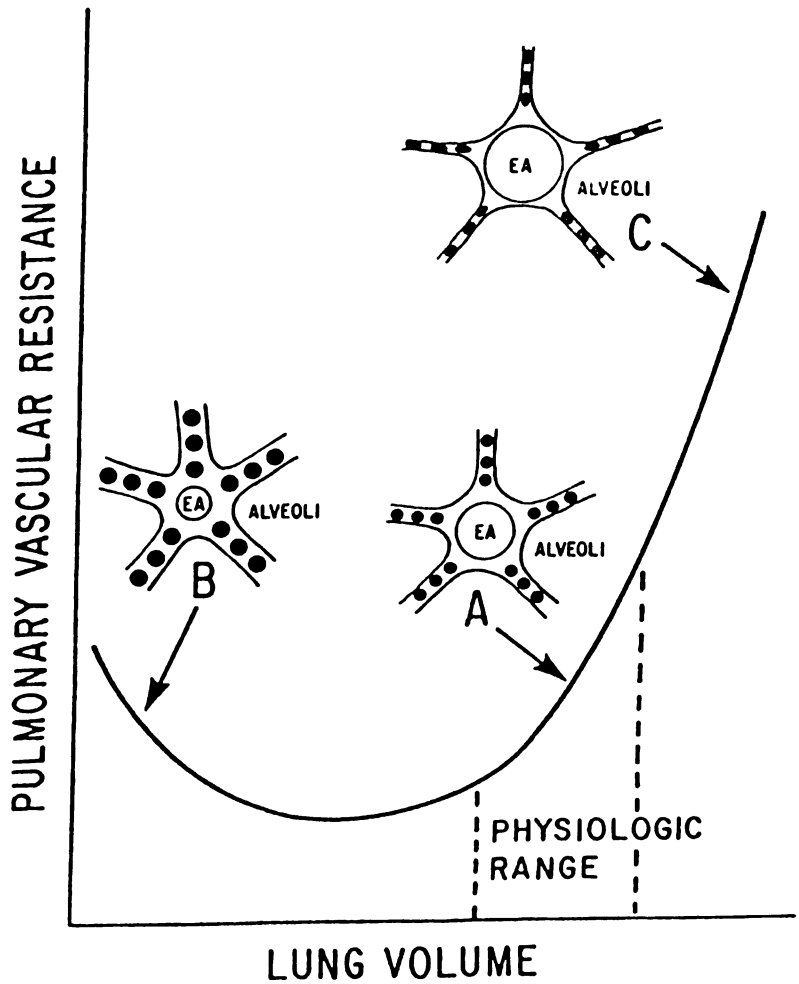

Figure 9. Lung Volume - Pulmonary Vascular Resistance Curve. Pulmonary vascular resistance (PVR) can increase by either increasing or decreasing lung volume from the physiologic range (A). At high lung volumes (C), PVR is increased because of high resistance in alveolar vessels; at low lung volumes (B), PVR is increased because of high resistance in extra-alveolar vessels. (Adapted from Niden, 1964).

alveolar vessels. At very high lung volumes PVR is also increased, this time because of the diminished caliber of the alveolar vessels, despite the fact that radial traction has expanded the extra-alveolar vessels.

Because of the role of smooth muscle tone in determining the caliber of the extra-alveolar vessels, PVR can also be influenced by anything that alters the vessel's muscular tone. Vasoconstriction of these vessels can be caused by chemical stimuli, such as alveolar hypoxia, acidemia and alveolar hypercarbia (in experimental animals but not in man), by humoral substances such as catecholamines, and by sympathetic stimulation (in experimental animals but not in man) (Murray, 1976, p. 128). Substances which cause active vasoconstriction are particularly effective at low lung volumes when the expanding force on the vessels is weak (West, 1979, p. 39).

The pressures which influence PBF are those found in the pulmonary artery (Ppa), the alveoli (Palv) and the pulmonary vein (Ppv). The Ppa must always be higher than the Ppv for flow to occur in the normal direction within the capillary bed. Flow can be obstructed to varying degrees, however, by the Palv. If the Palv is greater than the Ppa, no flow will occur. If the Palv is less than the Ppa but greater than the Ppv, the Palv will cause some resistance to flow. If the Palv is less than both the Ppa and the Ppv, the Palv will not influence flow at all.

Since all airways within the lung are connected, it is clear that as long as they are open, Palv will be the same throughout the lung. Normal regional variations in PBF then, must be explained in terms of differences in Ppa and/or Ppv. Variation in these pressures seen within the lung are

dependent upon the height to which the blood is pumped by the heart. Lower vascular pressures will be generated in areas where the heart must overcome gravity and higher vascular pressures will be generated in areas located below the level of the heart. Thus, the regional distribution of PBF is dependent on body position.

POSITIONING AND THE DISTRIBUTION OF PERFUSION

Perfusion in the normal lung has been shown to be distributed in a gradient with dependent regions receiving greater blood flow consistent with the effects of gravity. In upright man PBF increases in an almost linear fashion from top to bottom. With assumption of the recumbent position the distribution of $\dot{Q}$ from apex to base becomes nearly uniform, but a $\dot{Q}$ gradient is demonstrated between those regions which are superior and those which are dependent.

The change in flow with changes in position has been documented in the seated versus supine positions (Bryan et al., 1964), the supine versus right and left lateral positions (Katori, Amorim, Theye & Wood, 1970), and in a comparison of the prone, supine, lateral, Trendelenberg and reverse Trendelenberg positions (Reed & Wood, 1970). In the Reed and Wood study, basal flow was found to decrease with the head down. In contrast to this, Guntheroth, Morgan and Lintermans (1967), while finding increased upper lobe flow in the Trendelenberg position, did not find consistent decreases in the lower lobe flow.

The factors involved in determining the pressure gradient in which PBF occurs divides the lungs into three zones which are well accepted (see Figure 10) (West, 1979, p. 40).

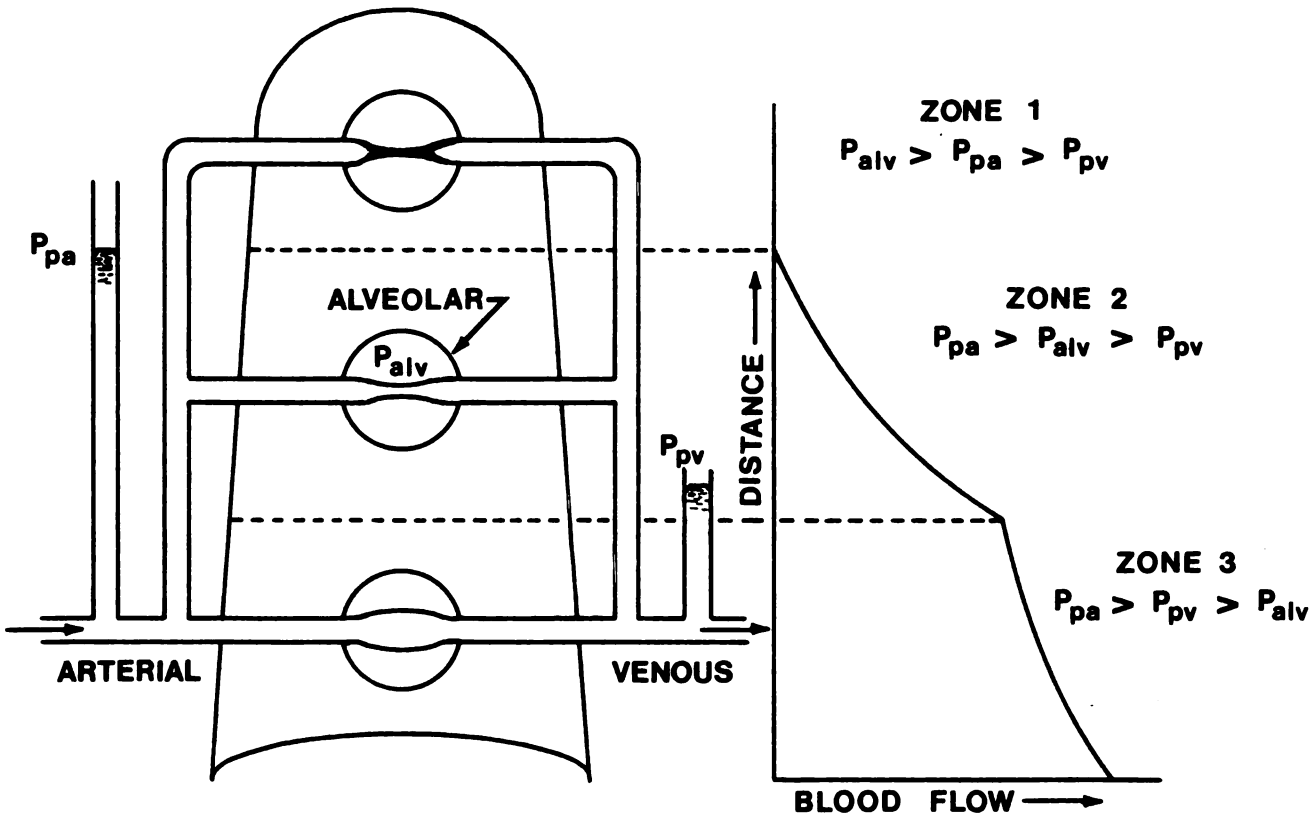

Figure 10. Distribution of Pulmonary Blood Flow by Lung Zones. In zone 1, alveolar pressure exceeds arterial pressure and no flow occurs. In zone 2 blood flow increases with gravitational increases in arterial pressure. Alveolar pressure, however, still exceeds venous pressure and so acts to impede flow. In zone 3 both arterial and venous pressures are greater than alveolar pressures, so flow is not inhibited by alveolar pressure. (Adapted from West, 1979).

There may be an area at the top of the lung (zone 1) in which Ppa falls below Palv and no flow occurs. Some authors identify this zone as extending down approximately 4 cm from the top of the lung in a man seated upright (Bates, Macklen & Christie, 1971, p. 48). West (1979, p. 42), however, concluded that this zone does not occur under normal conditions, but may develop if the Ppa is low, such as in shock, or if the Palv is increased, such as in positive pressure ventilation.

Below this superior region is zone 2. Here the Ppa is greater than the Palv, but the Palv in turn is greater than the Ppv. Flow is thus determined by the difference between Ppa and Palv. Since Ppa increases within this zone due to gravitational forces, blood flow also increases. Venous pressure does not influence flow in this zone.

Zone 3 is defined as that region toward the base of the lung where Ppa>Ppv>Palv. Driving pressure is now determined by the difference between Ppa and Ppv. Alveolar pressure remains the same throughout this zone but Ppa and Ppv increse, consistent with the effects of gravity. The increase in flow within this zone can be explained by capillary distension and perhaps recruitment.

In addition to the three well accepted zones, a small region where flow is decreased at the very base of the normal lung (zone 4) has been identified (Hughes, Glazier, Maloney & West, 1968). The cause of this reduction in flow is not certain, however, it may be due to increased interstitial pressures around the small vessels resulting from decreased expansion of lung parenchyma or from edema. When Hughes et al. (1968) increased lung volume to a P_L of 20 cm H_2O, this zone

disappeared.

ATELECTASIS AND THE DISTRIBUTION OF PERFUSION

Alterations in blood flow when part of the lung becomes atelectatic have been attributed to a change in local PVR. Disagreement exists as to the cause, the amount, the direction and the time course of the change. The two most prevalent theories used to explain the alteration in blood flow are (a) active vasoconstriction, mediated by elevated CO_2 in the pulmonary veins ($PpvCO_2$) or diminished O_2 in the alveoli (P_AO_2) and (b) passive mechanical compression. It may be that both of these factors are involved.

Most of the studies on blood flow in atelectasis have been designed to measure the change in flow and explain the physiology responsible for the change; conflicting results and interpretations have been reported. This may be due in part to the variety of models and methods which have been used to examine the problem. The studies are summarized in table 1. A discussion of the physiology responsible for alterations in blood flow follows, as does an attempt to reconcile some of the disagreement in findings based on the differences in experimental techniques.

Cause of Blood Flow Changes in Atelectasis

If the alterations in PBF seen with atelectasis were due strictly to hypoxic vasoconstriction, ventilation of the lung with hypoxic gas mixtures would result in changes in flow similar to that seen in atelectasis. Niden (1964) found that unilateral ventilation with N_2 produced less shunt that that seen in atelectasis. He concluded that mechanical factors were primarily responsible for the changes in PBF seen in atelectasis. Peters and Roos (1952) reported similar results. In contrast,

Author & date	Area of collapse	Method of obtaining atelectasis	Subjects	Ventilatory mode	State of chest	Anesthesia	FIO_2	Time to stabilize atelectasis before calculating flow	Method of assessing flow	Results
Aviado 1960	LLL	endo-bronchial obstruction with ligature	dogs	+ pressure ventilator	open or intact	morphine & chloralose	not specified	10 min. & every 10 min. for 1 hour	CaO_2 PVR	mean decrease of 1.6 vol%(closed chest) 3.1 vol%(open chest) decreasePVR within 30 sec. followed by a progressive increase blood flow decreased to approx. 85% of control
Barer et al 1979	LLL	endo-bronchial obstruction or ligature	dogs cats	+ pressure ventilator with periodic sigh breath or with 3-5 mmHg PEEP	open	ethyl chloride & ether followed by chloralose, or chloralose alone, or pentobarbital for cats, morphine and pentobarbital for dogs	100% or 21%	15 min.	flowmeter PVR	flow fell to 29% of control (cats) and to 46% of control (dogs) rapid increase
Benumof 1979	LLL	ligature	dogs	+ pressure ventilator	open	pentobarbital & gallamine	100%	20 min.	flowmeter	flow fell to 41% of control
Björk & Salén 1950	R lung	endo-bronchial obstruction	dogs	not specified but probably spontaneous	not specified but probably intact	narcotal	100%	not specified	angiography SaO_2	contrast filling of pulmonary arteries & veins simultaneously on both sides fell to 88% concluded decreased but still considerable flow through atelectatic tissue
Camishion et al 1961	L lung	ligature after manual compression	dogs	+ pressure ventilator	open	pentobarbital	not specified	30 min. & every hour for 3 hrs.	flowmeter PaO_2	unpredictable (increasing, decreasing, or remaining unchanged) in 1st hr. gradually decreasing to approx. 60% of control by 3 hr. fell from approx. 100 to 88 at 1 hr. and rose to 94.5 by 3 hr.
Elebute et al 1966	L lung	bronchus transected with ends sutured closed	dogs	+ pressure ventilator with periodic sigh breath	open or closed after opening with aspiration of pneumothorax	pentobarbital & succinylcholine	21% (no denitrogenation)	1 hr. every 30 min. for 3hr.	$\dot{Q}s/\dot{Q}t$ flowmeter	7.8% control 59.3% post-atelectasis (closed chest) 53.2% control 70% post-atelectasis (open chest - this represents an apparent 60% decrease in flow but data was invalidated due to high value for control shunt) 25% increase in flow
Enjeti et al 1979	sublobar	endo-bronchial obstruction	pigs	+ pressure ventilator	intact	pentobarbital & succinylocholine	21% (after denitrogenation for 20 min.)	45 min.	microspheres PVR	flow fell to 12% of control approx. 10 x increase
Finley et al 1963	L lung	endo-bronchial obstruction	dogs	spontaneous	intact	pentobarbital	100%	several min.	$\dot{Q}s/\dot{Q}t$	decrease in flow to 22% CO with Ppl range of -3to -12cmH_2O (assumed control of 45%) remained at 45% CO with more negative Ppl range of -7.5 to -24cmH_2O

Table 1. Comparison of Studies on Blood Flow to Atelectatic Tissue. Variations in models and methods used to study the effect of atelectasis on perfusion to the collapsed area may explain some of the differences in results. (Adapted and expanded from Hobbs et al. 1972.)

Author & date	Area of collapse	Method of obtaining atelectasis	Subjects	Ventilatory mode	State of chest	Anesthesia	FIO_2	Time to stabilize atelectasis before calculating flow	Method of assessing flow	Results
Fisher et al 1979	R or L lung	endo-bronchial obstruction	humans	+ pressure ventilation	open	thiamylal & flurothane	100%	observations made over 2 hr. period	$\dot{Q}s/\dot{Q}t$	18% control shunt rose to 36% at 5 min. gradually falling to 25% at 2 hr.
Hobbs et al 1972	LLL	endo-bronchial obstruction	dogs	spontaneous with sighs	intact	halothane nitrous oxide	50%	measured at 15, 30, and 120 min. after occlusion	microspheres	immediate and sustained decrease in flow to 80% of control
Kersten et al 1977	LLL	endo-bronchial obstruction	dogs	spontaneous	intact	pentobarbital	100%	measured every 30 min. for 5 hrs.	$\dot{Q}s/\dot{Q}t$	rose from 11.2% to 17.2% and fell to 11.9% by 2 hr.
MacVaugh et al 1961	L lung	ligature	dogs	+ pressure ventilator	open	pentobarbital	not specified (after de-nitrogenation)	10 min.	flowmeter	flow fell to 62% of control
Morgan & Guntheroth 1970	R or L lung	endo-bronchial obstruction	dogs	spontaneous	closed (data collected 5 days-6 weeks after chest had been opened for flowmeter implantation)	pentobarbital	not specified	30 min.	flowmeter PVR	flow fell to 96% of control in atelectatic lung increased by 15% in other lung increased by 8% Total PVR increased by 11%
Newell et al 1976	L lung	endo-bronchial obstruction	dogs	+ pressure ventilation, 3-5cmH_2O PEEP and periodic sighs	open	pentobarbital	21% or 100%	at least 15 min.	flowmeter	flow fell to 80% of control (with 21% O_2) 54% of control (with 100%O_2)
Niden 1964	segment lobe, or whole lung	endo-bronchial obstruction	dogs	- pressure ventilation or spontaneous	open or intact	morphine & chloralose	21%(increased to 100%, 10-15 min. before each blood gas measurement	variable 10-260 min.	$\dot{Q}s/\dot{Q}t$ PVR histological preparation	shunt ranged from 30-83% (intact chest) shunt increased more than % of tissue collapsed so concluded blood flow increased decreased in atelectatic tissue dilated capillary bed filled with RBC's
Peters & Roos 1952	L lung	ligature	dogs	+ pressure ventilator	open	pentobarbital or chloralose & morphine	not specified (after de-nitrogenation)	from 10 min. to 2½ hrs.	Fick principle PVR	flow reduced to 0-34% of CO within 10-45 min. with no significant progression after this (assumed 40-45% of CO perfused L lung in control period - was not measured)
Woodson et al 1963	RLL	endo-bronchial obstruction with ligature	dogs	+ pressure ventilator	open	pentobarbital	21%	at least 15 min.	flowmeter PVR	flow decreased to 63% of control increased 93%

Table 1. Comparison of Studies on Blood Flow to Atelectatic Tissue (continued).

Barer, Howard, McCurrie and Shaw (1969) found that ventilation with hypoxic mixtures caused a decrease in flow similar to that seen in atelectasis as long as O_2 tension in the pulmonary veins ($PpvO_2$) was equivalent. Neither Niden (1964) nor Peters and Roos (1952) measured $PpvO_2$ from the atelectatic tissue. Bjork and Salen (1950) found equivalent arterial oxygen saturations (SaO_2) with unilateral atelectasis and with N_2 ventilation.

Woodsen, Raab and Ferguson (1963) examined the relative importance of the effect of hypoxia, hypercapnia and atelectasis on pulmonary blood flow. Hypoxia was created by N_2 ventilation with O_2 or CO_2 mixtures and atelectasis by bronchial occulsion. In each condition the affected lobe was perfused independently with mixed venous blood and with arterial blood. Nitrogen ventilation decreased flow by 19% (venous perfusion) and 14% (arterial perfusion). Atelectasis decreased flow by 37% (venous perfusion) and 23% (arterial perfusion). Ventilation with CO_2 mixtures produced no significant alterations in flow. The authors concluded that the decrease in flow to an atelectatic lobe resulted primarily from mechanical factors, with associated hypoxia significant, but of secondary importance. Other authors (Aviado, 1960; Barer et al., 1969), however, were able to completely reverse the decrease in flow to atelectatic tissue by perfusing it with arterial blood, suggesting no role for mechanical factors.

Although Woodsen et al. (1962) found no evidence of a local chemoreceptor mechanism for hypercarbia, Aviado (1960) concluded that this mechanism was the principle cause of reduced blood flow in atelectasis.

Because he was able to completely reverse the increased PVR in the atelectatic lobe by perfusing it with normoxemic arterial blood from a donor dog, he concluded that the decrease in PBF through atelectatic tissue occurred because of exposure of pulmonary capillaries and veins to desaturated venous blood. Citing his previous findings (Aviado, Ling & Schmidt, 1957) that anoxemia locally dilated pulmonary vessels while hypercapnea locally constricted them, Aviado concluded that the mechanism responsible for increasing PVR in atelectasis was high $PpvCO_2$.

Barer et al. (1969) have since refuted this conclusion by measuring the gases in the blood draining from the atelectatic lobe. As the oxygen was absorbed from a collapsing lobe, the $PpvO_2$ fell and there was a rapid reduction in flow which corresponded to a decrease in $PpvCO_2$. This surprising decrease in $PpvCO_2$ was suggested to reflect overall improvement in gas exchange as flow through the atelectatic lobe was diminished.

Pulmonary vasoconstriction in response to alveolar hypoxia has been found to occur within 1 minute, with PVR returning to control values within 2 minutes when alveoli were again ventilated with normoxemic gas mixtures (Kersten & Humphrey, 1979). If alveolar hypoxia alone were responsible for the decrease in flow seen with atelectasis, flow would decrease within minutes of collapse and remain stable at this lower level as long as the atelectasis persisted. Hobbs, Hinchcliffe and Greenspan (1972) examined changes in PBF over the first 2 hours after the onset of atelectasis in dogs. Differentially-labeled radioactive microspheres were injected at 25 and 5 minutes prior to bronchial occlusion and again at 15, 30 and 120 minutes after occlusion. Blood flow

to the atelectatic lobe decreased rapidly to 80% of control within 30 minutes and remained at this value when assessed 2 hours after occlusion. Aviado (1960) noted systemic hypoxemia within 10 minutes after occlusion and found this value to remain constant over the next hour.

Other researchers, however, found that the mechanism responsible for diverting blood away from atelectatic tissue took several hours to develop fully. Camishion, Ota, Cuddy and Gibbon (1961) utilized flowmeters to study blood flow in left lung atelectasis with an open chest canine model. Flow was found to be unpredictable for the first 45 minutes, only slightly reduced after 1 hour, and significantly reduced by the second hour. In man, Fiser, Friday and Read (1979) measured shunts in whole lung collapse during therapeutic chest surgery. The initial shunt of 18% rose to 36% within 5 minutes of collapse and dropped to 30% after 15 minutes. The shunt gradually lessened with time, reaching 25% after 2 hours. Kersten, Mayer, Varco and Humphrey (1977) found the shunt rose with the onset of atelectasis from 11.2% to 17.2% and gradually returned to 11.9% by the end of 2 hours. The control group, who had no atelectasis, maintained a 9% shunt throughout the experiment.

In addition to having a rapid onset of action, hypoxic vasocontriction should reverse quickly upon correction of alveolar hypoxia. Thus, if hypoxic vasoconstriction alone were responsible for decreasing flow in atelectasis, the reinflation of the lung would rapidly restore normal blood flow. Creating a lobar atelectasis in closed chest canine models, Kersten et al. (1977) assessed the effect of reversing and then re-creating the atelectasis on pulmonary shunt. The atelectasis was allowed to

stabilize for 2 hours, then the authors state the lobe was re-inflated. This was followed by the atelectasis being re-created at either 20 minutes, 1 hour or 4 hours post re-inflation. Only in the group whose lobe was allowed to remain re-inflated for 4 hours preceeding the second collapse did the shunt rise again to the initial high value. The groups whose atelectasis had been reversed for shorter periods of time before being re-collapsed had a rise in shunt only comparable to that seen in the group whose atelectasis was maintained throughout the experiment. The authors speculated that the mechanism responsible for diverting blood flow away from atelectatic tissue persisted for somewhere between 1 and 4 hours despite re-expansion. This was in contrast to the immediate reversal which would have been expected if only hypoxic vasoconstriction were responsible for the blood flow diversion. It must be mentioned, however, that the authors did not state how they evaluated their ability to re-inflate the lobe in this closed chest preparation. If the lung were not fully expanded, then persistent alveolar hypoxia or mechanical factors could be responsible for the data obtained.

MacVaugh, Hardesty, Demuth, Yalav and Blakemore (1961) studied flow during left lung atelectasis. Prior to atelectasis, flow to the left lung was 37% of the cardiac output. Ten minutes after atelectasis was created, flow decreased to 23% of the cardiac output. Flow returned to 36% ten minutes after re-expansion. Similar results were found during collapse of the left lower lobe (LLL).

If the alterations in PBF were due strictly to mechanical factors, re-expansion of collapsed tissue should restore flow to normal regardless

of the type of gas used. Benumof (1979) observed a 59% decrease in flow when the LLL was collapsed. Re-expansion and ventilation with a mixture of 95% N_2 and 5% CO_2 did not cause any significant increase in flow. When the ventilating gas was changed to 100% O_2, blood flow returned to levels not significantly different from control. Hypoxic vasoconstriction was concluded to be the main mechanism for decreasing flow to atelectatic tissue.

If the pulmonary vessels to the collapsed lung tissue were merely compressed from without and experienced no active vasoconstriction, vasodilator drugs would not be expected to increase the flow. Barer et al.(1969) found lobar atelectasis to cause 71% and 54% decrease in flow in cats and dogs respectively. By controlling perfusion at a constant level they identified increased PVR as the cause of the decrease in flow. Reversal of the increased resistance was obtained with vasodilator drugs and by perfusing the lungs with arterial blood. The authors concluded that the increase in PVR seen in atelectasis was caused by an active mechanism rather than a passive mechanical one.

The Effect of Experimental Techniques

Some of the differences in findings of the studies on blood flow in atelectasis might be attributed to differences in experimental techniques. Blood flow has been measured both directly and indirectly and over varying periods of time. Atelectasis has been created in a variety of ways in both open and closed chest models, using man, dogs, pigs or cats as subjects. Respiratory modes have included spontaneous breathing as well as both positive and negative pressue mechanical ventilation. Anesthesia

has been achieved in various ways; supplemental oxygen was not always given. All of these factors may alter pulmonary blood flow in atelectasis; they are discussed below.

Fraction of Inspired Oxygen

The use of room air to ventilate the lungs may result in systemic hypoxemia once atelectasis has been created. Elebute, Masood, Faulkner, Yu and Schwartz (1966) used no supplemental oxygen and had PaO_2 values as low as 33 mmHg 1 hour after the atelectasis was produced. Systemic hypoxemia may result in increased ventilation (Bates et al., 1971, p. 102), tachycardia and hypertension (West, 1977, p. 158), local vasodilation of pulmonary vessels, which may be overridden to some extent by neurogenic reflexes to vasoconstrict them (Aviado et al., 1957), and failure of the atelectatic tissue to redirect blood flow to healthier lung regions (Kersten et al., 1977; Newell, Levitzky, Krasney & Dutton, 1976). All of these effects of systemic hypoxemia may alter the distribution of PBF and make it difficult to differentiate between the effect of the hypoxemia and that of the atelectasis.

Newell et al. (1976) demonstrated that blood flow to an atelectatic lobe fell to 54% of control when the animal was ventilated with 100% O_2. When the inspired gas was changed to 21% O_2 and the systemic PaO_2 dropped to 64 mmHg, flow to the atelectatic lobe rose to 80% of control. The mild systemic hypoxemia reported by Aviado (1960), particularly in his open chest models might, in part, explain the relatively small drop in blood flow (15%) which he reported. Camishion et al, (1961) studying 16 dogs found that in the first 30 minutes after lung collapse blood flow

was unpredictable. In about half their animals flow increased and in the other half it decreased. With the exception of three dogs who had increased flow despite an SaO_2 of 90-93%, all of the animals who were able to decrease flow through the atelectatic tissue had an SaO_2 of greater than 85% and all of the animals in whom flow increased had an SaO_2 of less than 67%.

When PaO_2 drops following atelectasis, it may or may not occur because of shunting in the atelectatic tissue. Other causes of hypoxemia must be considered, including hypoventilation, $\dot{V}/\dot{Q}$ mismatching and diffusion barriers. The various causes of hypoxemia are explained in Figure 11. Ventilation with 100% O_2 eliminates gradients between the alveoli and the capillaries, thus correcting all causes of hypoxemia except shunt. When PaO_2 is low during ventilation with 100% O_2, it can more reliably be attributed to shunting through the tissue where the atelectasis was created. Another explanation which must be considered, however, is that shunting exists elsewhere in the lung, such as would occur if areas of atelectasis developed spontaneously during the experiment.

Because O_2 is so soluble, its use potentiates the problem of absorption atelectasis occurring in areas of the lung which were not subject to experimental collapse. Enjeti, O'Neill, Terry, Menkes and Traystman (1979) demonstrated on autopsy spontaneously developed areas of atelectasis in anesthetized animals who had been breathing 100% O_2 during the experiment. Niden (1964) assessed the effect of alternating administration of 100% O_2 for 20 minutes with room air for 30 minutes in four dogs over a 3-4 hour period. He found the shunt rose 6% in one

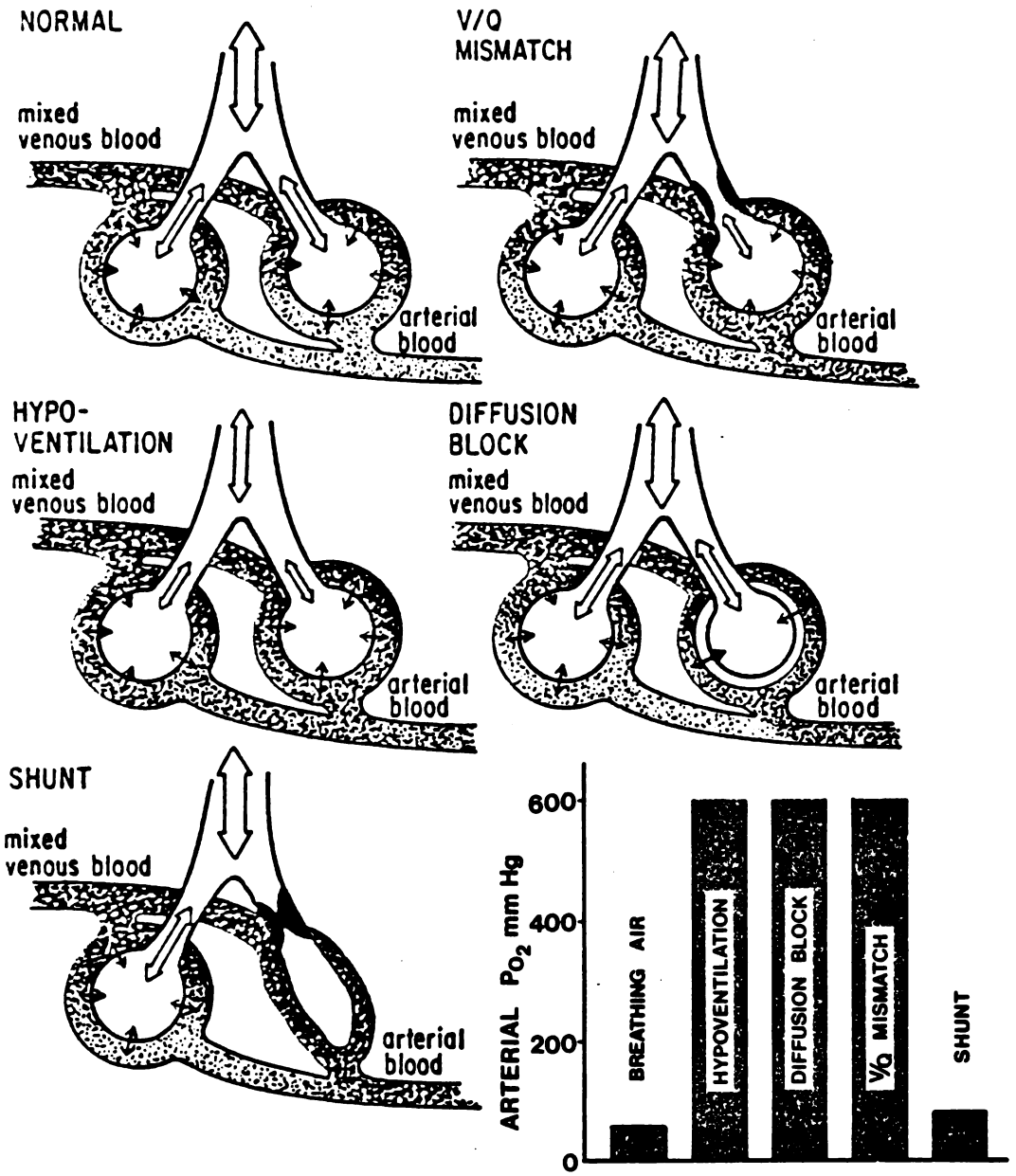

Figure 11. Causes of Hypoxemia. In normal lung tissue ventilation and perfusion are well matched and diffusion of gases between the alveoli and capillary permits adequate oxygenation of blood during its passage through the lung. In V/Q mismatching, perfusion may exceed ventilation as it does in hypoventilation, permitting venous blood to enter the arterial circulation before it is fully oxygenated. When a diffusion block exists oxygen moves less readily from the alveoli into the blood, resulting in hypoxemia. In shunt, venous blood is illustrated perfusing an alveoli which has no ventilation. The response of each cause of hypoxemia to ventilation with 100% O_2 is illustrated. Shunt is the only cause which cannot be corrected by 100% O_2. (Figures redrawn from Murray, 1976; graph redrawn from West, 1977.)

dog, 4% in two dogs and remained unchanged in the last. Kersten et al. (1977), however, measured shunt in dogs without atelectasis, who were ventilated spontaneously with 100% O_2 and found that shunt remained stable at 9% over a 6 hour period.

The experimental use of 100% O_2 has advantages and disadvantages. It prevents systemic hypoxemia and eliminates all causes of decreased PaO_2 except shunt, but it may result in a lack of control over the location and extent of atelectasis.

Method Used to Produce Atelectasis

The pulmonary blood vessels and nerves travel alongside the bronchi. Therefore, the technique used to obstruct a bronchus could influence blood flow independent of the effect of atelectasis. To evaluate the effect of using ligatures to obstruct the bronchus, Woodsen et al. (1963) performed 8 consecutive preliminary studies. They found that when a ligature was applied around the bronchus, or when extensive surgery was carried out in that area, there resulted a consistent absence of any hemodynamic response to variation in inspired gas mixtures. In their later experiments these investigators mention that care was employed in applying the ligature to avoid damage to the surrounding vessels and nerves. Other researchers using ligatures made no mention of any special precautions taken in their application (Benumof, 1979; Camishion et al., 1961; MacVaugh et al.,1961; Peters & Roos, 1952).

Endobronchial obstruction also has the potential to distort the pulmonary vasculature. In one dog, Hobbs et al. (1972) demonstrated with angiography that excessive inflation of a balloon inside the bronchus

distorted the pulmonary vein from a circular to an elliptical shape. Although no objective information was available on the degree of balloon inflation, these same authors demonstrated no significant distortion or obstruction of peribronchial blood vessels with "normal" balloon inflation. Enjeti et al. (1979) confirmed this finding by injecting microspheres into one animal 27 seconds after endobronchial obstruction. Flow was found to be 100% of control, suggesting that obstruction of the bronchus per se did not alter blood flow. Enjeti et al. (1979) also demonstrated that spontaneously developing dependent atelectasis caused similar reduction in flow compared to the atelectasis created by endobronchial obstruction.

The studies on blood flow in atelectasis used several different techniques to obtain endobronchial obstruction. Catheters were used which obstructed all air flow in and out of the lung (Aviado, 1960; Barer at al. 1969) or which permited air to escape to the atmosphere as the lung collapsed (Hobbs et al. 1972; Niden, 1964). Björk & Salén (1950) used suction to remove air from the area to become atelectatic. This variation in technique may have altered the time course of atelectasis.

Time Elapsed Before Post-Collapse Measurements Obtained

The length of time over which changes in blood flow were examined varied with the experiments. This is an important issue because there has not been complete agreement on how long it took for the absorption atelectasis to occur once ventilation had ceased, nor has there been agreement on how long it took for blood flow to stabilize once the

atelectasis had occurred. If, after bronchial obstruction, blood flow was measured before atelectasis was complete or before flow had stabilized, the findings would be difficult to interpret.

Björk and Salén (1950) found some air remained in the distal lung 2 hours after endobronchial obstruction when suction was not applied. Enjeti et al. (1979) found islands of air remaining in pigs killed 10 and 20 minutes after bronchial obstruction but not in one killed at 30 minutes post obstruction. Most investigators, however, found a complete collapse within 15 minutes (Aviado, 1960; Barer et al., 1969; Ford, Bradley & Anthonisen, 1980; Hobbs et al., 1972; Newell et al., 1976; Niden, 1964; Peters & Roos 1952).

The solubility and volume of gas left in the obstructed lung and the ability of that gas to escape to the atmosphere may have influenced the speed with which atelectasis occurred. After washing N_2 out of the lung by ventilation with 100% O_2, Barer et al. (1969) demonstrated that the reduction of PBF through atelectatic tissue occurred in two distinct phases. The first phase resulted in maintenance of $PpvO_2$ and only a small fall in flow as the oxygen was absorbed from the lung. The second phase was associated with a fall in $PpvO_2$ and a rapid reduction in flow, the tissue having become airless. When the bronchus was occluded at end expiration or the lungs were filled with room air, the first phase was shortened or absent.

Niden (1964) compared the effect of acute bronchial obstruction while breathing room air and while breathing 100% O_2. The drop in PaO_2 following the obstruction was the same in both groups except for a delay

of 4-8 minutes before PaO_2 fell in the dogs breathing oxygen. This was true despite the fact that lobes filled with room air at the time of bronchial obstruction took several hours to completely collapse. Barer et al. (1969), who observed changes in flow over 15 minutes, found that when the lobe had been filled with air prior to collapse it was easily re-expanded. Lobes which had been denitrogenated with O_2 required intra-bronchial pressures of 20-30 mmHg to fully re-expand them, suggesting more complete collapse of the latter.

A completely collapsed area of tissue, however, cannot be assumed to have stable blood flow. It may take considerably longer for flow to stabilize than it took for the gas to be absorbed from the obstructed area. Researchers who examined flow over several hours post-atelectasis demonstrated a gradual reduction in flow (Camishion et al., 1961), or a gradual improvement in shunt (Fisher et al., 1979; Kersten et al., 1977; Niden, 1964). Elebute et al. (1966) reported an initial rise in flow sometime in the first hour followed by a gradual reduction over the next few hours. Others, however, demonstrated that the acute change in flow did not progress with time (Aviado, 1960; Hobbs et al., 1972; Peters & Roos, 1952).

It is important, when studying the effects of positioning on the distribution of PBF in the presence of atelectasis, to have complete collapse and stability of post-atelectasis blood flow before turning occurred. Otherwise, it might be unclear whether blood flow changed due to the new position or due to an ongoing process in the lung.

Method of Measuring Flow

Numerous techniques have been used to assess flow through atelectatic tissue. These techniques have been either direct or indirect; they have included measures of flow by PVR, angiography, blood gases, shunt, the Fick principle, flowmeters and distribution of injected radioactive microspheres. A discussion of the theory, the advantages and the disadvantages of each technique follows, as does a review of some of the findings obtained with the different techniques.

Pulmonary Vascular Resistance. Changes in pulmonary vascular resistance is an indirect measure of PBF. A decrease in blood flow reflects either a smaller pressure drop or an increase in resistance. The resistance equation is rearranged from:

$$R = \frac{\Delta P}{f}$$

to:

$$f = \frac{\Delta P}{R}$$

The researchers who used PVR to reflect flow in atelectatic tissue usually calculated it in one of two ways. Either measurements were taken for f, Ppa and some measure of outflow pressure such as capillary wedge pressure (Pcw), left arterial pressure (LAP), or pulmonary vein pressure (Ppv) (Enjeti et al., 1979; Morgan & Guntheroth, 1970), or the pressures were measured while flow was held constant (Aviado,1960; Barer et al., 1969; Niden, 1964).

The validity of measuring flow by these methods is questionable for

two reasons. The first relates to the sites at which the pressures were measured, and whether pressure measured at those sites provided an accurate assessment of the actual vascular pressure to which the atelectatic tissue was exposed. The second reason for questioning the validity of this technique for measuring flow is the assumption which is made that flow is actually determined by the vascular pressures, that Palv and interstitial pressure play no role in determining resistance.

Due to the regional gradient of Ppa seen in the lung, pressures should be measured as close to the atelectatic tissue as possible. A mid-lung site for measuring vascular pressures may underestimate actual pressures in the dependent portions of the lung, while it may overestimate the actual pressures in the non-dependent regions. The use of the general measures Ppa and Pcw to reflect inflow and outflow pressures of a sublobar region (Enjeti et al., 1979) was probably not as accurate as when the vessels immediately adjacent to the collapsed tissue were cannulated (Woodsen et al., 1963).

The second issue of validity relates to an examination of which pressures are actually determining driving pressure. In zone 3 lung tissue, Palv plays no role in determining flow and ΔP is in fact Ppa-Pcw. In this circumstance, use of the above formula for PVR is probably valid. However, in the other 3 lung zones, resistance is influenced by other variables and Ppa-Pcw may not reflect the driving pressure.

In zone 4, blood flow may be influenced by the interstitial pressure. Zone 4 is particularly prominent at low lung volumes (Hughes et al., 1968). If the variables affecting flow at low lung volumes can be applied

to atelectatic tissue, it may be inaccurate to assume flow to be dependent on the driving pressure: Ppa-Pcw.

If the Palv were greater then the Pcw, the use of Ppa-Pcw to determine resistance also might not be accurate. In zones 1 and 2, this is the case and driving pressure is determined, at least in part, by Palv. In non-atelectatic tissue Palv may be considered equal to Pao as long as the airways are open. In atelectatic tissue the Palv is probably equal to the pressure surrounding it, since no air is present in the alveoli. Assuming this is the case, in open chest models Palv would be zero since the collapsed tissue is exposed to the atmosphere; in closed chest models Palv would be equal to the Ppl immediately surrounding the collapsed region.

The use of Ppa-Pcw to reflect driving pressure when Palv may have been greater than Pcw has lead to difficulty in interpreting results. Aviado (1960) and Peters & Roos (1952) did not measure outflow pressure but assumed it constant so it is not possible to estimate the relationship of Palv to Ppv in their studies. Niden (1964) only reported this pressure data for one of the six dogs studied. In this dog, Ppa$>$LAP$>$Palv, so at least in this one case, the formula was probably used accurately. In all but one of their experiments on one lung atelectasis, Morgan and Guntheroth (1970) reported the Ppv to be greater than both the Pao and the Ppl on the atelectatic side. Thus, Ppa-Ppv presumably provide an accurate reflection the driving pressure in that lung.

In the creation of atelectasis, if alveolar vessels were found to be contributing to the change in PVR, it would be likely that zone 1 or

2 was present. The influence of Palv on resistance in these two zones would be felt on the vessels surrounding the alveoli. On the other hand, if extra-alveolar vessels were the only vessels contributing to the change in PVR, it would be probable that zone 3 or 4 existed since Palv would not influence the resistance of the vessels.

By examining the change in Ppa-Pcw when an exised lobe is exposed to different flow rates, it is possible to distinguish between the influence which alveolar and extra-alveolar vessels have on resistance. Barer and his collegues (1969) have shown that when a resistance graph is drawn with ΔP plotted on the "X" axis against perfusion on the "Y", data clusters around a straight line. At increasing flow rates, the pressure difference increases in a linear fashion. The line has both a slope and an intercept. These investigators also showed that when resistance is altered by a change in the diameter of the extra-alveolar vessels (zone 3 or 4), both the slope and the intercept are affected. When resistance is altered by a change in the pressure surrounding the alveolar vessels (zone 1 or 2), only the intercept is affected, there is no change in slope (see Figure 12).

Barer et al. (1969) found that atelectasis usually resulted in a change in both slope and intercept, indicating the presence of zone 3 or 4. This permitted the accurate use of the formulas for PVR noted above. However, there were some experiments in which atelectasis caused a change in intercept with little or no change in slope. When resistance curves are shifted in this parallel manner without changing slope, it may be due to the presence of zone 1 or 2 tissue. This would

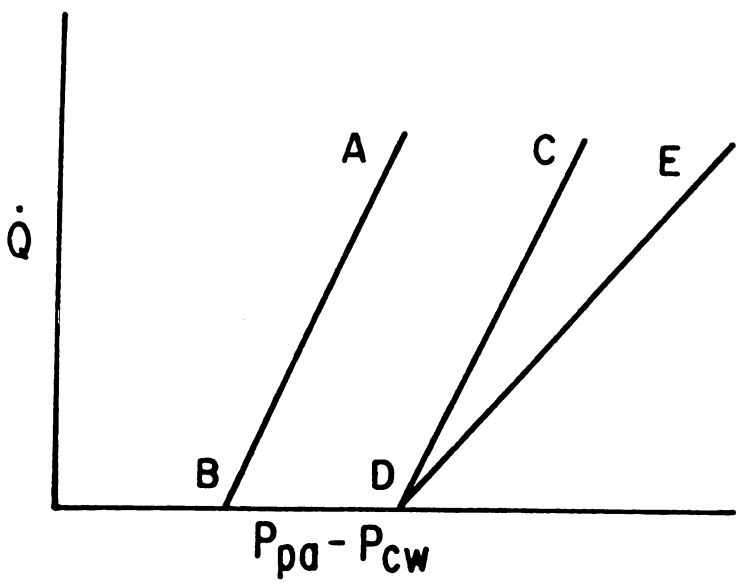

Figure 12. Influence of Alveolar and Extra-alveolar Vessels on the Slope and Intercept of Resistance Lines. Diagram of the relationship between blood flow ($\dot{Q}$) and the pressure drop across the pulmonary circulation (Ppa-Pcw). The line AB represents normal pulmonary vascular resistance. Resistance can be increased in either the alveolar or the extra-alveolar vessels. When resistance is increased in the alveolar vessels, the line changes only its intercept, the slope remains unchanged (AB becomes CD). When resistance is increased in the extra-alveolar vessels the line changes both its intercept and its slope (AB becomes ED). (Redrawn from Barer, 1969.)

make the use of Ppa-Pcw an inaccurate reflection of driving pressure in the calculation of PVR.

The two issues of validity raised in relation to the method of calculating PVR make interpretation of resistance changes between the various studies difficult to do. It is also difficult within any one study to compare pre and post-atelectasis measures. This is because PBF is very dependent on lung volume, and lung volume is rarely reported in these studies. In accordance with the "U" shape of the PVR-lung volume curve, resistance increases both at high and low lung volumes. As the lung volume decreases in atelectasis, PVR may increase or decrease, depending on the lung volume at which control values were taken (see Figure 13). If control measurements were taken at a high lung volume, collapse of a part of the lung would result in a fall in PVR. If, however, control measurements were taken at a lower lung volume, the change in volume when atelectasis was created would result in a net increase in PVR.

Researchers examining PVR have reported conflicting findings. Niden (1964) found atelectasis caused a decreased PVR. Aviado (1960) found that there was an immediate decrease in resistance followed by a progressive rise. The initial decrease was attributed to cessation of positive pressure ventilation. In a closed chest model of atelectasis, Morgan and Guntheroth (1970) found a 15% increase in PVR, while those who used an open chest model found an increase of 93% (Woodsen et al.,1963). This discrepency is consistent with the lung volume-PVR curve. In an open chest model, lung volumes might be expected to be lower than in a closed chest

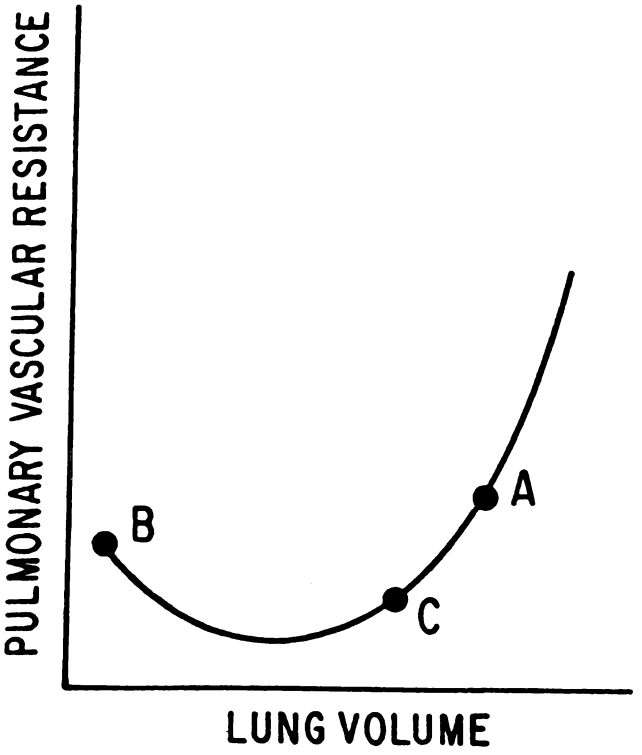

Figure 13. Effect of Changing Lung Volume on Pulmonary Vascular Resistance. As lung volume decreases in atelectasis, resistance may either increase or decrease depending upon the lung volume at which control values are taken. If control volume is at point A, creation of ateletasis would result in a decrease in resistance as Volume dropped to point B. If control volume is lower (at point C) atelectasis would result in a rise in resistance as lung volume dropped to point B. (Redrawn from Niden, 1964.)

model, since the lungs elastic recoil is not opposed by the chest wall. If open chest lung volume lay at a low point on the curve, further reduction in volume would result in a large increase in resistance. Physiological closed chest lung volume, being larger, would lay higher on the curve and thus would result in less dramatic changes in PVR when atelectasis was created.

Enjeti et al. (1979), however, found very different results in a closed chest model, with a 10-fold increase in PVR following atelectasis. Some of this difference may be attributed to the fact that they were looking at sublobar rather than lobar or whole lung atelectasis, the implications of which will be discussed later. Newell et al. (1976) attempted to minimize the effect of low lung volume on PVR in an open chest model by maintaining volumes higher with 3 - 5 cm H_2O of PEEP.

Atelectasis probably alters the PVR. To use changes in PVR to reflect regional distribution of blood flow, however, is a difficult and potentially inaccurate procedure. Inflow and outflow pressures should be measured as close to the collapsed tissue as possible. This means cannulation of vessels which may not be readily accessible in a closed chest model or in a model examining lobar or sublobar collapse. Some attempt should also be made to revise the pressures used in the resistance formula based on knowledge of what lung zones are present. This involves either (a) measuring the Pao within and/or measuring the Ppl adjacent to the atelectatic tissue, or (b) measuring changes in the slope and intercept of the resistance lines during constant flow perfusions. In addition, knowledge of the lung volume pre and post-atelectasis would facilitate interpretation

of the meaning of any increases or decreases found in PVR.

Angiography Angiography is another technique which has been used to assess the distribution of PBF in atelectasis. Early researchers (Björk & Salén, 1950) were unable to demonstrate a change in PBF through atelectatic and nonatelectatic lungs by using pulmonary angiography. However, this may have been due to the insensitivity of the technique for detecting small changes in flow, as well as the somewhat subjective manner in which the test results are interpreted.

Blood Gases Blood gases have been used in a variety of ways to assess the distribution of PBF. Changes in SaO_2 reflect flow through the atelectatic lung only if it is assumed that no other cause for hypoxemia exists. Use of 100% O_2 rules out developing diffusion blocks and $\dot{V}/\dot{Q}$ mismatch during the experiment but cannot rule out the possibility that shunting exists elsewhere in the lung, a strong possibility in anesthetized animals breathing O_2, as has already been discussed. Ventilating their animals with 100% O_2 and assuming 100% SaO_2 Björk & Salén (1950) found whole lung atelectasis to cause a drop in SaO_2 to 88%. They concluded that atelectasis resulted in a decreased but still considerable flow.

Shunt The shunt equation is a better measure of flow through the atelectatic tissue than is SaO_2 alone. Shunt ($\dot{Q}s/\dot{Q}t$) measures the percentage of cardiac output which travels from the right to the left heart without passing ventilated lung tissue. Total shunt includes intracardiac and intrapulmonary components. A small amount of intracardiac shunting exists normally as some of the blood which perfuses the heart muscle itself is added to the left side of the heart without having

been re-oxygenated. However, since this portion of shunt would not be expected to change significantly during the course of an experiment, changes in total shunt have frequently been used to estimate the intrapulmonary shunt: that blood flowing through the atelectatic tissue. Shunt is calculated as follows:

$$\dot{Q}s/\dot{Q}t = \frac{Cc'O_2 - CaO_2}{Cc'O_2 - CvO_2}$$

where: $Cc'O_2$ = ideal end-capillary oxygen content,

CaO_2 = arterial oxygen content, and

CvO_2 = mixed venous oxygen content.

True shunt can only be measured when other causes of hypoxemia are ruled out by ventilation with 100% O_2. However, a form of the equation can be used with a lower FiO_2 for the calculation of venous admixture. The term shunt will be used for the remainder of this discussion to be inclusive of venous admixture. The shunt equation has often been used to measure blood flow in atelectasis since it is easily measured, clinically pertinent, and does not require opening the chest. It does not, however, directly measure regional flow and several assumptions must be made when evaluating the data produced by this equation.

The most obvious assumption is that there are no other areas of the lung which are contributing desaturated venous blood to the systemic arterial circulation. The danger in making this assumption in an anesthesized animal breathing O_2 has already been discussed. Interpretation

of shunt must be made with particular caution when control values are elevated. These animals obviously have some other cause for shunting besides the atelectasis which has yet to be created. With elevated control values for shunt, it would be difficult to determine how much of the post-atelectasis shunting was due to the experimentally created collapse, and how much was due to the original pathology. In their chest model Elebute et al. (1966) reported control values for venous admixture of 53%, making the post-atelectasis value of 70% difficult to interpret.

There are several additional assumptions which are made when using the shunt equation. End-capillary gases are considered to be equal to alveolar gases:

$$P_ACO_2 = PaCO_2$$

and:

$$Cc'O_2 = 1.34ml\ O_2 / Gm\ Hgb \times Gm\ Hgb + .003ml\ O_2 / mmHg\ O_2 \times P_AO_2$$

This probably introduces a very small error if any, particularly when the animal is breathing 100% O_2. To calculate alveolar gases, the respiratory quotient (RQ) must be used. The RQ refers to the amount of CO_2 produced/minute ($\dot{V}CO_2$) over the amount of O_2 consumed/minute ($\dot{V}O_2$). RQ is used in the calculation of P_AO_2 during ventilation with 100% O_2 as follows:

$$P_AO_2 = P_B - P_{H_2O} - P_ACO_2 / RQ$$

Although some have actually measured RQ (Elebute et al., 1966), most have made assumptions of its value, which again, probably introduces negligible error. Niden (1964) did not use the alveolar air equation to calculate

$Cc'O_2$ but rather assumed it equal to the pre-atelectasis value for CaO_2.

When using the shunt equation, it is more accurate to calculate O_2 saturation based on measured animal temperature, rather than presuming the temperature to be stable and normal. Anesthesia may result in a fall of temperature during the experiment. However, animal temperature has often been assumed (Elebute et al., 1966; Finley et al., 1963). These latter investigators point out that an error in this presumption by 1°C would have introduced only a 5% error in gas tension measurement. This is an insignificant error for arterial gases when 100% O_2 is used but may be more significant for mixed venous gases which lie on a steeper part of the oxyhemoglobin curve. Despite these limitations, the shunt equation is a fairly accurate reflection of intrapulmonary shunt and has often been used in examining PBF in atelectasis. It must be reemphasized, however, that it is an indirect measure, and since it reflects a relationship between $\dot{V}$ and $\dot{Q}$, an increase in shunt could result from an increase or a decrease in blood flow, once ventilation had ceased. Niden (1964) overcame this limitation by comparing the percent shunt to the percent of lung tissue collapsed. He concluded that since the former was greater than the latter, blood flow must have increased through the atelectatic tissue.

Fick Principle The Fick Principle has also been used to examine blood flow (Peters & Roos, 1952). It states that $\dot{V}O_2$ is equal to the amount taken up by the lungs. The amount of O_2 entering the lungs is CvO_2; the amount leaving is CaO_2. Therefore:

$$\dot{V}_{O_2} = \dot{Q}(CaO_2 - CvO_2)$$

which can be rearranged to:

$$\dot{Q} = \dot{V}_{O_2} / CaO_2 - CvO_2.$$

This is a measure of total PBF. Actual flow through the atelectatic region can be figured only by multiplying total PBF by the fraction of blood perfusing the collapsed tissue. Peters & Roos calculated this in the following manner:

$$\text{total PBF} \times \frac{\dot{Q}\ (\text{atelectatic lung})}{\dot{Q}\ (\text{atelectatic lung}) + \dot{Q}\ (\text{ventilated lung})} = \text{actual } \dot{Q} \text{ through atelectatic lung}$$

where: 1. total PBF has been calculated by the Fick principle,

2. $\dot{Q}$ (atelectatic lung) = $^{C}(\text{ventilated lung})^{pvO_2} - CaO_2$, and

3. $\dot{Q}$ (ventilated lung) = $CaO_2 - CvO_2$

Utilizing this method of determining flow in atelectasis involves cannulation of the pulmonary vein(s) draining all the ventilated lung tissue, a difficult procedure in a closed chest or lobal model of atelectasis. Calculation of O_2 contents involves the use of some of the same limitations and assumptions as were discussed for the shunt equation.

Flowmeters. Blood flow can be measured directly by either cannulating the lobar vein and collecting the effluent or by use of flowmeters. Both of these techniques necessitate opening the chest wall, which limits the generalizabiltity of the results, as will be discussed. Flowmeter

studies have the advantage of providing a continuous record of flow as the atelectasis is created but provide observations limited to the region supplied by the monitored vessel. The meters can be difficult to calibrate. Obtaining zero flow baselines in vivo requires techniques such as clamping the proximal pulmonary artery (Camishion et al.,1961) or creating a temporary cardiac arrest (Newell et al.,1976). Both of these procedures leave the distal lung ischemic for a brief time. Ischemia may effect the ability of the lung to diminish blood flow when collapsed. Complete ischemia of the LLL for one hour prior to the onset of atelectasis was associated with a rise in shunt from 0.123 to 0.230 compared with a non-ischemic group whose shunt increased from 0.112 to only 0.172 (Kersten et al.,1977).

Implantation of the meters must be done carefully to avoid damage to nerves and blood vessels. Investigators using flowmeters have reported finding no hemodynamic changes resulting from manipulations in this area (Elebute et al.,1966). Others(Woodson et al.,1963), however, found extensive surgery in this region could influence PBF.

Flowmeters may overestimate blood flow if refluxing blood is not subtracted from the flow. Newell et al.(1976) have demonstrated a large retrograde flow out of the pulmonary artery from the collapsed lung during diastole. The reduction in flow to atelectatic tissue was found to be almost entirely due to the retrograde flow, the antegrade component, during systole, being essential identical before and after collapse. The reflux was particularly large when the animal was not hypoxemic. Most investigators

using flowmeters provide little information about the nature of the wave form obtained just proximal to the atelectasis. These investigators have reported increased (Elebute et al., 1966), upredictable (Camishion et al., 1961) or decreased (Barer et al., 1969; Benumof, 1979; MacVaugh et al., 1961; Morgan & Guntheroth, 1970; Woodson et al., 1963) flow to the atelectatic tissue. Morgan and Guntheroth (1970) calculated flow by "planimetric integration of the forward flow over several respiratory cycles." If this means refluxing flow was not subtracted, it could explain the high value (96% of control) of flow they reported to the atelectatic lung.

Radioactive Microspheres The use of microspheres to study circulation is a variation of the indicator dilution technique for determination of blood flow. In the most general sense, the kinetics of an indicator substance can be described as:

$$Q'(t) = fCi - fCo$$

This states that the change in the amount of indicator in a system [Q'(t)] is equal to the difference between the amount entering the system (fCi) and the amount leaving (fCo), where f represents flow, and Ci and Co represent the concentration of the indicator entering and leaving the system respectively.

The use of radioactive microspheres as the indicator to measure the regional distribution of PBF, involves the injection of small (15 micron) tracer particles into the venous blood upstream from the lungs. The particles are too large to pass through the capillary bed of the lungs and so become trapped. The use of microspheres with different radionucleide

labels allows multiple measurements of PBF distribution.

The validity of the microsphere technique rests on three basic assumptions:

1. The microspheres are uniformly mixed with the blood and are distributed in the same manner as the blood;
2. The microspheres themselves do not alter blood flow;
3. The microspheres are removed from the blood stream by becoming trapped in the capillary bed.

A discussion of some of the research which has verified these assumptions is provided in the review article by Wagner, Rhodes, Sasak, and Ryan (1969). Guidelines for use of the microsphere technique can be drawn from these three assumptions.

To be distributed in the same manner as blood, the microspheres must be uniformly mixed with that blood. Injection must take place far enough upstream to allow thorough mixing of the particles with the venous blood before it enters the capillary bed. In the study of PBF the right atrium provides an ideal injection site since it is easy to locate with pressure monitoring and allows blood to be mixed in the right ventricle before it enters the pulmonary circulation.

To eliminate random errors in the distribution of PBF caused by respiratory or cardiac cyclic variations, injection of the microspheres must be done in a consistent manner throughout the experiment. Injection should be done slowly, preferably over several respiratory cycles (Hobbs et al., 1972) or while the ventilator is stopped at FRC (Enjeti et al., 1979).

To ensure that the microspheres themselves do not alter blood flow they should theoretically be of small enough size to prevent impaction of large vessels and be used in low enough quantities to prevent widespread impaction of small vessels. Edmunds, Gold and Heyman (1970) compared the microsphere technique with a technique involving collection of venous effluent to measure pulmonary artery flow in dogs. They used microspheres with a mean diameter of 50 ± 10 microns in total number of approximately 50,000 - 100,000 injected during the course of the experiment into each animal. They found a correlation coefficient of .99 between the two techniques.

Although there may be theoretical advantages to use of relatively small total numbers of microspheres, estimates of the distribution of perfusion can be imprecise if too few microspheres are used. Random errors in radioactive counts can be minimized by injection of a suitably large number of microspheres. Hobbs et al. (1972) injected 15 micron microspheres in total quantities of approximately 309,000-686,000 during the course of their experiment. Although this large number essentially eliminated random errors, they did report a transient rise in Ppa following each injection. Enjeti et al. (1979) used sufficient numbers of microspheres to result in at least 400 being present in any single lung region. They did not report the size of microspheres used.

Evidence that the microspheres become trapped in the first capillary bed they encounter can be obtained by measuring the amount of radioactivity found in subsequent capillary beds. Hobbs et al. (1972) reported fewer

than 0.05% of the 15 micron microspheres present in analysis of kidney and spleen tissue at the conclusion of their experiment. Since essentially all of the microspheres are impacted in the first capillary bed encountered, there is no need to determine transit time. The fraction of flow to any region can be determined by the number of microspheres in that region divided by the total number in all regions; actual flow to a region can then be determined by multiplying this fraction by the cardiac output.

Once the microspheres have become impacted in the capillary bed, the amount of radioactivity in various lung regions can be measured later; it is proportional to the blood flow to these regions at the time of microsphere injection. Each differentially-labeled microsphere emits a different level of gamma rays and the gamma counter is programmed to read only a narrow channel of radiation for each isotope. There is, however, spillover of radiation from some of the microspheres into the channels of the others and there is a small amount of background radiation appearing in all channels. Thus, the spillover and background radiation must be subtracted from the gross radiation count to accurately reflect the distribution of PBF.

The use of radioactive microspheres to measure the distribution of PBF has advantages and disadvantages. The major disadvantage of this technique is that it provides only a limited number of flow observations, that number being dependent upon how many different microspheres are available. The number of different microspheres which may be used is limited due to the need to preserve accuracy in subtracting spillover

counts from the total radioactivity in any given channel. Enjeti et al. (1979) used only four different microspheres while Hobbs et al.(1972) used only five. The advantages of this technique include the fact that it provides direct information about the distribution of flow throughout the entire lung, not just in a single monitored vessel. It is considered a valid and reliable measure of flow and is possible to use in an intact chest model.

Ventilatory Mode

The mode of ventilation used when studying the effect of atelectasis on the regional distribution of PBF could, by itself, influence the distribution of $\dot{V}$ and $\dot{Q}$. Positive pressure ventilation alters the distribution of $\dot{V}$ to favor the non-dependent lung zones; it elevates Palv which in turn increases PVR and decreases blood flow. Thus, this ventilatory mode increases the amount of zone 1 and zone 2 in the lung. Spontaneously breathing subjects create negativity in the intrapleural space which promotes venous return and increases the volume of blood in the lungs at any given time. It may not be valid to compare the results of studies which used different ventilatory modes.

As long as the level of anesthesia is not too deep, acute atelectasis has been found to cause hyperpnea in the aerated lung of spontaneously breathing animals (Camishion, 1961; Morgan and Guntheroth, 1970; Niden, 1964). By varying anesthesia levels, Finley et al. (1963) were able to control this response to acute atelectasis. Hyperpnea was evaluated by the negativity of the Ppl, with more negative pressure reflecting greater degrees of hyperpnea. They found that when animals were lightly anesthetized, Ppl

was more negative and intrapulmonary shunt was higher than when the same animal was more heavily anesthetized. Thus, they demonstrated a positive correlation between negativity of the intrapleural space and blood flow through the atelectatic tissue. This lends credence to the hypothesis that hyperpnea and larger lung volumes in the aerated lung result in higher PVR in this ventilated area, which restores flow to the atelectatic region. Similarly, positive pressure ventilation might be expected to increase $\dot{Q}$ through atelectatic tissue by increasing volume in the aerated lung. However, large increases in ventilated lung volume, by the application of positive end expiratory pressure (PEEP), was not found to restore flow to the atelectatic region (Enjeti et al., 1979).

One disadvantage of the spontaneously breathing model is that there is no control over the $PaCO_2$, and high CO_2 levels may enhance PVR (Aviado, 1960). This problem has been mitigated by controlling rate and tidal volume to achieve a desirable $PaCO_2$ (Benumof, 1979; Elebute et al., 1966; Fisher et al., 1979; Newell et al., 1976). Spontaneously breathing subjects, who develop hyperpnea in response to atelectasis, may lower $PaCO_2$ enough to influence flow through the collapsed region independent of the effects of atelectasis.

State of the Chest

The loss of intrapleural negativity when the chest was opened may have resulted in open chest models having had smaller lung volumes and smaller transpulmonary pressures than closed chest models. Thus, there

may be theoretical difficulties in comparing control and experimental values for blood flow which resulted from the two models. Elebute et al. (1966), however, found the effects of opening the chest of PBF to be negligible when sham operations were preformed.

The theoretical differences in PVR seen in open versus closed chest models and the influence of the pressure surrounding the lung on blood flow have been discussed. Some researchers have been able to minimize the difference in lung volume and P_L between open and closed chest models by giving small amounts of PEEP to their subjects (Barer et al., 1969; Newell et al., 1976). This, however, would not restore intrapleural negativity.

Ford et al. (1980) found that when a lobe of the lung became atelectatic in an intact chest, part of that lobe maintained contact with the pleural surface in sharp angulation. This mechanical deformation may have altered blood flow in a manner not seen in the open chest models.

The ability to generalize the results from open chest models to the patient population is limited. Except during operation in the thoracic area or in some cases of trauma, patients maintain a closed chest wall. The widespread use of flowmeters, however, has resulted in a predominance of open chest models in the literature. Some of the limitations in generalizability of open chest models have been overcome by closing the chest after implantation of the flowmeter, evacuating any hemo or pneumothorax, and running the experiments after hemostasis had presumably returned (Elebute et al., 1966; Morgan and Guntheroth, 1970). Niden (1964) was able

to overcome some of the limitations of the open chest preparation by using a negative pressure body box for ventilation instead of a positive pressure system.

Area of Collapse

Research on blood flow in atelectasis has used models of sublobar, lobar, and whole lung atelectasis; the models may not be equilavent. Variation in extent of atelectasis studied could potentially alter the results due to the interdependence of alveoli within the lung and the differences in intrapleural pressure. Since elastic tissue runs through the interstial space, connecting alveoli within each lobe, an atelectatic sublobar segment may be subject to large expanding forces from the surrounding inflated lung, which would not be seen in a whole lung model.

The negativity of the intrapleural space also exerts an expanding force on the lung. Atelectasis probably results in a drop in Ppl in the intact chest, but models of sublobar, lobar and whole lung collapse may not result in equivalent drops in Ppl. Morgan and Guntheroth (1970) found an average drop in Ppl of 3.1 cm H_2O which was essentially equal on both sides of the thorax during collapse of one lung. Niden (1964) observed mean Ppl to fall from -9 cm H_2O to -14 cm H_2O with collapse of the LLL. Ford et al (1980) showed that with collapse of the LLL alone, translobar pressure was more negative than P_L when the whole lung was collapsed. Thus, based on these results, a collapsed lobe would be subject to larger expanding forces than would a collapsed lung.

At the very low lung volumes seen in atelectasis, any force tending

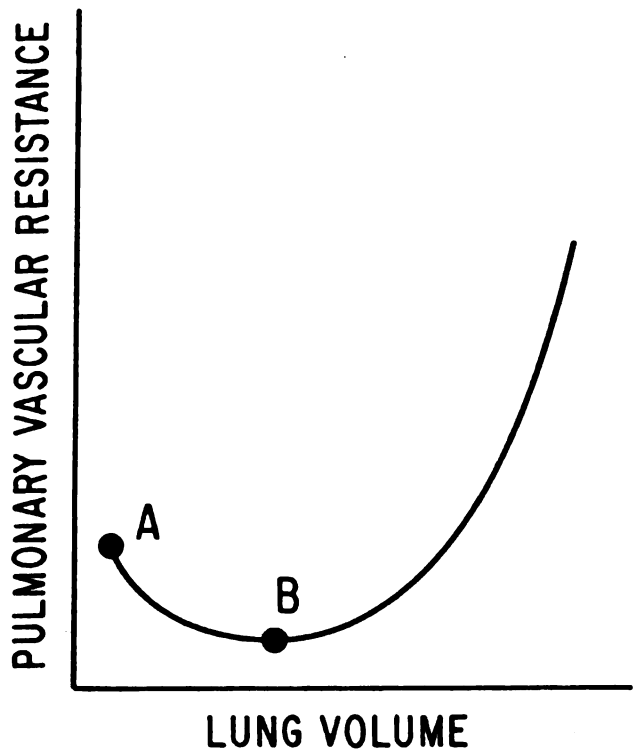

Figure 14. Effect of Forces Tending to Re-inflate Atelectasis on Pulmonary Vascular Resistance. At the very low lung volumes seen in atelectasis (point A) any force tending to re-expand the lung,(toward point B, for example)might be expected to initially cause resistance to decrease in the collapsed tissue. (Redrawn from West, 1979).

to re-expand the lung would be expected to result in a drop in PVR and an increase in flow (see Figure 14). Thus, if the expanding forces are greater for sublobar than for lobar and greater for lobar than for whole lung collapse, one might expect a greater rentention of pre-collapse blood flow for smaller regions of atelectasis. The studies do not support this hypothesis. Enjeti et al. (1979) found that flow to a sublobar atelectatic area decreased to 12% of control. Hobbs et al. (1972) found that lobar atelectasis decreased flow to 80% of control. Whole lung atelectasis resulted in blood flow changes which varied between 22% of control (Finley et al.,1963), 96% of control (Morgan & Guntheroth.,1970) and 125% of control (Elebute et al., 1966).

Enjeti et al. (1979) attempted to enhance the expanding forces on a sublobar atelectatic region by applying PEEP to the rest of the lung. Blood flow to this region was expected to increase due to interdependence as well as due to increased PVR in the expanded lung (see Figure 15). The authors, however, found no significant change in blood flow to the atelectatic region. They concluded that sublobar atelectasis probably resulted in geometric distortion of the vessels and changes in the elastic recoil which opposed the forces of interdependence. The increase PVR in the ventilated lung tissue, instead of restoring flow to the collapsed region, resulted in a decrease in venous return.

Level and Type of Anesthesia

The type and amount of anesthesia used may influence PBF. Most of the principles relating to the effect which anesthesia may have on PBF in atelectasis have already been discussed. Soluble anesthetic gases,

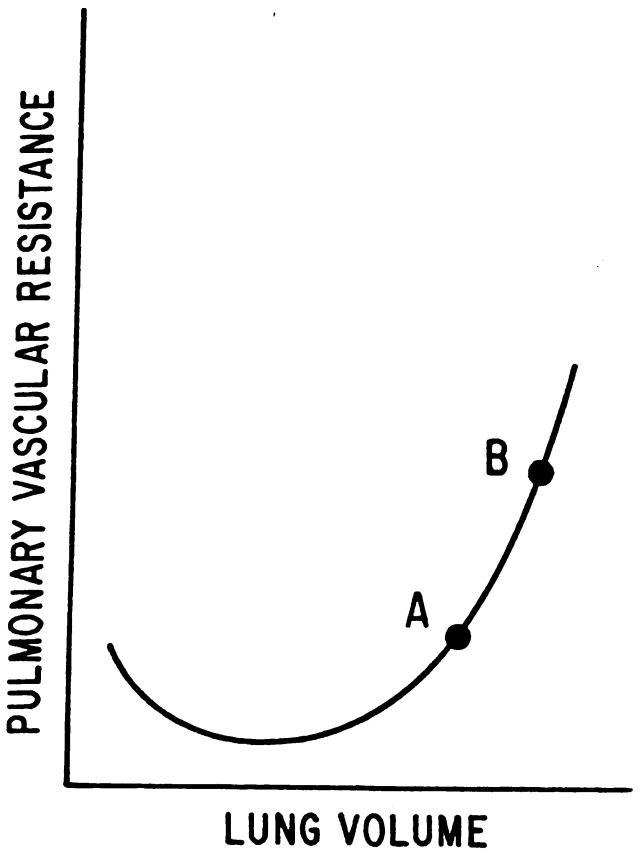

Figure 15. Effect of Increased Volume in the Aerated Tissue on Pulmonary Vascular Resistance. Increased volume in the ventilated lung,(moving from point A to point B for example), such as might be seen with application of positive end-expiratory pressure or hyperpnea, may cause increased pulmonary vascular resistance regionally in the ventilated tissue. (Redrawn from West, 1979).

such as N_2O, can potentiate spontaneously developing atelectasis. Lightly anesthetized animals may be able to initiate breaths as well as hyperventilate in response to atelectasis. This lightly anesthesized model is a very different model from the animal whose ventilation is controlled. The results of studies using these two approaches may not be comparable.

Finley et al. (1963) used different levels of anesthesia to change intrapleural pressure. With low levels of anesthesia, Ppl ranged from -7.5 to -24 cm H_2O and there was essentially no decrease in blood flow when atelectasis was created. With higher levels of anesthesia, Ppl varied from -3 to -12 cm H_2O and blood flow fell from 45 to 22% of cardiac output. Morgan and Guntheroth (1970) used half the anesthetic levels reported by Finley et al. for the more heavily sedated group. Their findings of only a 4% decrease in flow correspond closely to Finley et al's lighter anesthesia group.

Subject Selection

The studies on blood flow in atelectasis have also varied in the subjects used. Obviously the use of humans provides the best generalizability to the patient population. Ethical considerations, however, prevent controlling the extent of atelectasis except in elective thoracotomy. Human studies depend on indirect measures of flow such as the shunt equation. Patients undergoing thoracic surgical procedures often have some pathology which made their control shunt values high (Fisher et al., 1979). The limitations in interpreting post-atelectasis shunt when control values are high have already been discussed.

Most of the studies on blood flow in atelectasis have utilized dogs as subjects. This probably provides a model reasonably close to humans for a positioning study. The dog's lower lobes are primarily dorsal in location and so correspond fairly well to the position of the lower lobes in humans in both the supine and lateral positions.

One of the problems often cited in using dogs for models of the human pulmonary system is their well developed interlobar collateral ventilation. Dogs occasionally have been found to have an intralobar airway which travels in a ligament from the left upper lobe (LUL) to the LLL. The presence of collateral ventilation should not present a problem for interpreting data as long as the location and extent of the atelectasis is confirmed. In open-chest models, where the presence of a liver-like section of tissue can be visualized directly, this presents no problem. In closed-chest models, however, placement of an obstructing catheter in a certain airway is not enough to assure that the distal lung tissue will completely collapse; collateral ventilation may keep it inflated.

The method of assessing the location and extent of atelectasis was not discussed by one author (Aviado, 1960). However, most researchers with a closed-chest canine model employed some method to confirm atelectasis. Niden (1964) checked the N_2 content of expired air during unilateral ventilation with 100% O_2 to determine the ability of a tracheal divider to completely separate one lung from the other. He found that the distortion of the lung caused by atelectasis made it impossible to maintain the lungs sealed off from each other using this technique. When Morgan and Guntheroth (1970) used a tracheal divider, they checked for leaks before and after

the atelectasis in all experiments and confirmed the completeness of atelectasis by the development of a P_L of zero in the atelectatic lung. In some experiments, chest X-ray was used as a secondary confirmation of atelectasis (Hobbs et al., 1972; Morgan and Guntheroth, 1970). Other reserachers (Björk & Salén, 1950) mention X-ray as their only technique used to assess atelectasis. X-rays can confirm only large areas of collapse; they are not sensitive enough to detect small areas of atelectasis or pockets of remaining air.

As long as the obstructing catheter is not moved once it has occluded the bronchus, the location and extent of atelectasis in a closed-chest model can be observed accurately on autopsy (Finley et al., 1963; Hobbs et al., 1972; Morgan and Guntheroth, 1970). Investigators who have removed the catheter, re-inflated the lobe and then replaced the catheter to re-create the atelectasis (Kersten et al., 1977) are open to question when they describe the extent of atelectasis based on atuopsy findings. There can be no certainty that the extent and location of atelectasis seen when the chest was opened was the same atelectasis as had been originally created.

Because the collateral ventilation of the dog makes canine models difficult to use when studying sublobar atelectasis, the pig has been used (Enjeti et al., 1979) and is an appropriate model since pigs lack collateral ventilation.

Other Variations in Technique

Hobbs et al. (1972) insufflated tantalum into the left mainstem bronchus to enable placement of the obstructing catheter into the LLL

bronchus by fluroscopy. Tantalum has a side effect of causing bronchospasm. To the extent that this may have caused diminished volume of the non-obstructed LUL, and, therefore, increased intrapleural negativity or altered PVR in the LUL, it may have either assisted to diminish or enhance flow to the atelectatic lobe.

POSITIONAL INFLUENCE ON BLOOD FLOW IN LUNG DISEASE

Whatever the mechanism responsible for diverting blood away from atelectatic tissue, there is evidence that its efficiency can be influenced by body position. Temple, Pircher and Sieker (1965) demonstrated that when patients with pulmonary disease were positioned with the diseased tissue dependent, the increase in blood flow to this area was not as great as would be expected if the lung were healthy, yet there was an increase in blood flow. The improvement in blood gases seen when patients with respiratory distress syndrome were placed prone (Douglas, Rehder, Beynen, Sessler & Marsh, 1977; Piehl & Brown, 1976; Wagaman, Shutack, Moomjian, Schwartz, Shaffer & Fox, 1979) may have been due to the greater involvement of disease in the lower lobes. The lower lobes assume a non-dependent position when the body is prone.

Several researchers have found that in unilateral lung disease positioning with the healthy lung dependent results in improved gas exchanged (Falke et al., 1972; Remolina et al., 1981; Schimmel et al., 1977; Zack et al., 1974). The patients involved in these studies had a variety of different lung pathologies. The case study presented by Schimmel et al. (1977) had X-ray findings of right lung consolidation. Falke et al. (1972)

reported on two patients with unilateral infiltrates. The larger sample size of 38 patients studied by Zack et al. (1974) reported the X-ray findings only according to distribution of disease, not by type of disease.

It is conceivable that positioning might effect the distribution of PBF differently if atelectasis was present than it would if other types of lung pathologies were present. The morphology of atelectatic tissue is distinctly different from tissue which is consolidated or infiltrated, the former involving collapse of alveoli, the latter involving filling of the alveoli with substances other than air. It may not be reasonable, therefore, to extrapolate from the above mentioned studies with their variety of lung pathologies to patients with atelectasis. Little information is available regarding the effect of positioning on the distribution of PBF in the presence of atelectasis.

When Newell et al. (1976) studied left lung atelectasis their dogs were in the right lateral decubitus position. In accordance with the clinical studies cited above, and the gravitational distributions of perfusion, one might expect their shunt perfusion values to be lower than those reported using somewhat similar models in the supine position. This expectation is not supported. Newell's group reported perfusion to the collapsed area dropped to 54% of control. This compares to others using supine positioning who found perfusion to the collapsed area dropped to 62% of control (MacVaugh et al., 1961), 46% of control (Barer et al., 1969), and 41% of control (Benumof., 1979). It must be emphasized, however, that while the studies are similar, there are some differences in the models used

by these investigators and caution must be used in comparing their findings.

Remolina et al.(1981) reported both the distribution and type of X-ray findings on their patients. Four were described with either whole lung or lobar atelectasis. Each responded with decreased PaO_2 when lateral positioning was assumed with the collapsed tissue dependent. This suggests that despite the altered morphology of atelectatic tissue its blood flow behaves the same way in positioning as does flow in other types of lung pathologies.

SUMMARY

Limited information regarding the effects of atelectasis and lateral positioning on the regional distribution of PBF can be extrapolated from the current literature. Despite a large number of studies on blood flow in atelectasis, there is little agreement in findings. Many different models and methods have been used to study the problem; variation in the experimental techniques may be responsible for some of the variation in results.

Studies on pulmonary diseases of various morphology have shown that PaO_2 decreases when the diseased tissue is dependently positioned. Four case studies with unilateral atelectasis, reported by Remolina et al. (1981), had similar findings. Blood gases are an indirect measure of PBF. To the extent that a decrease in PaO_2 reflects increased flow through the diseased tissue, dependent positioning of atelectatic tissue may result in increased right to left intrapulmonary shunt. Since none of

the patients with atelectasis were breathing 100% O_2, however, increased shunt is only one of several possible explanations for the decrease in PaO_2. Diffusion blocks or $\dot{V}/\dot{Q}$ mismatching may have caused the hypoxemia; hypoventilation may be ruled out as $PaCO_2$ was 38 mmHg or below in each patient.

A review of the literature revealed no studies directly measuring the effect of position on the distribution of PBF or on shunt in atelectasis. Therefore, this study was designed to measure the effect of atelectasis and lateral positioning on the regional distribution of PBF.

Chapter 3

METHODOLOGY

The study was developed to measure the effects of atelectasis and lateral positioning on the regional distribution of pulmonary blood flow and on shunt.

Independent Variables

The variables manipulated by the investigator were atelectasis and body position. Atelectasis was created by occluding the left lower lobe bronchus with the inflated balloon of a Foley catheter. The balloon was inflated after the lungs had been denitrogenated by ventilation with 100% O_2 for a minimum of 90 minutes. The effect of atelectasis on regional distribution of PBF and on shunt was assessed while the dogs were in the supine position. Following a 2 hour period to allow the atelectasis to stabilize, the dogs were turned into the left lateral decubitus position and blood flow reassessed.

Dependent Variables

The dependent variables measured (a) the ability of the lungs as a whole to supply oxygen to the body and (b) the regional distribution of pulmonary perfusion. The variables reflecting overall lung efficiency were operationalized as: shunt ($\dot{Q}s/\dot{Q}t$), pulmonary vascular resistance (PVR), pressure at the airway opening (Pao), and the respiratory rate (RR) which was required to maintain $PaCO_2$ between 33 and 43 mmHg. These variables were measured frequently throughout the experiment.

The variable measuring regional distribution of perfusion was operationalized as the percentage of PBF going to each individual lobe. This was measured three times during the experiment by injection of one of three differentially-labeled radioactive microspheres.

Measurements were taken pre-atelectasis, 2 hours post-atelectasis and 15 minutes post-turning. Lobar distribution of perfusion ($\dot{Q}_{(lobe)}/\dot{Q}t$) at each of these times was determined by individually examining the radioactive counts for each of the three microspheres. The percent of cardiac output perfusing any given lobe was expressed as the ratio of the microsphere count for the lobe over the total lung count for that microsphere. Lobar distribution of perfusion was calculated for each lobe in each of the three time periods. The lobe in question appears as a subscript replacing (lobe) in $\dot{Q}_{(lobe)}/\dot{Q}t$: $\dot{Q}_{RUL}/\dot{Q}t$ for the right upper lobe, $\dot{Q}_{RML}/\dot{Q}t$ for the right middle lobe, $\dot{Q}_{RLL}/\dot{Q}t$ for the right lower lobe, $\dot{Q}_{CL}/\dot{Q}t$ for the cardiac lobe, $\dot{Q}_{LUL}/\dot{Q}t$ for the left upper lobe and $\dot{Q}_{LLL}/\dot{Q}t$ for the left lower lobe.

In addition to the dependent variables listed above, certain hemodynamic parameters were also measured frequently during the experiment. These included mean arterial blood pressure ($\overline{BP}$), cardiac output (CO) and heart rate (HR). Methods used to calculate the dependent variables, including those measuring whole lung efficiency, lobar perfusion and hemodynamic parameters are discussed further in the following section.

Definitions of Terms and Calculations

Atelectasis

Atelectasis was defined as the complete loss of alveolar airspace. When confined discretely to a lung lobe it was referred to as lobar atelectasis. In this study, lobar atelectasis was created in the left lower lobe (LLL). The onset or creation of LLL atelectasis was considered to occur at the time of bronchial obstruction. The successful achievement of

atelectasis was initially suspected when PaO_2 fell and when fluroscopy revealed shifting of the mediastinum or elevation of the hemidiaphragm. However, atelectasis was confirmed on autopsy in all animals by visualizing the LLL as dark, solid tissue, similar to that seen in the liver.

Positioning or Turning

This is the placement of the dog onto its back (supine position) or onto its left side (when turned into the left lateral decubitus position).

Microspheres

The microspheres used were small (15 micron) particles labeled radioactively with either strontium (^{85}Sr), chromium (^{51}Cr) or cerium (^{141}Ce).

Blood Gases

Blood samples were placed on ice and analyzed within 15 minutes for PO_2, PCO_2, pH and base excess on a Corning 165-2 analyzer. Two point calibration was done prior to the first sample and intermittently during the experiment. One point calibration was done between each observation point.

Hemoglobin

Arterial and venous blood samples were analyzed for hemoglobin level on an Instrument Lab 282 Co-oximeter. The average of the values obtained for the two simultaneously drawn samples was the number used in calculating shunt for that observation point.

Oxygen Saturation

When PO_2 was greater than 170 mmHg 100% saturation was assumed. When PO_2 was 120 mmHg or less a canine nomogram (Rossing & Cain, 1966) was used to calculate oxygen saturation.

Shunt

Shunt ($\dot{Q}s/\dot{Q}t$), as used in this study, referred to total shunt. It

included intrapulmonary shunt as well as any contributions from cardiac or other sources. The formula used to calculate $\dot{Q}s/\dot{Q}t$ was:

$$\dot{Q}s/\dot{Q}t = Cc'O_2 - CaO_2 \,/\, Cc'O_2 - CvO_2$$

where, as has been previously described, $Cc'O_2$, CaO_2 and CvO_2 are the oxygen contents respectively of ideal end-capillary blood, arterial blood, and mixed venous blood. These contents were calculated as follows:

$Cc'O_2$ = 1.34 ml O_2/Gm Hgb(Hgb) + .003ml O_2/mmHg $PO_2(P_B - P_{H_2O} - PaCO_2/0.8)$

CaO_2 = 1.34 ml O_2/Gm Hgb(Hgb)(SaO_2) + .003 ml O_2/mmHg PO_2 (PaO_2)

CvO_2 = 1.34 ml O_2/Gm Hgb(Hgb) (SvO_2) + .003 ml O_2/mmHg PO_2 (PvO_2)

Barometric pressure (P_B) was measured at the beginning of each experiment in the same facility where the study was conducted. Water vapor pressure (P_{H_2O}) was assumed equal to 47 mmHg.

Distribution of Perfusion

Distribution of perfusion was calculated by measuring the lobar distribution of each microsphere. Three samples were taken from each lung lobe. In each sample appropriate corrections were made for background counts (bkg) and spillover counts (k) by subtracting them from the gross count:

Sr(corrected) = Sr(gross) -bkg - k(from Cr) - k(from Ce)

Cr(corrected) = Cr(gross) -bkg - k(from Sr) - k(from Ce)

Ce(corrected) = Ce(gross) -bkg - k(from Sr) - k(from Cr)

Following these corrections average lobar counts were expressed for each microsphere as a percentage of average total lung counts:

$\dot{Q}_{(lobe)}/\dot{Q}t$ % = 100 x corrected lobe count/ Σ (corrected lobe count)

where (lobe) was replaced by the abbreviation for the actual lobe being analyzed. The relative perfusion to each lobe was calculated three times, each time using a different microsphere. This gives the perfusion of the lobe as a percentage of CO pre-atelectasis (when the ^{85}Sr counts are examined), post-atelectasis (when the ^{51}Cr counts are examined), and post-turning (when the ^{141}Ce counts are examined).

Cardiac Output

Cardiac output was measured on an Electronics for Medicine (E for M) VR12 using a thermodilution technique. Three values were obtained at each observation point and the average value recorded.

Blood Pressure

Indwelling vascular catheters were connected to Staham PID23 transducers with pressure tracings recorded on the E for M VR12 Optical Recorder. Mean blood pressures for the systemic and pulmonary circulations were calculated in the following manner:

$$\frac{2\,(\text{diastolic BP}) + \text{systolic BP}}{3}$$

The Pcw was obtained by inflating the balloon on the catheter in the pulmonary artery until a typical "wedge" pattern was obtained.

Respiratory Rate

Respiratory rate was assumed equal to the value set on the ventilator.

Heart Rate

The electrocardiogram was printed on the E for M VR12 Optical Recorder.

Heart rate was determined by counting the number of beats in a 10 second period and multiplying by 6. This procedure was repeated twice in each observation period and the average value recorded.

Airway Opening Pressure

A side port on the connector between the ventilator tubing and the endotracheal tube was connected to a Staham PID23 transducer. Tracings for pressure at this airway opening site were recorded on the E for M VR12 Optical Recorder. Mean airway pressure was determined by drawing a line through the tracing where the area above and below the line were estimated to be equal.

Pulmonary Vascular Resistance

The overall pulmonary vascular resistance was calculated in the following manner:

$$\frac{\overline{Ppa} - Pcw}{CO}$$

No attempt was made to analyze regional resistance or to determine the distribution of lung zones within the lung which might have affected PVR.

Wet/Dry Ratio

The wet weight of each lobe was divided by its dry weight to obtain the wet/dry ratio. This ratio measures lung water. It was not a dependent variable in the strictest sense in that it was not expected to be altered by either atelectasis or body position. It was measured to allow evaluation of the possibility that increased lung water in the form

of pulmonary edema may have inadvertently developed during the experiment. Had pulmonary edema been present, it may have influenced the ability of the lungs as a whole or as individual lobes to supply oxygen to the body.

Design

The study was a quasi-experimental, repeated measures design. It can be diagramed as:

$$O_1\ X_1\ O_2\ O_3\ O_4\ O_5\ O_6\ O_7\ X_2\ O_8\ O_9$$

where: O_1 = baseline measurements

core temperature (T), blood pressure (BP), heart rate (HR), respirator rate (RR), pulmonary artery pressure (Ppa), capillary wedge pressure (Pcw), cardiac output (CO), airway pressure (Pao), hemoglobin (Hgb), arterial and mixed venous partial pressures of oxygen (PaO_2 and PvO_2), carbon dioxide ($PaCO_2$ and $PvCO_2$), oxygen saturation (SaO_2 and SvO_2) and pH, as well as distribution of an injected microsphere

X_1 = inflation of balloon to create atelectasis

O_{2-6} = measurements as described for O_1 but without distribution of injected microsphere

O_7 = measurements as described for O_1 obtained 2 hours after bronchial occlusion

X_2 = position change to left lateral decubitus

O_8 = measurements as described in O_1 obtained 15 minutes after position change

O_9 = measurements as described in O_{2-6} obtained 60 minutes after position change

Sample

Twenty mongrel dogs were studied. Development of the protocol to allow consistent atelectasis confined to the LLL required 15 experiments. The final sample consisted of 5 animals.

Protocol

Animal Preparation

Five mongrel dogs were anesthetized with intravenous pentobarbital (30mg/kg body weight) and supplemented as necessary to abolish the corneal reflex. The animals were placed supine. Endotracheal intubation was accomplished and the dogs ventilated with 100% O_2, a tidal volume of 15ml/kg body weight, and a ventilatory rate adjusted to maintain $PaCO_2$ between 33 and 43 mmHg throughout the experiment. Sigh breaths of approximately 23-30ml/kg body weight were given every 15 minutes during animal preparation.

A femoral vein was cannulated for the administration of drugs and maintenance fluid (30cc/hr of 0.9% NaCL). An arterial line was placed in the aorta for measurement of systemic BP and sampling of arterial blood. All but one animal (dog 19) received a single 10cc dose of 7.5% sodium bicarbonate solution to correct base excesses which were less than -4 or -5. This was administered early in the experimental procedure. A thermistor tipped flow directed catheter was inserted into the pulmonary artery for measurements of Ppa and Pcw as well as for sampling of mixed venous blood. A second flow-directed catheter was advanced into the right ventricle and withdrawn under pressure monitoring into the right atrium.

This catheter was used for injection of radioactively labeled microspheres in the determination of lobar perfusion and for injection of 3-ml saline boluses at room temperature in the determination of cardiac output.

When the animals were thus prepared, and 15 minutes after the last sigh breath, baseline measurements (O_1) were obtained. The first microsphere (^{85}Sr 0.1cc) was injected over 45 seconds while the ventilator was stopped at FRC.

Experimental Procedure

A Foley catheter was advanced via a tracheostomy into the left lower lobe bronchus under visualization by fluroscopy. A fiberoptic bronchoscope was advanced via a side port on the endotracheal tube to a site just proximal to the Foley balloon. Inflation of the Foley balloon with a dilute solution of renographin then allowed fluroscopic visualization of complete bronchial obstruction by the onset of deformation of the balloon into a slightly elongated shape, as well as direct visualization by bronchoscopy. Fifteen minutes after inflation of the balloon, data (O_2) were collected and the dog sighed. Successive data collection points (O_{3-7}) were taken at 20 minute intervals. Following each observation point (O_{2-8}) the dog was sighed. Since all measurements could be made in approximately 5 minutes, 15 minutes elapsed between each sigh breath and the next observation point. Additional sigh breaths were given before O_9. As part of O_7 the second microsphere (^{51}Cr 0.25cc) was injected with the same technique as that described for the first. The dogs were then turned onto their left sides.

Fifteen minutes later, measurements O_8 were obtained with injection of

the third microsphere (^{141}Ce 0.1cc), again by the same technique. When the dog had been in the lateral position for 60 minutes, measurements O_9 were obtained.

After assuring adequate levels of anesthesia, an intravenous bolus of potassium was given to exterminate the animal. The chest was opened and the lung examined for completeness of LLL atelectasis and proper location of the balloon. The lungs were excised and separated into lobes. Each lobe was place in a preweighed beaker to obtain the wet weight before being frozen for 24 hours. Following this, the lobes were oven dried at 60° centigrade until the dry weight was stable (±0.3Gm) for two measurements at least 24 hours apart. The dried lobes were then homogenized individually with 200cc of water. Three 10ml samples were extracted during stirring and centrifuged before being placed in a gamma well counter.

Statistical Analysis

Blood gas results are expressed either as the mean ± the standard deviation (SD) or as the range of values obtained. Some hemodynamic and respiratory variables are reported in table form but were not subject to statistical analysis. Data involving shunt, CO, $\overline{Ppa}$, Pcw, and PVR were examined using analysis of covariance (ANACOVA). Pre-atelectasis, post-atelectasis and post-turning periods were compared, blocked on dogs and adjusted for the covariable time. Perfusion data for the LLL were examined using a 2-way analysis of variance (ANOVA), comparing periods blocked on dogs. To determine which periods or lobes were different from each other, both the ANACOVA and the ANOVA were followed up with Tukey's studentized range

test using an overall procedure-wise error rate of .05.

Chapter 4

RESULTS

The effects of lobar atelectasis and lateral position on regional distribution of perfusion, whole lung gas exchange efficiency and several hemodynamic parameters were assessed. All values discussed are the mean ± the standard deviation unless otherwise specified.

Blood Gases

Pre-atelectasis, PaO_2 was 506 ± 31 mmHg. Fifteen minutes after bronchial occlusion it had dropped to 290 ± 115 mmHg. It remained stable in the 2 hours following the onset of atelectasis. Just before the animal was turned, PaO_2 was 307 ± 151 mmHg. Fifteen minutes after turning it had risen to 347 ± 126 mmHg; sixty minutes after turning it was 376 ± 109 mmHg (see Table 2).

Values for PvO_2 ranged from 43 to 91 mmHg. The mean PvO_2 changed from a pre-atelectasis control value of 69 ± 13 mmHg to 64 ± 13 mmHg fifteen minutes after bronchial occlusion. Then it remained stable throughout the rest of the experiment at approximately 55 mmHg (see Table 3).

$PaCO_2$ was controlled by alterations in respiratory rate. It remained between 33 and 43 mmHg for all dogs at all times. Arterial pH ranged between 7.32 and 7.41 except for dog #20 at 15 minutes post occulsion when pH was 7.29. The individual values for pH are listed in Table 4.

Hemoglobin

In most cases, the simultaneously drawn arterial and mixed venous blood samples had hemoglobin levels within 0.5 Gm of each other, and the average value was used in calculating the shunt. On seven occasions the hemoglobin measurements varied by more than this, but never by more than 1.0 Gm. On the one occasion when the arterial and venous blood samples

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	511	281	228	258	265	245	252	325	371
17	500	396	413	441	459	458	468	466	477
18	548	106	120	104	109	96	94	171	223
19	507	376	416	381	413	390	435	471	482
20	462	291	257	280	300	312	285	302	326
mean	506	290	287	293	309	300	307	347	376
SD	30.7	114.6	127.3	129.2	137.2	139.5	151.0	125.5	108.9
SEM	13.7	51.3	56.9	57.8	61.4	62.4	67.5	56.1	48.7

Table 2. Arterial Oxygen Tension. PaO_2 decreased dramatically following atelectasis, remained fairly stable in the 2 hours post-collapse, and increased when the lateral position was assumed. Calculations are included on the table for the mean, standard deviation (SD) and standard error of the mean (SEM). PaO_2 was measured in mmHg.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	64	58	52	53	54	54	52	56	56
17	64	60	52	51	53	51	50	53	52
18	72	50	50	49	47	46	43	53	54
19	56	69	56	51	53	53	52	56	53
20	91	84	75	71	72	70	67	62	60
mean	69	64	57	55	56	55	53	56	55
SD	13.3	13.0	10.3	9.1	9.5	9.0	8.8	3.7	3.2
SEM	6.0	5.8	4.6	4.0	4.2	4.0	3.9	1.6	1.4

Table 3. Mixed Venous Oxygen Tension. Values for PvO_2 ranged between 43 and 91 mmHg throughout the experiments. Means, standard deviations (SD) and standard errors of the means (SEM) are reported.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	7.35	7.32	7.34	7.34	7.36	7.37	7.37	7.36	7.37
17	7.34	7.33	7.34	7.35	7.33	7.32	7.32	7.34	7.35
18	7.33	7.34	7.34	7.36	7.39	7.38	7.41	7.40	7.43
19	7.35	7.33	7.35	7.35	7.36	7.37	7.38	7.38	7.41
20	7.34	7.29	7.35	7.36	7.36	7.39	7.37	7.36	7.36

Table 4. Arterial pH. Values for arterial pH ranged between 7.29 and 7.41 throughout the experiments.

had hemoglobin levels 1.0 Gm apart the samples were remeasured and the average of all 4 values used in the calculation of shunt.

Oxygen Saturation

Blood samples with oxygen tensions of at least 170 mmHg were assumed to be 100% saturated. Samples with oxygen tensions of 120 mmHg or less had oxygen saturation calculated using a canine homogram (Rossing & Cain, 1966). There were no samples with PO_2 levels between 120 and 170 mmHg.

Distribution of Perfusion

The first hypothesis proposed prior to the execution of this experiment was that lobar atelectasis would result in a significant decrease in perfusion to the collapsed lobe. It was also predicted that lateral positioning with the atelectatic lobe dependent would result in a significant increase in perfusion to that lobe (hypothesis 4).

There was a significant difference ($p<.001$) in LLL perfusion when pre-atelectasis, post-atelectasis and post-turning periods were compared. Mean $\dot{Q}_{LLL}/\dot{Q}t$ dropped from 29.3 ± 1.2% to 20.7 ± 6.2% two hours after endobronchial occlusion and hypothesis 1 was accepted. Left lateral positioning resulted in further decrease in $\dot{Q}_{LLL}/\dot{Q}t$ to 11.7 ± 7.9%; hypothesis 4 was rejected. When the animal was still in a supine position, post-atelectasis perfusion was primarily redistributed to the RLL with some portion also going to the LUL. On turning to the left lateral position the blood flow was redistributed in large part to the LUL with the CL and the RML receiving smaller portions of the increase. (see Figure 16). Perfusion data to all lobes are presented in Table 5.

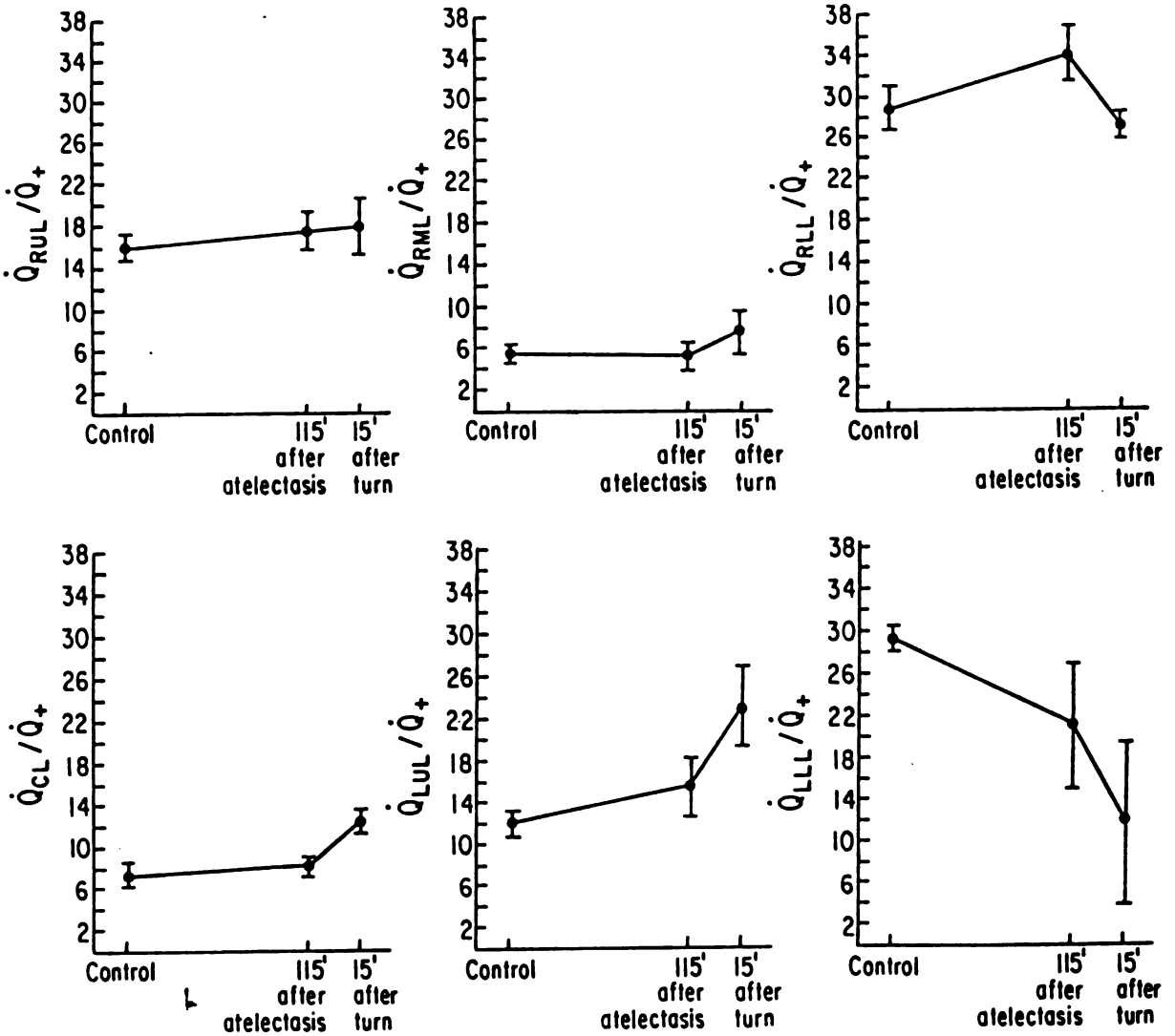

Figure 16. Lobar Perfusion. The percentage of cardiac output perfusing each lobe ($\dot{Q}_{(lobe)}/\dot{Q}t$) is compared pre-atelectasis, 2 hours post-atelectasis, and 15 minutes after the animal was turned onto the left side. The values represented are the mean ± the standard deviation.

Exp. #	$\dot{Q}_{RUL}/\dot{Q}t$			$\dot{Q}_{RML}/\dot{Q}t$			$\dot{Q}_{RLL}/\dot{Q}t$			$\dot{Q}_{CL}/\dot{Q}t$			$\dot{Q}_{LUL}/\dot{Q}t$			$\dot{Q}_{LLL}/\dot{Q}t$		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
16	14.7	16.0	15.1	6.6	6.6	9.2	27.3	31.9	26.9	7.1	7.8	12.2	14.1	14.2	21.5	30.1	23.5	15.0
17	17.1	18.0	19.4	5.1	4.6	5.7	31.1	37.0	28.8	7.5	8.8	14.0	11.7	17.7	29.0	27.6	13.9	3.1
18	17.6	15.5	14.1	5.9	3.9	6.2	26.4	32.5	25.7	8.9	7.6	11.1	11.0	13.3	20.3	30.1	27.0	22.6
19	16.6	20.4	20.7	4.5	3.7	8.1	31.7	35.8	28.7	6.5	6.9	11.8	12.4	18.8	25.6	28.4	14.4	5.1
20	15.0	16.1	18.3	6.0	6.4	9.4	28.3	30.4	27.3	9.2	9.5	13.0	11.2	12.7	19.5	30.1	24.9	12.6
mean	16.2	17.2	17.5	5.6	5.0	7.7	29.0	33.5	27.5	7.8	8.1	12.4	12.1	15.3	23.2	29.3	20.7	11.7
SD	1.29	2.03	2.82	0.82	1.38	1.70	2.34	2.77	1.30	1.17	1.03	1.12	1.25	2.74	4.01	1.18	6.15	7.87
SEM	0.58	0.91	1.26	0.37	0.62	0.76	1.04	1.24	0.58	0.52	0.46	0.50	0.56	1.22	1.79	0.53	2.75	3.52

Table 5. Lobar Perfusion. The percentage of cardiac output perfusing each lobe is compared pre-atelectasis (A), 2 hours post-atelectasis (B), and 15 minutes post-turning (C). Atelectasis and left lateral positioning both resulted in a redistribution of perfusion from the LLL to other lung lobes. The mean, standard deviation (SD) and standard error of the mean (SEM) are reported.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	13.5	23.5	25.5	24.0	24.0	26.0	22.2	21.7	18.0
17	12.5	16.0	14.8	12.1	9.6	8.6	9.2	10.5	10.3
18	8.9	34.2	31.5	34.6	31.1	33.3	32.9	27.8	26.4
19	11.9	24.3	17.8	18.8	17.4	17.4	14.6	14.6	14.3
20	20.7	32.4	33.3	30.8	28.9	27.5	26.8	22.7	21.7
mean	13.5	26.1	24.6	24.1	22.2	22.6	21.1	19.5	18.1
SD	4.37	7.37	8.16	9.04	8.79	9.66	9.44	6.87	6.28
SEM	1.96	3.30	3.65	4.04	3.93	4.32	4.22	3.07	2.80

Table 6. Shunt. $\dot{Q}s/\dot{Q}t$ rose with the onset of atelectasis and gradually decreased throughout the remainder of the experiment. There was no change in the rate of decrease with lateral positioning. The table includes calculations of means, standard deviations (SD) and standard errors of the means (SEM).

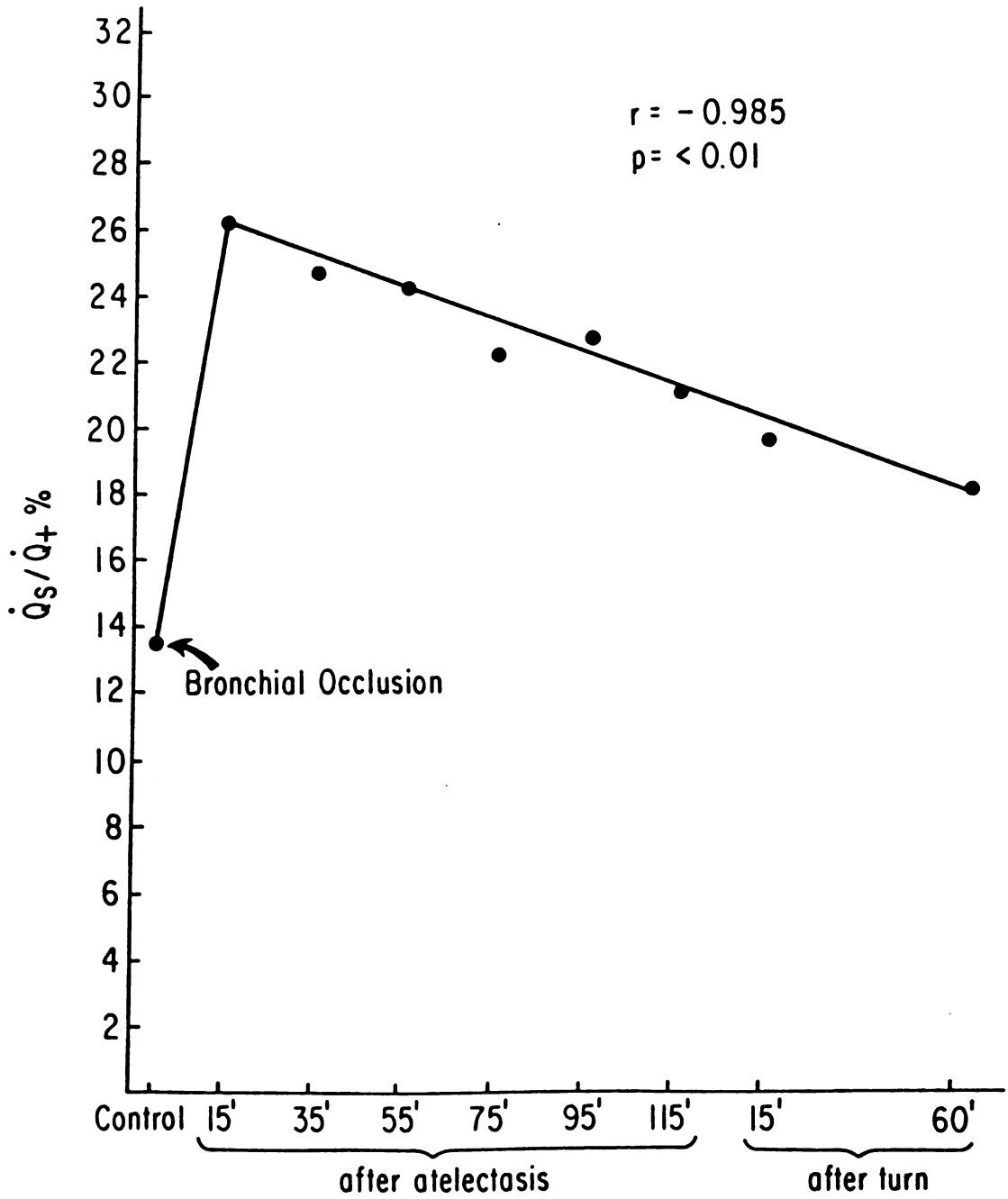

Figure 17. Shunt. $\dot{Q}s/\dot{Q}t$ was measured pre-atelectasis, every 20 minutes for 2 hours after bronchial occlusion, as well as 15 and 60 minutes after the animal was turned onto the left side. The mean values are graphed, along with the line of best fit for the post-collapse values. The correlation factor (r) and the p value are reported.

The dose of microspheres used resulted in no less than a gross count of 226 for any 10cc sample.

Shunt

Hypothesis 2 stated that lobar atelectasis would result in a significant increase in intrapulmonary shunt. Fifteen minutes after atelectasis was created, shunt increased from 13.5 ± 4.4% to 26.1 ± 7.4% (see Table 6). This was significant with a $p < .001$, and hypothesis 2 was accepted. Over the ensuing time, up until the animal was turned, there was a gradual drop in shunt at an average rate of 1.0% every 22 minutes (see Figure 17).

Shunt did not appear to stablize before the animal was turned, however, there were an insufficient number of data points to determine this statistically. Therefore, testing could not be done of hypothesis 3, which had predicted that the initially high post-atelectasis shunt would decrease over time stabilizing by the second hour somewhere still above the pre-atelectasis control value.

After the animal was turned into the left lateral position, the shunt continued to fall at a rate not significantly different from the rate of fall seen before turning. Just prior to turning, $\dot{Q}s/\dot{Q}t$ was 21.1 ± 9.4%; fifteen minutes after turning it was 19.5 ± 6.9%; sixty minutes after turning it was 18.1 ± 6.3%. This led to the rejection of hypothesis 5, which predicted that lateral positioning with the atelectatic lobe dependent would result in a significant increase in intrapulmonary shunt and the rejection of hypothesis 6, which stated that shunt would decrease significantly if lateral positioning was maintained.

Wet/Dry Ratio

Wet/dry ratios are listed in Table 7. The lobes all had equivalent ratios except that the LLL was significantly greater than either the RLL or the CL. However, all wet/dry ratios were within or below the range reported for healthy lung tissue (Fisher & Wood, 1980).

Hemodynamic Variables

Data for $\overline{Ppa}$, Pcw, CO and PVR are presented in Tables 8-11. When these data were compared using ANACOVA, small differences were found for each variable. The follow-up procedure, however, which is a more sensitive test, revealed the only significant difference to be that the post-turning Pcw was lower than either the pre-atelectasis or the post-atelectasis values.

Data for HR and $\overline{BP}$ are presented in Tables 12 and 13. Both were stable throughout the 2 hours following the atelectasis but decreased slightly when the animal was turned.

Respiratory Variables

Tables 14 and 15 contain the data for Pao and RR. Pao was stable throughout the experiment at 3-5 mmHg. Only one animal (dog #16) had the RR changed after the experimental protocol had begun.

Exp #	RUL	RML	RLL	CL	LUL	LLL
16	4.59	4.54	4.27	4.67	4.73	4.75
17	4.12	4.27	3.89	3.74	3.93	4.86
18	4.00	4.18	4.03	3.56	4.06	4.07
19	4.33	5.12	4.19	4.44	4.04	5.12
20	4.20	4.25	4.03	3.93	4.45	4.72
mean	4.25	4.47	4.08	4.07	4.24	4.70
SD	0.23	0.39	0.15	0.47	0.34	0.39
SEM	0.10	0.17	0.07	0.21	0.15	0.17

Table 7. Wet/Dry Ratios. The lobes had equivalent wet/dry weights except that the LLL's ratio was significantly greater than that reported for either the RLL or the CL. All lobes had ratios within the normal range reported in the literature for heathly lung tissue (Fisher & Wood, 1980.) Means, standard deviations (SD) and standard errors of the means (SEM) are reported.

Exp #	Control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	9	10	10	11	11	11	10	6	9
17	10	10	11	11	11	12	12	10	10
18	11	9	10	10	11	11	11	13	11
19	10	12	11	7	10	9	11	10	10
20	10	14	14	13	13	13	13	9	9
mean	10	11	11	10	11	11	11	10	10
SD	0.71	2.00	1.64	2.19	1.10	1.48	1.14	2.51	0.84
SEM	0.32	0.89	0.73	0.98	0.67	0.66	0.51	1.12	0.37

Table 8. Mean Pulmonary Artery Pressure. There was no significant difference found in $P\bar{p}a$ throughout the course of the experiment. Means, standard deviations (SD) and standard errors of the means (SEM) are reported. Ppa was measured in mmHg.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	2	3	2	2	2	1	2	-2	1
17	2	1	1	2	3	3	2	0	2
18	2	1	1	1	1	1	2	2	data not available
19	4	3	3	3	3	3	3	0	1
20	2	4	3	2	2	3	2	0	1
mean	2	2	2	2	2	2	2	0	
SD	0.89	1.34	1.00	0.71	0.84	1.10	0.45	1.41	
SEM	0.40	0.60	0.45	0.32	0.37	0.49	0.20	0.63	

Table 9. Capillary Wedge Pressure. There was no significant difference in Pcw when the control and post-atelectasis periods were compared. Left lateral positioning, however, resulted in a small but significant decrease in Pcw. Means, standard deviations (SD) and standard errors of the means (SEM) are reported.

Pcw was measured in mmHg.

Exp #	Control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	4.4	2.4	3.2	3.2	3.4	3.8	3.4	4.5	4.9
17	3.2	3.5	3.2	2.7	2.8	2.2	2.0	2.5	2.8
18	3.8	3.7	4.0	3.7	3.9	3.6	3.6	4.5	4.4
19	4.7	3.2	3.2	2.8	2.4	5.2	5.3	5.4	4.4
20	4.9	5.5	5.7	5.9	5.8	6.0	5.9	5.5	6.0
mean	4.2	3.7	3.9	3.7	3.7	4.2	4.0	4.5	4.5
SD	0.70	1.14	1.09	1.31	1.33	1.48	1.57	1.20	1.15
SEM	0.31	0.51	0.49	0.59	0.59	0.66	0.70	0.54	0.52

Table 10. Cardiac Output. There was no significant difference found in CO throughout the course of the experiments. Means, standard deviations (SD) and standard errors of the means (SEM) are reported. CO was measured in liters per minute.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	1.6	2.9	2.5	2.8	2.6	2.6	2.4	1.8	1.6
17	2.5	2.6	3.1	3.3	2.9	4.1	5.0	4.0	2.9
18	2.4	2.2	2.2	2.4	2.6	2.8	2.5	2.4	data not available
19	1.3	2.8	2.5	1.4	2.9	1.2	1.5	1.9	2.0
20	1.6	1.8	1.9	1.9	1.9	1.7	1.9	1.6	1.3
mean	1.9	2.5	2.4	2.4	2.6	2.5	2.7	2.3	
SD	0.54	0.46	0.44	0.74	0.41	1.12	1.37	0.97	
SEM	0.24	0.20	0.20	0.33	0.18	0.50	0.61	0.44	

Table 11. Pulmonary Vascular Resistance. The PVR for the entire pulmonary system was measured and no significant differences found. Means, standard deviations (SD) and standard errors of the means (SEM) are reported. PVR was measured in arbitrary units.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	180	174	174	168	180	180	174	156	132
17	192	186	198	180	192	186	186	156	168
18	174	180	180	180	180	180	180	138	138
19	162	162	156	168	174	168	162	144	120
20	168	168	168	162	168	150	150	126	120
mean	175	174	175	172	179	173	170	144	136
SD	11.5	9.5	15.5	8.0	8.9	14.3	14.4	12.7	19.7
SEM	5.2	4.2	6.9	3.6	4.0	6.4	6.5	5.7	8.8

Table 12. Heart Rate. The HR remained stable in the post-atelectasis period but decreased when the animal was turned. Means, standard deviations (SD) and standard errors of the means (SEM) are reported.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	145	134	131	138	133	134	130	107	135
17	113	123	126	123	133	121	122	105	107
18	145	139	139	140	144	143	147	147	137
19	137	134	130	130	121	127	120	111	114
20	139	141	142	141	141	153	153	123	131
mean	136	134	134	134	134	136	134	119	125
SD	13.2	7.0	6.7	7.7	8.9	12.7	14.9	17.3	13.5
SEM	5.9	3.1	3.0	3.4	4.0	5.7	6.7	7.8	6.0

Table 13. Mean Arterial Blood Pressure. The $\overline{BP}$ remained stable throughout the experiments but decreased when the animal was turned. Means, standard deviations (SD) and standard errors of the means (SEM) are reported. BP was measured in mmHg.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	3	3	3	3	4	4	4	3	3
17	2	4	3	4	4	4	4	4	4
18	3	3	4	4	4	4	4	5	3
19	3	3	3	3	3	3	4	3	3
20	3	4	3	3	4	3	4	3	4
mean	3	3	3	3	4	4	4	4	3
SD	.45	.55	.45	.55	.45	.55	0	.89	.55
SEM	0.2	0.2	0.2	0.2	0.2	0.2	0	0.4	0.2

Table 14. Airway Opening Pressure. The Pao remained stable throughout the course of the experiments.Means, standard deviations (SD) and standard errors of the means (SEM) are reported.
Pao was measured in mmHg.

Exp #	control	Post-atelectasis						Post-turn	
		15'	35'	55'	75'	95'	115'	15'	60'
16	15	15	15	15	17	17	17	17	17
17	9	9	9	9	9	9	9	9	9
18	18	18	18	18	18	18	18	18	18
19	18	18	18	18	18	18	18	18	18
20	12	12	12	12	12	12	12	12	12

Table 15. Respiratory Rate. Only one dog (#16) required RR to be adjusted once the experimental protocol had begun.

Chapter 5

DISCUSSION

The effect of atelectasis and lateral positioning with the collapsed tissue dependent was studied in a closed-chest canine model. Regional distribution of pulmonary blood flow was measured with differentially-labeled microspheres and the shunt equation.

The Effect of Atelectasis on Regional Distribution of Pulmonary Blood Flow

As expected, atelectasis of the LLL resulted in a decrease in perfusion to that lobe and an increase in intrapulmonary shunt. $\dot{Q}_{LLL}/\dot{Q}t$ dropped from 29.3 ± 1.2 to 20.7 ± 6.2% when measured 2 hours after endobronchial obstruction. This represented a drop in perfusion to 71% of that measured prior to atelectasis. While this is a lower value for retained perfusion than those reported by some researchers (Aviado, 1960; Hobbs et al., 1972; Morgan and Guntheroth, 1970; Newell et al., 1976), it is higher than the values reported by others (Barer et al., 1969; Benumof 1979; Camishion et al., 1961; Enjeti et al., 1979; MacVaugh et al., 1961; Newell et al., 1976; Woodson et al., 1963). The current study offers no data which would quantitate the relative importance of hypoxic vasoconstriction versus mechanical factors in diminishing flow to the atelectatic region.

Mean $\dot{Q}s/\dot{Q}t$ rose immediately following endobronchial obstruction from 13.5 ± 4.4 to 26.1 ± 7.4%. This probably represented some degree of retained perfusion to the LLL, which was confirmed when microspheres were injected almost 2 hours later. Following the initial increase in shunt there was a gradual fall over the next 1 3/4 hours to 21.1 ± 9.4% just prior to turning. Although the general pattern of $\dot{Q}s/\dot{Q}t$ rising rapidly then falling

slowly was the same as reported elsewhere in literature, the shunt values in this study were higher than those reported by Kersten et al. (1977) and lower than those reported by Fisher et al. (1979).

The reason for the gradual reduction in shunt is not entirely clear. In a similar model, Hobbs et al. (1972) had injected microspheres 15, 30, and 120 minutes after endobronchial obstruction. They found that perfusion dropped immediately and remained stable at this lower level. There was not a gradual reduction in flow. It is unlikely, in the present experiment, that post-collapse $\dot{Q}_{LLL}/\dot{Q}t$ remained stable. Rather, the gradual reduction in shunt was interpreted to represent a gradual reduction in perfusion to the LLL. Had microspheres been injected 15 minutes after endobronchial occlusion, the $\dot{Q}_{LLL}/\dot{Q}t$ would have been expected to be somewhere between the value obtained pre-atelectasis and that obtained 2 hours post-atelectasis.

There are several possible explanations for what may have caused the presumed gradual decrease in perfusion to the LLL. If the fraction of cardiac output perfusing the atelectatic lobe decreased gradually, it is likely that either (a) total flow through the lungs decreased gradually, (b) the resistance in the ventilated lung decreased gradually or (c) the resistance in the atelectatic lobe increased gradually.

If total flow through the lungs decreased and perfusion pressures were lower, less blood may have been forced through the collapsed tissue. In the present experiment there was no significant change in either CO, $\overline{BP}$, HR, $P\bar{p}a$ or Pcw during the 2 hours post-atelectasis. Thus, decreased

total flow is an improbable explanation for the gradual reduction in $\dot{Q}_{LLL}/\dot{Q}t$ believed to have occured.

Had the resistance in the ventilated lung decreased gradually there could have been a gradual reduction in $\dot{Q}_{LLL}/\dot{Q}t$ as more blood began to perfuse areas of lower vascular resistance. Since there was no significant change in total PVR, it would appear that, if resistance had increased in the atelectatic lobe, it would have had to decrease in other areas of the lung. This may not be an accurate assumption, however, since the formula used to calculate total PVR in this study may have been used inappropriately. Mean Pao was consistently above Pcw in this study, although there were individual cases where the reverse was true. During conditions of no airflow, when the airways are open, Pao is equal to Palv. If Pao is greater than Pcw, it follows that Palv is also greater than Pcw. This indicates the presence of zone 1 or zone 2 tissue in the lung. In these zones, the driving pressure for PBF is influenced by Palv, which is not taken into account by the formula for PVR.

Although the formula used to calculate PVR may not have given an accurate reflection of conditions in the non-atelectatic regions, it was still possible that atelectasis influenced resistance in these areas. Due to hyperpnea, atelectasis may result in an immediate increase in lung volume and PVR within the ventilated tissue. If this occurred but was of a temporary nature, then as the initially high resistance in the aerated region decreased, perfusion to that area may have increased. Flow would have been diverted away from the higher resistance regions of atelectasis and perfusion

enchanced to the aerated tissue. In spontaneously breathing animals, Niden (1964) demonstrated that the hyperpneic response to atelectasis probably decreases over time. If this were true, then there might be a gradual reduction in PVR in the aerated lung and a gradual reduction in flow to the collapsed tissue as PBF was redirected. It is not likely, however, that this could explain the gradual reduction in $\dot{Q}_{LLL}/\dot{Q}t$ presumed to have occurred in this experiment, since the anesthetized and mechanically ventilated animals would not have developed reflex hyperpnea.

Despite anesthesia and controlled ventilation, however, there may have been a hyperpnea-like response in the aerated lung immediately post-collapse. The tidal volume was not decreased following bronchial obstruction of the LLL; this would have resulted in increased volume in the remaining lung. However, since the tidal volume was not changed during the rest of the experiment, any influence which volume in the aerated tissue may have had on PVR would have been expected to occur immediately following bronchial obstruction and not change further during the experiment. Thus, it would not explain the gradual reduction in flow to LLL which probably occurred over the 2 hours post-collapse.

The most likely explanation for gradual reduction in $\dot{Q}_{LLL}/\dot{Q}t$ is that PVR gradually increased in the LLL. Increased PVR reflects increased resistance either in alveolar vessels, extra-alveolar vessels or both. At the low lung volumes present in atelectatic tissue it is improbable that alveolar vessels were responsible for the increased resistance. Niden (1964) demonstrated with histological preparations that the capillary beds in atelectatic

tissue were dilated and filled with red blood cells. Barer et al. (1969) demonstrated that, in most cases, atelectasis caused changes in both slope and intercept of resistance lines; this reflected increased resistance of extra-alveolar vessels.

Resistance in extra-alveolar vessels can be increased by intraluminal obstruction, thickening or contraction of the vessel wall or external compression. Intraluminal obstruction may have been caused by the microspheres. However, the size of microspheres used and the total quantities in which they were injected make this an unlikely possibility. Active vasoconstriction of the extra-alveolar vessels probably did occur in this experiment in response to alveolar hypoxia. If complete collapse of the lobe had occurred rapidly this reflex vasoconstriction would have been expected to be fully activated shortly after endobronchial obstruction. Whether this mechanism could then have been responsible for gradual reduction in flow over the 2 hours post-collapse is questionable.

Reflex vasoconstriction is probably inhibited by systemic hypoxemia (Kersten et al., 1977; Newell et al., 1976). If atelectasis resulted in a drop in PaO_2 to a level which inhibited vasoconstriction, and then, through some unknown mechanism, PaO_2 was able to rise slowly, gradual return of active vasoconstriction could have explained the gradual reduction in flow to the LLL. It is improbable that this is what happened in the present experiment because despite the post-atelectasis drop in PaO_2 none of the dogs were hypoxemic. Systemic oxygen tension was consistently above 94 mmHg; mixed venous oxygen tension was consistently above 42 mmHg.

External compression of the extra-alveolar vessels is the most likely explanation of the gradual reduction in flow presumed to have occurred in the LLL over the 2 hours following bronchial occlusion. Interstitial pulmonary edema or diminished elastic recoil may have resulted in external compression of the alveolar vessels. The presence of pulmonary edema can be evaluated by examining the ratio of wet to dry lobar weights. Wet/dry ratios for edematous lung tissue have been reported as 6.5 ± 0.6, compared to ratios of 5.1 ± 0.4 for normal lung tissue (Fisher & Wood, 1980). In this experiment the wet/dry ratios for the LLL were consistently equal to or less than 5.1 ± 0.4, thus making the presence of pulmonary edema in the LLL an unlikely possibility. Loss of elastic recoil as lung volume decreased could have explained the immediate decrease in perfusion to the LLL, but whether this mechanism could have explained a gradual reduction in flow over 2 hours is doubtful. Lungs filled with 100% oxygen prior to bronchial obstruction probably reached minimal volume and thus minimal elastic recoil long before 2 hours had passed.

In summary, although external compression of the extra-alveolar vessels causing increased resistance in the atelectatic lung is the most likely cause of the gradual reduction in $\dot{Q}_{LLL}/\dot{Q}t$, the exact mechanism of this compression is unclear.

The Effect of Lateral Positioning on the Regional Distribution of Pulmonary Blood Flow in Atelectasis

It was predicted that lateral positioning with the atelectatic LLL dependent would result in a significant increase in $\dot{Q}_{LLL}/\dot{Q}t$. However, the

findings indicated that there was a dramatic decrease.

The finding of decreased flow to the LLL on dependent positioning is in apparent contradiction to the findings of the clinical studies on positioning with unilateral lung disease. Although these clinical studies relied on indirect measures of flow, they all showed clearly and consistently that PaO_2 deteriorates when the diseased tissue is dependent. This has been assumed to reflect an increase in perfusion through the diseased tissue. Although in these studies, only four cases were reported with atelectasis, (Remolina et al., 1981) the findings were the same as for the other types of lung disease.

Several of the possible explanations for the decrease in $\dot{Q}_{LLL}/\dot{Q}t$ on dependent positioning are the same as those discussed for the effect of atelectasis on the regional distribution of PBF and can be ruled out for the same reasons. Intraluminal obstruction by microspheres was improbable due to the size and total numbers of microspheres used; enhanced vasoconstriction as PaO_2 rose was improbable since hypoxemia did not exist. External compression of extra-alveolar vessels by pulmonary edema was essentially eliminated since the wet/dry ratio of the LLL was within normal limits. External compression of extra-alveolar vessels by loss of elastic recoil was unlikely since the volume of the lung was probably at its minimum before turning occurred. The most likely explanation for diminished perfusion of the LLL on dependent positioning was an external compression of vessels leading to or within this lobe by the weight of the right lung and mediastinal contents.

It was interesting to note in the present study that the lateral position, which was associated with a dramatic decrease in $\dot{Q}_{LLL}/\dot{Q}t$, was not

associated with an equally dramatic decrease in shunt. The shunt instead continued on the same slow decline as had been occurring prior to turning. Thus, it may not be reasonable to assume that the atelectatic LLL was the only part of the lung which was unable to exchange gas efficiently. The lack of improvement in $\dot{Q}s/\dot{Q}t$ when $\dot{Q}_{LLL}/\dot{Q}t$ decreased after turning suggested that the decrease in perfusion to the LLL was matched by an increase in perfusion to some other part of the lung in which intrapulmonary shunting existed. After turning, LLL perfusion was redistributed primarily to the LUL, although the CL and RML also received increases.

The cause of intrapulmonary shunting in any of these three lobes is unclear. One animal (dog #20) had a high control $\dot{Q}s/\dot{Q}t$ and so may have had shunt producing disease present in one of these lobes prior to the experiment. An alternative explanation of this elevated shunt, however, is that it was an artifact created by a sampling error and that the animal's actual shunt was lower. Careful examination of the blood gas values reveal that dog #20 had an abnormally high PvO_2. If the pulmonary artery cateter was advanced too far when it was inserted, the blood sample obtained from this catheter may have contained oxygenated blood pulled back across the capillary bed. Using an incorrectly high value for CvO_2 in the shunt equation would result in a falsely elevated shunt. However, even it the control shunt reported for dog #20 was accurate, this represented the only animal with an elevated shunt prior to atelectasis. Therefore, at least in the other four dogs, the process responsible for shunting in the LUL, CL and/or the RML probably occurred during the course of the experiment.

Pulmonary edema, pneumonia and atelectasis are common causes of shunting. Airway closure must also be considered as a potential cause. Pulmonary edema can essentially be ruled out since each of the three lobes whose perfusion increased on turning had wet/dry ratios within or below normal limits. The development of pneumonia during the short course of this experiment is highly unlikely. None of the animals spiked fevers, but in part their temperatures were controlled with application or removal of a heating pad and a down blanket. The times at which the pad and blanket were applied or removed were not recorded. On autopsy, several of the animals were noted to have areas of lung tissue which were darker red than normal. These areas may have been consistent with the red-hepatic appearance of acute pneumonia. In dog #16 there was a slightly accentuated redness along one border of the CL; all lobes of dog #17 were darker red than normal expect for the RML which was surrounded by fatty tissue. In dog #18 there was a small section of both the RUL and the RLL which had the reddened appearance; neither of these lobes, however, received increased perfusion after turning.

The development of unplanned atelectasis is the most plausible explanation of the presumed shunting in the LUL, CL or RML. The possibility of atelectasis was particularly high in the LUL which not only assumed a dependent position when the animal was turned, but theoretically also may have developed some airway obstruction from the Foley catheter passing by its bronchus. Although the reddened areas discussed above may have been areas of atelectasis, they differed in appearance from the dark purple coloring of the collapsed LLL. While microscopic atelectasis cannot be

ruled out in any of the dogs, only 3 had visible atelectasis outside of the LLL. In dog #16 there was a spotty atelectasis over above half of the LUL; in dog #18 there was a small area on the edge of the LUL as well as at the LUL hilum; in dog #20 the LUL hilum had a small area of atelectasis.

If the LUL bronchus were partially obstructed by a catheter, it is conceivable that ventilation to this lobe may have decreased. The subsequently diminished lobar volume may have created shunting by a combination of two factors. First, airway closure may have occurred, trapping air in the lung as the volume of the lobe decreased and radial traction on the airways was diminished. Second, the smaller lung volume may have resulted in decreased PVR with resultant increase in blood flow. While the phenomenon of airway closure may have contributed to the deterioration of PaO_2 in the clinical studies on positioning reported in the literature, it is unlikely that it was a factor in the present study for the following reasons. When enough airway closure had occurred to contribute to shunt, it would be surprising if alveoli filled with 100% O_2 did not collapse. In any event, as long as the alveoli had not collapsed, $PpvO_2$ from this lobe would have remained high and thus would not have contributed to shunt.

Conclusions

Several clinical studies have described the effect of positioning on arterial blood gases in the presence of various different lung pathologies. It may not be reasonable, however, to equate unilateral atelectasis with other unilateral lung diseases; the morphology of atelectatic tissue is distinctly different from that seen in other lung diseases.

Therefore, it is logical only to compare the four cases of unilateral atelectasis reported by Remolina et al. (1981) with the five cases reported in this study. These are extremely small samples to draw conclusions from, especially because the findings were different. The studies are difficult to compare due to dissimilarities in the models and methods used; of most interest among these differences are ventilatory mode, anesthesia, length of time before post-collapse measurements were obtained, FiO_2, and subject selection.

Although Remolina et al. (1981) reported one patient out of the total sample of nine who was mechanically ventilated, they did not specify whether this was one of the patients with atelectasis. In any event, at least three of the four cases of atelectasis were spontaneously breathing without anesthesia, both factors which might tend to assist perfusion through the collapsed tissue more than seen in the present study.

The study reported in this manuscript dealt with a model of acute atelectasis; no information was given on whether Remolina et al's patients had acute or chronic collapse. Mechanical factors may develop in atelectatic tissue over time. Thus, blood flow to chronically collapsed tissue may be influenced by different factors than influence flow to acutely collapsed tissue; the two may respond differently to positioning.

Also of significance, when comparing this study with Remolina et al's, is that due to differences in the FiO_2, none of the dogs in the present study had hypoxemia, while the PaO_2 for the patients ranged between 46-77 mmHg while in the lateral position with the collapsed tissue dependent.

There is some possibility that this degree of hypoxemia may have limited the ability of the atelectatic tissue to reduce flow. The dog's mediastinum may be less well connected to the thorax than is the human's. If this were the case, lateral positioning might result in the models having different degrees of external compression to the vessels in the atelectatic region. In the dog model, the mediastinum might drop and compress the vessels which would reduce flow while in the human model where the mediastinum is better supported, gravitational factors might predominate resulting in increased flow.

Data from this study showed that in acute lobar atelectasis (a) perfusion to the collapsed lobe decreased (b) there was an initial increase in shunt followed by a slow decline over the next few hours and (c) positioning with the atelectatic lobe dependent resulted in further decrease in perfusion to the collapsed lobe. The discrepancy between the findings of this study and the study by Remolina et al. (1981) are puzzling and deserve further investigation. Future research should include work in both laboratory and clinical settings, to determine if the difference in results can be attributed to differences in the models used. Related areas to be examined might include seeing if the results of this study are repeatable in a mildly hypoxic or a spontaneously breathing animal, in a model of chronic atelectasis or in an animal whose mediastinum is better supported than the dog's. In clinical research, studies on positioning should identify the type as well as the distribution of disease.

Nurses have the responsibility for selecting the position in which

an immobile patient will lay. In the final analysis, however, even if one position can be identified in which blood flow through diseased tissue is minimized or blood gases are optimized, it is clear that a patient cannot remain in that position indefinitely. Complications of immobility must still be prevented by turning. Therefore, research should be conducted to determine the effect of many different positions on gas exchange in the presence of various lung diseases. The effect of non-dependent positioning on blood flow through atelectatic tissue should be measured in the laboratory setting. Clinically, alternatives to the lateral decubitus position should be investigated. Turning a patient past the standard lateral turn partially onto the stomach (the 3/4 prone, swimmers, or coma position) may provide a good alternative to the lateral position for patients with unilateral lung disease or to the prone position for patients with respiratory distress syndrome.

The importance of the present study is that it challenges the assumption that positioning has the same effect on the distribution of pulmonary blood flow regardless of the type of lung disease. Although dependent positioning of many types of diseased pulmonary tissue may usually result in deterioration of blood gases, dependent positioning of atelectatic tissue may cause blood gases to improve. The discrepancies between the results reported in this study and the interpretation of Remolina et al!s results should be resolved before making blanket clinical decisions of position choice based on either one. Until these discrepancies are resolved, positioning of patients with atelectasis should be done on an individual basis with attention paid to the position of the patient when blood gases are drawn or signs of hypoxemia noted.

APPENDIX

Symbols and Abbreviations

The symbols and abbreviations used in this manuscript are defined below. A dot ($\dot{}$) appearing over a symbol should be read as "per unit time;" a dash ($\bar{}$) appearing over a symbol indicates a mean value.

ANACOVA	analysis of co-variance
ANOVA	analysis of variance
bkg	background radiation
BP	blood pressure
CaO_2	arterial oxygen content
$Cc'O_2$	ideal end-capillary oxygen content
^{141}Ce	radioactive cerium
Ci	concentration of indicator entering a system
CL	cardiac lobe
cm	centimeters
cmH_2O	centimeters water pressure
Co	concentration of indicator leaving a system
CO	cardiac output
CO_2	carbon dioxide
$CpvO_2$	pulmonary vein oxygen content
^{51}Cr	radioactive chromium
CV	closing volume
CvO_2	mixed venous oxygen content
f	flow
FiO_2	fraction of inspired oxygen

FRC	functional residual capacity
Gm	gram
Hgb	hemoglobin
HR	heart rate
k	radioactive spillover
K	constant
LAP	left atrial pressure
LLL	left lower lobe
LUL	left upper lobe
ml	milliliters
mmHg	millimeters mercury pressure
N_2	nitrogen
N_2O	nitrous oxide
O_{1-9}	observation points
O_2	oxygen
ΔP	change in pressure
PaO_2	arterial oxygen tension
P_AO_2	alveolar oxygen tension
Palv	alveolar pressure
Pao	airway opening pressure
P_B	barometric pressure
PBF	pulmonary blood flow
PCO_2	carbon dioxide tension
Pcw	capillary wedge pressure

PEEP	positive end expiratory pressure
PH_2O	water vapor tension
P_L	transpulmonary pressure
PO_2	oxygen tension
Ppa	pulmonary artery pressure
Ppl	intrapleural pressure
Ppv	pulmonary vein pressure
$PpvCO_2$	pulmonary vein carbon dioxide tension
$PpvO_2$	pulmonary vein oxygen tension
P-V	pressure volume
PvO_2	mixed venous oxygen tension
PVR	pulmonary vascular resistance
$\dot{Q}$	perfusion
$\dot{Q}_{CL}/\dot{Q}t$	fractional perfusion of cardiac lobe
$\dot{Q}_{LLL}/\dot{Q}t$	fractional perfusion of left lower lobe
$\dot{Q}_{(lobe)}/\dot{Q}t$	fractional perfusion of any lobe
$\dot{Q}_{LUL}/\dot{Q}t$	fractional perfusion of left upper lobe
$\dot{Q}_{RLL}/\dot{Q}t$	fractional perfusion of right lower lobe
$\dot{Q}_{RML}/\dot{Q}t$	fractional perfusion of right middle lobe
$\dot{Q}_{RUL}/\dot{Q}t$	fractional perfusion of right upper lobe
$\dot{Q}s/\dot{Q}t$	shunt
$\dot{Q}'$ (t)	amount of indicator in a system
R	resistance
RLL	right lower lobe
RML	right middle lobe

RQ	respiratory quotient
RR	respiratory rate
RUL	right upper lobe
SaO_2	arterial oxygen saturation
SD	standard deviation
SEM	standard error of the mean
^{85}Sr	radioactive strontium
SvO_2	mixed venous oxygen saturation
T	temperature
$\dot{V}$	ventilation
$\dot{V}_A$	alveolar ventilation
$\dot{V}CO_2$	carbon dioxide exhaled
$\dot{V}O_2$	oxygen consumed
X_{1-2}	experimental manipulations

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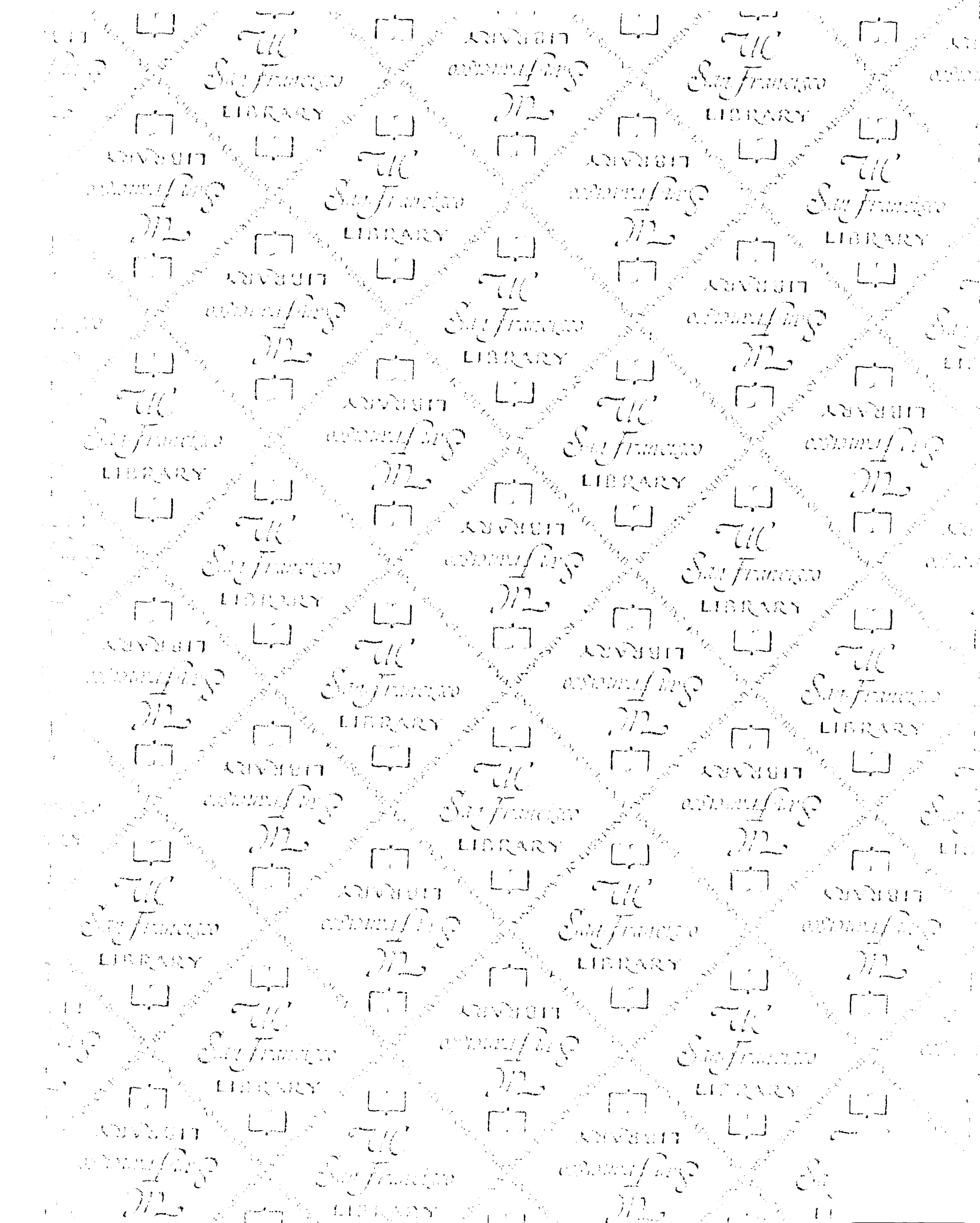
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