PULMONARY OEDEMA: A REVIEW

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ABSTRACT

Pulmonary oedema results from derangement of a normal physiological process which is continuously producing and removing extravascular lung water according to principles stated by Starling's equation of fluid flow across semipermeable membranes. The parameters in Starling's equation cannot all be measured. However, experiments have suggested that increased pulmonary capillary hydrostatic pressure forces fluid extravascularly, diluting the colloid osmotic pressure of tissue fluids and increasing the hydrostatic pressure of lung tissue fluids. Once these reserves and the ability of pulmonary lymphatics to remove lung water are overcome, pulmonary oedema results. This oedema can also result from reduced colloid osmotic pressure in the pulmonary capillaries and increased capillary permeability, even at low pulmonary capillary hydrostatic pressure.

Perhaps because of the reserve created by colloid osmotic pressure of tissue fluids, hydrostatic pressure of lung tissue fluids and lymphatic drainage, pulmonary oedema accumulates at a slow rate initially, and at a much more rapid rate in later stages of oedema development. The rate of oedema formation may also relate to damage to the lung created by interstitial oedema, which opens the barrier to a later stage of alveolar oedema. While lung compliance is reduced with each successive increase in oedema formation, increased shunting and hypoxaemia do not result until alveolar oedema is present, in normal lung.

The diagnosis of pulmonary oedema is best made by searching for causes of oedema and by chest radiographs.

The management of pulmonary oedema must begin with maintenance of oxygenation of blood. This can best be achieved by applying continuous positive pressure ventilation (CPPV). CPPV does not remove lung water (in fact it may slightly increase it), but it does improve oxygenation by ventilating alveoli that were previously filled with fluid. The improved oxygenation buys time, so that therapy directed at the cause of pulmonary oedema (Starling's law) can be applied.

Since current knowledge is inadequate we do not know how to reverse an increased capillary permeability, other than by removing its cause; or how to reduce tissue colloid osmotic pressure, or to increase the hydrostatic pressure of lung tissue fluids or the intracapillary colloid osmotic pressure or the lymphatic flow of fluid. This leaves only increasing intracapillary colloid osmotic pressure or decreasing pulmonary capillary hydrostatic pressure as the means available to reduce pulmonary oedema. In the face of a non-compliant left ventricle colloid infusions may be dangerous, as the attendant increase in blood volume may increase pulmonary capillary hydrostatic pressure and worsen pulmonary oedema. If increased capillary permeability is the cause of pulmonary oedema, colloids might leak extravascularly and draw fluid with them. Therefore the most important therapy in pulmonary oedema, regardless of cause, is to reduce pulmonary capillary hydrostatic pressure. Depending on the cause of pulmonary oedema and the associated cardiac output, pulmonary capillary hydrostatic pressure may be decreased by reducing left ventricular preload, increasing myocardial contractility, reducing left ventricular after-load or some combination of these.

The anaesthetic implications are that Starling reserves are large and pulmonary oedema should not occur in the normal patient. In the patient with pulmonary oedema or reduced cardio-pulmonary reserve preoperatively, every effort must be made to optimize Starling's forces before undertaking an anaesthetic in these life threatening situations.

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 - Time course of pulmonary oedema

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 - P_T
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CVP versus pulmonary artery
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blood gases
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chest radiograph

V Management

1. Maintain Oxygenation

FI_{O_2}
CPPV

2. Lower P_{mv}

lower ventricular preload
increase myocardial preload
reduce ventricular afterload
(improve ventricular compliance)

3. Remove the cause of increased capillary permeability

4. Increase COP_{mv} (cautiously)

VI Implications of Pulmonary Oedema for

the Anaesthetist:

normal patients

patients with pulmonary oedema preoperatively

patients with decreased cardio-pulmonary reserves

Gas Exchange

Pa_{O_2} arterial partial pressure of oxygen
 Q_s/Q_t shunt fraction
FRC functional residual capacity
CPPV continuous positive pressure ventilation
 V/Q ventilation perfusion ratio
 Pv_{O_2} mixed venous partial pressure of oxygen

I INTRODUCTION

PULMONARY OEDEMA may be defined as an abnormal collection of fluid in the extravascular tissues and spaces of the lung. It is important to realise that the lungs have a dynamic and not a static water content. Water and proteins do move into the interstitial space and are returned to the venous circulation by an extensive network of lymphatics. Once the capacity of the lymphatics to remove excess fluids is exceeded, fluid accumulates in the interstitial space and, if unchecked, will lead to alveolar flooding.

Theoretically it should be possible to distinguish between interstitial and alveolar oedema. However, an easy technique to detect small increases in extravascular water is not currently available. Consequently little is known about the early interstitial phase of pulmonary oedema. In animal experiments, determinations of volume and protein concentration of the lymphatic fluid from the lung or double indicator dilution techniques to quantitate lung water are shedding some light on the process of extravascular lung water formation in normal conditions and in disease. Since techniques to quantify lung water in patients are invasive, most of the patient data is gathered in cardiac surgery settings. It is assumed the principles learned there will apply to other patients as well. Other clinical information usually begins at the late alveolar oedema stage and makes assumptions about its cause.

In this review I will stress basic physiology and recent advances in knowledge of pulmonary oedema.

II PATHOPHYSIOLOGY

To understand the pathophysiology of pulmonary oedema we should start by studying the physical forces and permeability properties that produce shifts in water from one compartment to another. In 1896 Starling¹ stated the general

GLOSSARY OF TERMS

Haemodynamics

P_{mv} pulmonary capillary hydrostatic pressure
 PAO pulmonary artery occluded (wedge) pressure
 P_{PA} pulmonary artery pressure
 $LVEDP$ left ventricular end diastolic pressure
 $LVEDV$ left ventricular end diastolic volume
CVP central venous pressure
 $\dot{Q}$ cardiac output

Lung Liquid Flow

$\dot{Q}_f$ net transvascular flow of fluid
 K_f fluid filtration coefficient
 P_T tissue fluid interstitial hydrostatic pressure
 G_f reflection coefficient
 COP_{mv} colloid osmotic pressure of plasma proteins
 COP_T colloid osmotic pressure of tissue proteins
 ETV_L extravascular thermal volume of lung (a double indicator dilution measure of lung water)

transport equation for fluid flow across capillary membranes:

$$\dot{Q}f = Kf[(P_{mv} - P_T) - Gf(COP_{mv} - COP_T)] \quad (1)$$

where $\dot{Q}f$ is the net transvascular flow of fluid, Kf is the fluid filtration coefficient, P_{mv} is the microvascular hydrostatic pressure, P_T is the tissue interstitial fluid hydrostatic pressure, Gf is the reflection coefficient describing the "effective" transvascular protein osmotic pressure difference, COP_{mv} is the colloid osmotic pressure of plasma proteins, and COP_T is the tissue fluid colloid osmotic pressure. Together Kf and Gf describe pulmonary capillary permeability.

Examples of normal values and changes which can occur in Starling's equation will clarify how oedema formation is affected. In the normal these results might apply. Kf is assumed to be $1 \text{ ml H}_2\text{O/mmHg} \cdot \text{min}^{-1}$ and is a property of the system that expresses how much water will flow across the membrane per unit change in pressure. Gf is assumed to be 0.8, indicating that protein can cross the pulmonary capillary membrane; but the membrane is normally about 80 per cent effective as a barrier to protein crossing. P_{mv} is a calculated value which has not been directly measured. Since pulmonary capillary pressure (P_{mv}) is between pulmonary artery and left atrial pressure, Garr² has described an equation to define P_{mv} where:

$$P_{mv} = PAO + (P_{\overline{PA}} - PAO) \quad (2)$$

and PAO is the pulmonary artery occluded pressure (wedge pressure) and $P_{\overline{PA}}$ is the mean pulmonary artery pressure.

COP_T has been derived by measuring the protein concentration of lymph from the lung and assuming that it relates to interstitial protein concentration.^{3,5} P_T can not be measured directly with present techniques and it is the least well understood parameter in Starling's equation; but it may relate to pleural pressure and seems to be a negative number.^{6,7} Assuming normal values we obtain a $\dot{Q}f$ of 1.6 as follows:

Normal

Capillary	$P_{mv} = 5 \text{ mm Hg}$	$COP_{mv} = 25 \text{ mm Hg}$
Interstitial	$P_T = -7 \text{ mm Hg}$	$COP_T = 12 \text{ mm Hg}$

Substituting in (1)

$$\dot{Q}f = 1[(5 - (-7)) - 0.8(25 - 12)] = 1.6$$

Since $\dot{Q}f$ is normally a positive number fluid is continuously moving extravascularly. Lymph

ducts must return this fluid to the systemic venous circulation or pulmonary oedema will result.

If one variable in Starling's equation is changed, other variables will change. If an increase in hydrostatic pressure (P_{mv}) occurs fluid will immediately move into the extravascular lung and dilute the proteins (lymph proteins are reduced in the presence of an increased P_{mv}).⁴ P_T changes have not been measured in pulmonary oedema, but data from Parker, *et al.*⁷ suggest an increase. If we assume these changes we obtain a $\dot{Q}f$ of 3.6 as follows:

Elevated P_{mv}

Capillary	$P_{mv} = 22 \text{ mm Hg}$	$COP_{mv} = 25 \text{ mm Hg}$
Interstitial	$P_T = 0 \text{ mm Hg}$	$COP_T = 2 \text{ mm Hg}$

Substituting in (1)

$$\dot{Q}f = 1[(22 - 0) - 0.8(25 - 2)] = 3.6$$

This represents a small rise in the forces favoring pulmonary oedema (3.6 versus 1.6 in the normal). The lung lymphatics should be able to offset the development of pulmonary oedema by increasing lymph flow. But now the available tissue "reserves" have been reduced. P_T can not be increased and COP_T can not be effectively diluted further, so that any fall in COP_{mv} below 25 mm Hg (3.33 kPa) or rise in P_{mv} above 22 mm Hg (2.93 kPa) should lead to pulmonary oedema once lymphatic removal is overwhelmed.

This same argument could be applied to the patient with low serum protein concentrations or increased capillary permeability. Once tissue hydrostatic and colloid osmotic pressure "reserves" have been used and lymphatic ability to remove lung water overwhelmed, pulmonary oedema will result. In the case of pulmonary capillary permeability and low serum protein concentrations, pulmonary oedema will result at much lower levels of P_{mv} than 22 mm Hg (2.93 kPa). P_{mv} levels as low as 5 mm Hg (0.67 kPa) have been associated with clinical pulmonary oedema severe enough to allow collection of oedema fluid through a tracheal tube.⁸ pulmonary wedge pressures of $11 \pm 4.5 \text{ mm Hg}$ ($1.46 \pm 0.6 \text{ kPa}$) were found in 10 patients with sepsis and pulmonary oedema.⁹

Time Course of Pulmonary Oedema

The amount of water present in the extravascular compartment of the lung represents the resultant of the amount filtered (Starling's law) minus the amount removed (lymph flow). When the left heart is overloaded in a dog by infusion

FIGURE 1 When dextran 40 in normal saline is infused into dogs to increase and hold pulmonary artery pressure at 5.32–5.99 kPa (40–45 mm Hg), lung water (ETVL) accumulates slowly at first and much more rapidly later.

dextran, lung water accumulates slowly at first and much more rapidly later,¹⁰ in spite of a constant pulmonary artery pressure of 40–45 mm Hg (5.32–5.99 kPa) (Figure 1). This suggests that lymph flow can remove excess fluid initially when P_T and COP_T "reserves" are not exhausted. Once P_T has increased to 0 mm Hg and COP_T has fallen to 2 mm Hg the lymphatics will be overwhelmed and lung water accumulation will be time dependent. This is supported by Parker, *et al.*⁷ who found an increase in lung water of 1 per cent per mm Hg rise in P_T below 0 mm Hg. When P_T was just above or at 0 mm Hg, lung water increased by 15 per cent per mm Hg rise in P_T . A second suggestion might be that as the lung becomes oedematous, capillary endothelium and/or alveolar epithelium become more permeable to fluid or plasma.¹¹ The clinical implications of this are that pulmonary oedema on an overload basis will probably not occur immediately. Pmv is increased, but only after extravascular fluid movement has had time to reduce tissue "reserves" and removal of fluid by lymphatics has been overwhelmed will pulmonary oedema accumulate at a rapid rate. This also suggests treatment designed to remove pulmonary oedema may not be immediately effective and that time will be necessary to clear the lung water. This should be especially true if the late rapid rise in pulmonary oedema is a result of an increased membrane permeability.

Pathology

Pathologically, pulmonary oedema accumulation can be divided into two stages: interstitial

FIGURE 2 Normal dog lung exhibiting characteristic features. Note that one portion of the alveolar capillary membrane is very thin and should serve as an excellent gas exchanging surface. (A: alveolar lumen, C: capillary, arrow: tightly joined collagen fibres in interstitium, $\times 22,600$) (Reprinted by permission of Can. Anaes. Soc. J.)

FIGURE 3 Alterations in the same dog lung in interstitial pulmonary oedema. Interstitial fluid has separated the capillary endothelium from the basement membrane and slightly increased the diffusion distance from alveolus to red cell (top and middle of photograph). Most of the interstitial fluid, however, is not in the thin, gas exchanging surface between alveolus and capillary. (A: alveolar lumen, arrow: fluid in interstitium separating collagen fibres, $\times 16,000$.) (Reprinted by permission of Can. Anaes. Soc. J.)

oedema and alveolar oedema. This is valuable in terms of ultramicroscopic changes, ability to diagnose and effects of the fluid on gas exchange. Figure 2 (ETVL 6.5 ml/kg, Pa_{O_2} 13.3 kPa [100 mm Hg]) is an electron microphotograph of a normal dog lung.¹¹ In dogs, lung interstitial oedema without alveolar fluid is present when lung water increases are less than 60 per cent above control values (Figure 3, ETVL 7.5 ml/kg, Pa_{O_2} 11.84 kPa [89 mm Hg]).¹¹ This represents a 100 ml increase in lung water in a large dog. In spite of this lung water increase, oxygen exchange is not impeded.

FIGURE 4 Alveolar pulmonary oedema in the same dog lung. The alveoli (A) are filled with a proteinaceous material (possibly plasma), cellular debris and fibrin deposits. Oxygenation of blood cannot occur since oxygen cannot get into the alveolus. (A: alveolar lumen, C: capillary, $\times 11,300$.) (Reprinted by permission of Can. Anaes. Soc. J.)

This is so because, although the fluid has entered and thickened the interstitium and lifted the capillary endothelium away from the basement membrane, the oedema has not thickened the gas exchanging surface markedly and fluid has not crossed the alveolar epithelium to fill the alveolus and prevent gas from entering the alveolus.¹¹ Interstitial oedema may create a gas exchange problem in patients with lung disease when oedema may alter the relationship between the airway closure and FRC, so that closing lung volumes exceed FRC, creating low V/Q ratios and hypoxaemia.¹² However, as long as gas can enter the alveolus the slightly greater diffusion distance created by interstitial oedema does not seem to impede gas exchange.¹¹ Once oedema fluid enters the alveoli (lung water more than 85 per cent above control values) shunting develops and hypoxaemia results.¹¹ (Figure 4, ETV_L , 12 ml/kg, Pa_{O_2} 6.25 kPa [47 mm Hg].)

Effects of Pulmonary Oedema

As stated earlier, interstitial pulmonary oedema does not appear to create a diffusion barrier for oxygen.¹¹ While considerable lung damage seems to take place with interstitial oedema, most of the fluid is not in the thin gas exchanging membrane between alveolus and capillary (Figure 3). Once alveolar oedema develops, shunting increases leading to hypoxaemia (Figure 4). This stimulates respiration, but in the presence of a slow circulation may lead to periods of apnoea.¹³ At a late stage hypercapnoea may also occur, although this is not usual.

Lung mechanics are influenced by pulmonary

oedema. A fall in dynamic compliance consistently occurs with an elevated lung water, but the relationship is variable so that the amount of lung water cannot be predicted from compliance values.¹² FRC changes are variable, either rising if airway closure predominates or falling if compression or filling of alveoli predominates. Peripheral airway resistance increases with congestion¹⁴ but it is not until alveolar oedema is present that a marked increase in total pulmonary resistance occurs.¹² The surface lining layer might be changed in pulmonary oedema, but Cook, *et al.*¹⁵ found that the elastic behaviour of oedematous lungs was not significantly different from that of normal lungs when these excised lungs had surface forces minimized by ventilating with liquid.

An important effect of early pulmonary oedema is the reduction of tissue "reserves" of Starling forces. Small changes in Starling forces that would not have led to pulmonary oedema in normal lungs may now do so (Figure 1).

Work is now being done to determine how these effects might apply in patients with other lung disease, such as chronic obstructive lung disease.^{16,17}

III CLINICAL CORRELATES OF PATHOPHYSIOLOGY

COP_T

COP_T is being estimated clinically by measuring the protein concentration of fluid suctioned from the airways.^{8,18} Airway fluid is even further removed than lymph fluid from lung interstitial fluid, both temporally and spatially. This creates problems with the assumption that COP_T can be derived from COP of airway fluid and must account for COP of airway fluid > plasma COP in 40 per cent¹⁸ and 25 per cent⁸ of patients reported to have an increased capillary permeability type of pulmonary oedema. Nevertheless, airway fluid proteins may be helpful clinically in defining a pulmonary capillary permeability problem.

Pmv

Since the advent of the Swan Ganz catheter¹⁹ we can estimate Pmv in a clinical setting (equation 2). Pmv and $COPmv$ remain the only factors in the Starling equation which are measurable in patients, but they appear to be important factors in the pathogenesis of pulmonary oedema.

Pmv is elevated in many forms of heart disease and may result from either an elevated P_{PA} or PAO pressure (equation 2). In most cases,

FIGURE 5 The X-axis is the mm change in segment length of the left ventricular muscle as it is increased in size which is plotted against the left ventricular end-diastolic pressures (LVEDP) at the same times. (From Sardoff, S.J. & Mitchell, J.H.,²⁰ reprinted by permission of American Journal of Medicine.)

excluding mitral valve disease, acute aortic regurgitation with preclosure of the mitral valve, pulmonary veno-occlusive disease, and high pulmonary vascular resistance (PVR), PAO pressure elevations reflect left atrial pressures and left ventricular end-diastolic pressure (LVEDP) which relates to the size of the left ventricle just before it contracts.

The compliance curve of the normal left ventricle (Figure 5)²⁰ indicates that as the ventricle is filled to pressures beyond 20 cm H₂O (15 mm Hg, or 2 kPa) very small volume increases will result in very large pressure increases that should be transmitted to the pulmonary vessels as an increased Pmv and an increased tendency to pulmonary oedema. The non-compliant ventricle would worsen this tendency. An example of a non-compliant ventricle in a patient is presented in Figure 6, and was created by 60 minutes of ischaemic arrest for aortic valve replacement.²¹ After coming off bypass this patient has a smaller left ventricular end diastolic diameter and a higher left atrial pressure, indicating a tendency to a low cardiac output and high Pmv.

Regardless of why the left ventricle fails, increased preload or afterload, reduced myocardial contractility or heart rate and rhythm problems, left ventricular failure will increase Pmv and may lead to pulmonary oedema. After cardiopulmo-

FIGURE 6 Left ventricular end - diastolic pressure (LAP) - left ventricular end-diastolic diameter data before and after 60 minutes of ischaemic arrest for aortic valve replacement. (From Spotnitz, H., Bregman, D. et al;²¹ reprinted by permission of The American Heart Association, Inc.)

FIGURE 7 The change in Pmv (Δ Pmv) from preoperatively to the day following aorto-coronary bypass surgery is plotted against the change in lung water (Δ ETVL) over the same time. (Reprinted by permission of Can. Anaes. Soc. J.)

nary bypass for aortocoronary bypass procedures we found an increase in lung water the day after operation which relates to an increased Pmv²² (Figure 7).

In the cases where PAO does not reflect LVEDP, as in mitral valve disease, aortic regurgitation, pulmonary venous constriction (postulated to occur in shock²³) and high PVR, the result will still be an increased Pmv and tendency to oedema formation. It is difficult in patients with mitral valve disease to explain why they do not have pulmonary oedema more often. Several explanations have been proposed: The wall of dependent arterioles hypertrophy, reducing flow

to the lower lung and so tending to reduce the effect of a high Pmv in capillaries at the lung bases.²⁴ The dependent arterioles are surrounded by oedema fluid, increasing perfusion to the top of the lung.²⁵ Lymphatics may hypertrophy and increase the capacity for removal of fluid from the lung. An alternate explanation for the apparent lack of pulmonary oedema in patients with mitral valve disease is that the fluid is present in the interstitium of the lung and our techniques for diagnosing small increases in lung water are not adequate.

Pmv may also be elevated with an increase in P_{FA} (equation 2) without increases in PAO, when pulmonary vascular resistance (PVR) is elevated. The classic lesion creating this disturbance is pulmonary embolus. Pulmonary emboli may be large (fibrin clot), or small (platelet micro-aggregates). After haemorrhagic shock and blood reinfusion in dogs we have shown an immediate increase in lung water associated with increased PVR.²⁶ Staub has shown that various forms of emboli (glass beads, fibrin or fat) sufficient to increase pulmonary vascular resistance are associated with increased lymphatic flow from sheep lungs and, presumably, increased lung water.⁵ The increased lung water of these studies can be explained either by high Pmv in capillaries that remain open, pulmonary arteriolar fluid leakage when P_{FA} is elevated, or increased capillary permeability.⁵

P_T

Of the factors in Starling's equation, we know least about P_T . Many attempts have been made to measure P_T , with only partial success because to date there is no direct method to enter the interstitial space without altering it. Several techniques,^{6,7} each with their own assumptions, have now suggested that P_T is normally a negative number in animal experiments (-0.67 to -0.93 kPa [-5 to -7 mm Hg]). Parker, *et al.*⁷ have also found that P_T increases as pulmonary oedema increases and above $P_T = 0$ mm Hg the rate of oedema formation increases. The upper limit of P_T has not been defined, but the highest levels reported by Parker, *et al.*⁷ of $+5$ mm Hg ($+0.67$ kPa) P_T were associated with a doubling of lung water. Since very little is known about P_T in highly invasive animal experiments, it is not surprising that clinical data are not available. What there is suggests that pleural pressure may relate to P_T . If this is so, we may be able to alter P_T by changing ventilation patterns.

FIGURE 8 Colloid osmotic pressure before, during and after cardiopulmonary bypass (on pump). (Reprinted by permission of Can. Anaes. Soc. J.).

COPmv

The normal value quoted in most textbooks for colloid osmotic pressure is 3.33 – 3.72 kPa (25 – 28 mm Hg).²⁷ This is true in the normal mobile individual. However, in patients undergoing aorto-coronary bypass surgery we found control values of 2.51 ± 0.09 kPa (18.9 ± 0.7 mm Hg)²² (Figure 8). This agrees with data on supine subjects when COPmv fell 0.8 ± 0.33 kPa (6 ± 2.5 mm Hg) from their control mobile values.²⁸ This implies that patients in the operating room, recovery room or Intensive Care Unit will have COPmv at or below 2.53 kPa (19 mm Hg), depending on their fluid and nutritional status.

If haemodilution is used during cardiopulmonary bypass, COPmv is further reduced while on bypass. We studied two groups of patients undergoing cardiopulmonary bypass procedures.²² One group (Ringer's) had the pump primed with lactated Ringer's solution (2,000 ml), the second group (plasma) with lactated Ringer's solution and 2 units of plasma. Figure 8 indicates that the plasma group has a slightly higher COPmv (1.30 ± 0.04 kPa [9.8 ± 0.3 mm Hg]) than the Ringer's group (1.17 ± 0.04 kPa [8.8 ± 0.3 mm Hg]) while on cardiopulmonary bypass. Within one hour of surgery COPmv was the same in both groups at 1.89 ± 0.11 kPa (14.2 ± 0.8 mm Hg) and continued to rise over the next two days although it remained significantly lower than control values. Lung water was measured in these patients pre- and postoperatively with a double indicator dilution technique (ETV_L). There were no significant increases in lung water immediately after opera-

FIGURE 9 Pulmonary artery and colloid osmotic (COP) pressure in two patients preoperatively (PRE-OP), while on cardiopulmonary bypass (CPB) and postoperatively (POST-OP). Patient one developed a 57 per cent increase in lung water and 143 per cent increase in shunt fraction because the left ventricular vent was inadequate, while patient two had no increase in either lung water or shunt with a well functioning left ventricular vent. The brief increases in pulmonary artery pressure in patient two relate to episodes of lifting the heart. (Reprinted by permission of Anesthesiology.)

tion in either the Ringer's or plasma group of patients despite their low COPmv. This would suggest COPmv is not very important in the production of pulmonary oedema. However it is more likely that interstitial tissue "reserves" of P_T and COP_T had been used up by the low COPmv, for, with time and a slight rise in Pmv from 1.68 to 2.0 kPa (12.6 to 15 mm Hg) a significant increase in lung water occurred.

Figure 9 illustrates pressure in the pulmonary artery (P_{PA}) and COPmv values from two patients undergoing aortocoronary bypass surgery.²⁹ COPmv is low while on cardiopulmonary bypass in both patients. When the left ventricular vent was placed in patient number two blood was drained from the left ventricle and P_{PA} fell to below COPmv values. There were temporary rises in P_{PA} associated with lifting the heart, but on the whole $P_{PA} - COPmv$ was a negative number. This patient did not develop pulmonary oedema or increased shunting. For various reasons (aortic regurgitation and technical) the left ventricular vent was inadequate in patient number one and P_{PA} was high throughout the pump run and well above COPmv values. This patient developed radiologically visible pulmonary oedema immediately after operation, a 57 per cent increase in lung water and a 143 per cent increase in shunt fraction.

This is one example of how the difference between Pmv and COPmv is a major determinant of pulmonary oedema. In 12 patients undergoing aortocoronary bypass surgery, the most significant relationship emerged when we plotted the change in pre-operative to post-operative [Pmv - COPmv] against the change in lung water over the same time (Figure 10). Therefore the relationship between Pmv and COPmv is important in the formation of pulmonary oedema.

Lymphatic Removal of Oedema

Once fluids and proteins pass into the extravascular compartment of the lung, lymphatics must remove them. Since the lymphatics are not thought to be muscular vessels³⁰ movement of fluid is considered passive along pressure gradients created by respiratory movements. The lung lymph fluid finally empties into the central venous system. There is evidence^{30,31} that a high central venous pressure may impede lymphatic drainage from the lung. The reserve within the lymphatic drainage system of the lung seems to be very large. In sheep a tenfold increase above normal lung lymph flow has been measured at Pmv levels of 3.99 kPa (30 mm Hg).⁴

Capillary Permeability

Evaluation of membrane permeability to water and proteins remains a problem because we have no method to measure this parameter. Indirect evidence indicates that increased capillary permeability does occur.^{3,32,33} Brigham, *et al.*³ followed lymph flow from the lungs as an indicator of lung water while they increased Pmv (Figure 11). In normal sheep there was a slight rise in lymph flow; but in the same sheep, after pseudomonas bacteria were infused, smaller increases in Pmv created very large increases in lung lymph flow. This indicated a new increased capillary permeability so that fluid and proteins moved into extravascular lung at a low Pmv.

There is a long list of causes of increased capillary permeability. Table I is not exhaustive, but it indicates the kinds of clinical cases which may be associated with an increased pulmonary capillary permeability. A large number of diseases in this list are well known to be associated with a high Pmv. For example: shock, pulmonary emboli, uraemia, massive blood transfusion, post cardiopulmonary bypass, neurogenic and high altitude pulmonary oedema may all be associated with a high Pmv. This will compound any capillary permeability problem and should be consid-

FIGURE 10 Preoperative to postoperative changes in $[P_{mv}-COP_{mv}]$ in mm Hg after A-C bypass surgery relate well to changes in lung water (ETV_L) over the same time. (Reprinted by permission of Can. Anaes. Soc. J.)

FIGURE 11 Open symbols represent increases in lung lymph flow seen when P_{mv} is increased in normal sheep. Closed symbols represent changes in lung lymph flow with increased P_{mv} after pseudomonas bacteria. (From Brigham, K.L., Woolverton, W.C., *et al.*,³ reprinted by permission of J. Clin. Invest.)

ered in patient management, for we know of no specific therapy to reduce pulmonary capillary permeability. Steroids are not of proven benefit. Obviously we should remove any cause of increased capillary permeability. If we re-examine Starling's equation (1), we do not know how to influence K_f , G_f , P_T or COP_T . We are left with either reducing P_{mv} or increasing COP_{mv} . One of the problems with infusing colloids is their tendency to leak into the extravascular lung, worsening pulmonary oedema. The only alternative left is to reduce P_{mv} even when it is not elevated. There is evidence to support both the

TABLE I

CAUSES OF NON - CARDIOGENIC PULMONARY OEDEMA

Shock	- any aetiology
Infection	- pneumonias
Trauma	- fat embolism
	- lung contusion
	- pneumothorax - post re-expansion
	- radiation pneumonitis
Aspiration	- liquid - gastric contents
	- near drowning
	- gas - O_2
	- smoke
	- NO_2 , Cl_2 , NH_3
	- phosgene
Metabolic	- pancreatitis
	- uraemia
Drug related	- allergic reaction
	- overdose - heroin
	- barbiturates
	- methadone
	- acetylsalicylic acid
	- dextran
	- alloxan
	- oleic acid
Hematologic	- diffuse intravascular coagulation
	- massive blood transfusion
	- post cardio-pulmonary bypass
	- pulmonary embolism
Others	- neurogenic
	- high altitude pulmonary oedema

concept that Starling's law is still operative^{3,34,35} and the effectiveness of lowering P_{mv} in treating pulmonary oedema due to increased capillary permeability.

Pulmonary Oedema while on Cardiopulmonary Bypass

Since there is very little lung perfusion during cardiopulmonary bypass (CPB), pulmonary oedema during CPB would seem an unlikely event. What blood there is comes from the bronchial circulation and back flow of blood through incompetent aortic and mitral valves. If a left ventricular vent is used P_{mv} is kept below COP_{mv} and pulmonary oedema is not formed.²⁹ However, if a left ventricular vent is not used, or if the vent is not functioning properly, P_{mv} is elevated and pulmonary oedema may accumulate in spite of low blood flows through the lungs while on CPB.²⁹

The type of oxygenator used may also play a role as PVR was found to be elevated 100 per cent immediately after bubble oxygenation, but not after membrane oxygenation.³⁶ In the bubble oxygenator group of patients PVR had returned to control levels by the morning after operation. Presumably these results indicate that substances

have been released from platelets or cells damaged in the bubble oxygenator, since platelet and cell survival is better after membrane oxygenation.³⁶ Lung water was elevated the morning after operation in patients with bubble oxygenation and was not elevated in patients with membrane oxygenation.³⁶ Lack of lung perfusion apparently did not create an increase in capillary permeability as lung water was not increased immediately after operation when left ventricular venting was adequate,²⁹ and lung water was not related to the length of CP bypass.

IV DIAGNOSIS

The history and physical examination of the patient are valuable, looking for features which could lead to pulmonary oedema. Several points concerning this examination should be stressed. First, rales or rhonchi may occur only in the late stages of alveolar oedema and be absent in the interstitial phase. Second, the left and right ventricles can each fail independently of the other. Several papers have indicated there is no relationship between CVP and PAO or between changes in CVP and PAO after volume infusion.^{37,38} We have noted patients after aorto-coronary bypass surgery with high CVP and low PAO and, on the other hand, with high PAO and low CVP. The potential problems in attempting to relate CVP to PAO are the function of the pulmonary vessels and the different diastolic pressure volume curves of the two ventricles. If the pulmonary vascular resistance (PVR) were high, CVP might reasonably be expected not to relate to PAO. If the right ventricle were either failing or hypertrophied, CVP might not relate to PAO. It is also possible that differences in left and right ventricular compliance will remove any CVP to PAO relationship, or that pulmonary vascular responses will remove a relationship between changes in CVP and changes in PAO. While CVP and PAO sometimes parallel each other, we could not predict when this relationship would hold. An example of a situation that might be expected to lead to a low CVP and a high PAO would be the patient after closure of an atrial septal defect who is given large volumes of fluid to raise the CVP and keep the filling pressure high. The right ventricle is hypertrophied due to chronic volume overload and unlikely to fail. The previously protected left ventricle can only eject at the expense of a much higher filling pressure. This could lead to a high PAO while the CVP is low. This implies that CVP can be misleading,

resulting in incorrect treatment; and if initial therapy based on CVP information has not improved the patient, a pulmonary artery catheter should be placed at least in those patients where pulmonary oedema is suspected. An additional benefit of this catheter would be the determination of cardiac output using a thermodilution technique.³⁹

Blood gas and lung compliance changes¹² should be measured in pulmonary oedema, but they are not very helpful in diagnosing pulmonary oedema as they occur for many other reasons.

The best non-invasive method for recognition of early pulmonary oedema appears to be the chest radiograph.⁴⁰ In order to achieve diagnostic accuracy, films should be taken with the patient in the upright position, with fixed distances between machine and patient to allow sequential comparisons and with short exposures of less than 0.033 sec (producing 200MA) to minimize artifacts due to respiratory and cardiac motion.⁴⁰ Using these techniques the haziness of pulmonary vessel and bronchial borders are a valuable early sign of interstitial pulmonary oedema. At least in the intensive care unit (I.C.U.) these standards are difficult to meet, so that methods to quantify lung water may be needed. In I.C.U. patients, when both pulmonary artery and systemic arterial lines are needed, double indicator dilution techniques using thermal (ETV_L)^{41,42} or radioactive isotopes (tritiated water)⁴³ can be employed to quantify lung water.

V MANAGEMENT

Management of patients should be directed to preventing the causes of pulmonary oedema. If this fails, an early diagnosis may prevent the vicious cycle of:

and the late rapid rise in pulmonary oedema.

Once alveolar oedema is present, hypoxaemia will rapidly follow. This requires that oxygen therapy be instituted. This may be by nasal cannula, mask or positive pressure ventilation, depending on the severity. If positive pressure ventilation is to be undertaken, continuous positive pressure ventilation (CPPV) should be considered. Many investigators have shown^{10,12,31,44} that CPPV increases FRC and Pa_{O₂}, but it does not remove lung water.

FIGURE 12 The time course of lung water (ETVL) and PaO_2 before and after the rapid infusion of dextran 40 to increase and hold P_{FA} to 5.32 kPa (40 mm Hg). Once alveolar oedema was present CPPV was applied.

FIGURE 13 The same lung shown in Figure 11 but now with CPPV applied. There is still debris in the alveolus (A) but now air is forced in. Blisters (B) of interstitial fluid are still present and collagen fibres are still widely separated (arrow) $\times 10,200$. (Reprinted by permission of Can. Anaes. Soc. J.)

Figure 12 illustrates results from a dog when pulmonary oedema was induced by increasing P_{mv} with an infusion of dextran 40. The amount of pulmonary oedema (ETVL) shows the typical time course associated with a falling PaO_2 . When CPPV is applied the rate of rise of ETVL is not changed while there is a sudden increase in PaO_2 . Figure 13 (ETVL 19.7 ml/kg, PaO_2 9.18 kPa [69 mm Hg]) is an electron microscopic section taken from the same dog illustrated earlier (Figures 2, 3, and 4), but now with CPPV applied following alveolar oedema.¹¹ The lungs have more pulmonary oedema than in Figure 4, but now CPPV has opened alveoli so that in spite of a slight increase in alveolar capillary distance oxygenation can occur.

FIGURE 14 Normal and failing Frank-Starling curves. Left ventricular end-diastolic pressure (LVEDP) is plotted against cardiac index (C.I.). Once a patient has both pulmonary congestion and a low cardiac index the effect of three pharmacologic interventions are plotted.

Why CPPV does not reduce pulmonary oedema has been clarified by Bo, *et al.*⁴⁵ In isolated perfused rabbit lungs they found divergent effects of CPPV on fluid filtration in the lungs, depending on experimental conditions. When alveolar pressure was increased without increasing alveolar volume, fluid filtration decreased. This was thought to be due to an increased P_{T} . When alveolar volume was increased, fluid filtration increased. The effect of CPPV in the clinical situation should then depend on the balance between an increased alveolar volume (more oedema) and increased alveolar pressure (less oedema), since these are both applied with CPPV. This equation will also be influenced by the effects of CPPV on vascular pressures (both P_{mv} and central venous pressure^{31,46}) and hormonal influences⁴⁷ in the intact patient.

In summary, CPPV improves PaO_2 , probably by increasing FRC, but it does not remove pulmonary oedema. The improved PaO_2 gained with CPPV will provide time so that therapy directed at Starling's forces can be started. The difficulty with CPPV is that $\dot{Q}$ may be reduced and hence worsen oxygen transport¹² to tissues. This may reduce PvO_2 and magnify the effect of any existing pulmonary shunt. This is best handled by monitoring $\dot{Q}$ to determine the best CPPV level to apply, and whether vasoactive drugs are needed to support the circulation.

Obviously oxygenation must be maintained and either an increased inspired oxygen concentration or CPPV should do this. But to actually remove or prevent pulmonary oedema we must do one of three things: reduce P_{mv} , increase

FIGURE 15 Left ventricular pressure volume curves of patients exhibiting shifts following haemodynamic interventions are shown. The left panel shows continuity of curves with nitroprusside, but a marked shift with angiotensin. The middle panel shows a similar result following nitroprusside and angiotensin. The right panel shows a marked downward shift of the pressure volume curve with nitroprusside. (From Alderman, E.L. & Glantz, S.A.,⁴⁸ reprinted by permission of The American Heart Assoc. Inc.)

COPmv or remove the cause of the increased capillary permeability. Of these, the one we seem to have most influence over is Pmv. Left ventricular preload can be reduced with phlebotomy, increased venous capacity (eg. morphine or nitroglycerine), diuretics, valve repair, or decreased volume loading with appropriate intravenous therapy. Myocardial contractility can be increased by correcting acid base or electrolyte disturbances or adding digoxin, isuprel, dopamine, dobutamine or adrenaline. Afterload may be reduced with vasodilators such as phenolamine or nitroprusside, intra-aortic balloon counterpulsation support, or by repairing a stenosed valve. Arrhythmias must be controlled.

Patients with pulmonary oedema may also have a low cardiac output (Figure 14). This will determine whether one reduces Pmv by manipulation of preload, myocardial contractility or afterload. A diuretic may reduce Pmv but may decrease $\dot{Q}$. Dopamine or catecholamines may reduce Pmv and increase $\dot{Q}$, but may also increase myocardial oxygen consumption and, in the presence of a coronary artery stenosis, may create an imbalance between oxygen supply and demand in the myocardium. A vasodilator may improve both Pmv and $\dot{Q}$, but in the patient with a very low blood pressure might decrease coronary perfusion. All three therapeutic interventions reduce Pmv, and therefore the tendency to pulmonary oedema, but which is the best?

Re-examining Figure 14, the abscissa should not be left ventricular end-diastolic pressure (LVEDP). It should be left ventricular end-

diastolic volume (LVEDV), for this relates to the stretch of the myocardial fibres before contraction. But LVEDV is difficult to measure, so we assume there is a relationship between LVEDP and LVEDV. There is a compliance relationship but it is a linear; and the right and left ventricles are different. Figure 15 is taken from Alderman and Glantz⁴⁸ who have demonstrated shifts in the left ventricular pressure volume relationship depending on whether afterload was increased (less compliant) or decreased (more compliant). They suggest that the steep compliance curve created by increasing afterload with angiotension may be a result of increased right ventricular volume pushing the interventricular septum to the left. Reduction of afterload with nitroprusside would decrease right ventricular volume, shift the septum to the right and increase left ventricular compliance. Bemis, *et al.*⁴⁹ used an isolated perfused dog heart with an intact pericardium to show that increases in right ventricular filling pressure increased left ventricular filling pressure. Elzinga, *et al.*⁵⁰ found the same thing in an isolated cat heart. In addition they showed that removing the pericardium makes the left ventricular pressure less sensitive to right ventricular pressure changes. External forces acting on the left ventricle, including those that arise from pleural pressure, right ventricular pressure and the pericardium must be considered when interpreting LVEDP and LVEDV. Increases in pericardial and right ventricular pressures should create a steep compliance curve. Then, small increases in LVEDV (one of the determinants of stroke vol-

ume) will create large increases in LVEDP and, therefore, the flat failing Starling curve of Figure 14. The data of Alderman and Glantz⁴⁸ would suggest treatment of the patient with a steep left ventricular compliance curve (and therefore the failing Starling curve of Figure 14) with afterload reduction. This should create both an increased $\dot{Q}$ and a reduced LVEDP, which will lower Pmv and decrease the tendency to pulmonary oedema.

Following cardiac surgery, patients present with several of these problems. They are likely to be well volume loaded and, therefore, to have high right ventricular volumes; to be on a ventilator, increasing pleural pressure; and they may have some degree of pericardial tamponade. For these reasons Intensive Care Unit patients are also likely to have poor compliance of the left ventricle. Reduction of afterload may be beneficial in some of these patients.

There is a long list of vasodilating drugs available. The choice depends on the patient's predominant problem. If mitral regurgitation predominates, arterial vasodilation with hydralazine or phentolamine should be useful. If the worse problem is pulmonary congestion, nitroglycerine should reduce preload. If $\dot{Q}$ is reduced and pulmonary congestion is present, nitroprusside or prazosin should be helpful. Miller, *et al.*⁵¹ have shown that while reduction of afterload with nitroprusside improves $\dot{Q}$ while lowering Pmv, and improving myocardial contractility with dopamine does the same, the largest increase in $\dot{Q}$ and reduction in Pmv resulted from a combination of nitroprusside and dopamine. If nitroprusside or nitroglycerine are used in treatment of pulmonary oedema there must be close monitoring of Pa_{O_2} . Nitroprusside^{52,53} has been shown to impede hypoxic pulmonary vasoconstriction and in this way to increase pulmonary shunting and reduce Pa_{O_2} .

All of these therapies have potentially serious complications and an optimum level of application, so that either more or less would result in patient deterioration. For these reasons close monitoring of these patients during therapy must be undertaken. If the patient is so ill that intravenous isuprel, dobutamine, adrenaline, nitroprusside, nitroglycerine and/or phentolamine therapy is necessary, a Swan Ganz catheter should be placed and $\dot{Q}$ determined so that the optimum preload contractility afterload relationship can be established and the best drug combination and dosage for the particular patient used. The optimum PAO pressure for most patients is between 1.6–2 kPa (12–15 mm Hg). In 15 patients

after aorto-coronary bypass operations we found that PAO pressures of less than 2 kPa (15 mm Hg) did not lead to pulmonary oedema.²² If the patient has an adequate $\dot{Q}$ to maintain wakefulness, a good urine output and warm extremities with a PAO pressure of 1.33 kPa (10 mm Hg) there would seem little point in raising that pressure with further fluid infusions. On the other hand, an inadequate $\dot{Q}$ at PAO pressures of 2 kPa (15 mm Hg) may dictate further fluid infusions to raise PAO pressures to 2.39 kPa (18 mm Hg) or even higher. Finally, the patient with an increased capillary permeability should have the lowest PAO compatible with wakefulness, an adequate $\dot{Q}$ and renal function. This may mean reducing PAO well below pressures that are considered normal and may involve manipulations of preload, contractility or afterload that would otherwise not be necessary.

Attempts to reverse Starling's forces by increasing COPmv must be used cautiously. Colloid infusions will increase blood volume. If this volume increase occurs in the rapidly rising portion of the ventricular compliance curve (Figures 5, 6 & 15) a large increase in LVEDP will result and pulmonary oedema may be worsened. If any portion of the oedema accumulation is due to an increased capillary permeability, colloids may leak into the extravascular compartment and increase COP_T, thereby increasing the tendency to oedema formation. With these considerations in mind, slow infusions of colloid with the addition of a diuretic may reduce pulmonary oedema.

A "state of the art" review has been published⁵⁴ regarding the controversy surrounding the intravenous use of crystalloid or colloid for resuscitation and prevention or treatment of pulmonary oedema. I will not restate the arguments, but express the view that the controversy stems from our inability to measure tissue "reserves" in Starling's equation and interstitial oedema. Until we know COP_T and P_T we cannot know which patient has low or absent tissue "reserves" and therefore may need colloids. Again, because we can not measure COP_T and P_T, we do not even know if colloids will restore these tissue "reserves" to normal. The initial point at which tissue "reserves" and lymphatic drainage from the lung are overwhelmed, leading to interstitial oedema, is difficult to diagnose because interstitial oedema may not result in hypoxaemia, physical findings or changes in chest radiographs. These clinical problems need to be solved. In the meantime estimates of who will benefit from the infusion of colloids and who will not, have to be

made on the best information we have, which includes P_{mv} , COP_{mv} and an estimate of how P_T and COP_T might be expected to change in given circumstances. The potential benefits of colloid infusions must be balanced against the risks of increasing P_{mv} and of proteins moving extravascularly, as the patient who may benefit from colloids probably has limited cardiorespiratory and nutritional reserves.

VI IMPLICATIONS OF PULMONARY OEDEMA TO THE ANAESTHETIST

Since pulmonary oedema is associated with hypoxaemia and often with myocardial disease, it goes without saying that surgical and anaesthetic stress should not be added to this already life threatening situation. There are seldom exceptions to this, but these exceptions might include a patient in chronic pulmonary oedema whose condition and drug doses are considered optimum; a patient for emergency surgery where delay would be disastrous (but even here one or two hours of intensive therapy before operation might be useful); and a patient to undergo a procedure that would reduce the pulmonary oedema such as mitral valve replacement. If patients in these conditions are anaesthetized, intravenous fluids, drugs (both anaesthetic and other) and oxygen levels must be manipulated to reduce the tendency of Starling's forces to create more oedema. In these situations electrocardiogram and central venous pressure monitors must be added to routine monitoring, and the placement of a Swan Ganz catheter and arterial line for pressure monitoring and blood gas measurements should be seriously considered. These considerations must also be applied to patients who are not in difficulty at rest but whose cardiopulmonary reserves are so low that minimal exercise results in shortness of breath. The stress of surgery (increased catecholamine levels, acute fluid shifts, and compromised lung function) and anaesthesia (reduced myocardial contractility and heart rate changes) will encroach on cardiopulmonary reserves and may lead to oedema. If gross pulmonary oedema develops during the procedure, the airways should be suctioned for brief intervals only, to maintain some patency, and CPPV should be applied to improve oxygenation while attempting to reverse the Starling forces with other therapy. The fundamental principles in the pathophysiology and treatment of pulmonary oedema are the same in the operating room as in the Intensive Care Unit. The same

therapeutic manoeuvres are available and the anaesthetist should be conversant with their use during the surgical procedure in order to provide optimal care. Postoperatively, intensive monitoring and care must be applied. Oxygenation is best maintained by applying CPPV, assuming the cardiovascular system will tolerate it, rather than by increasing the FI_{O_2} which may, by itself, damage the lungs.

The patient with a normal cardiorespiratory system should not develop pulmonary oedema because of the large reserves implicit in Starling's equation. Even so, these reserves should not be encroached upon and fluid and other therapy should be applied with Starling's forces in mind.

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RÉSUMÉ

L'œdème pulmonaire est le résultat du dérangement d'un mécanisme physiologique qui permet la production et le retrait continus de l'eau extravasculaire pulmonaire selon les principes basés sur l'équation de Starling qui contrôlent les mouvements des fluides à travers une membrane semi-perméable. Tous les paramètres de l'équation de Starling ne peuvent pas être mesurés. Cependant, l'expérimentation permet de penser que l'augmentation de la pression capillaire hydrostatique pousse le liquide dans l'espace extravasculaire et dilue ainsi la pression osmotique colloïde tout en augmentant la pression hydrostatique des fluides du tissu pulmonaire. Lorsque ces réserves et la capacité du système lymphatique pulmonaire sont débordées, l'œdème pulmonaire survient. L'œdème peut aussi résulter d'une diminution de la pression osmotique colloïde à l'intérieur des capillaires pulmonaires et d'une augmentation de la perméabilité de ces mêmes capillaires en l'absence d'une pression osmotique capillaire pulmonaire élevée.

Si l'œdème pulmonaire se forme lentement au départ, et se développe beaucoup plus rapidement dans les stades avancés, il est probable que c'est à cause de l'ensemble des réserves formées par la pression colloïde osmotique des fluides tissulaires, de la pression hydrostatique des fluides du tissu pulmonaire et du drainage lymphatique. La vitesse de formation de l'œdème peut aussi être en rapport avec le dommage causé au poumon par l'œdème interstitiel, qui ouvre la voie au stade plus avancé de l'œdème alvéolaire. Bien que la compliance pulmonaire soit diminuée avec l'augmentation progressive de l'œdème, l'augmentation du shunt et de l'hypoxémie du poumon normal ne surviennent qu'avec l'œdème alvéolaire.

Le diagnostic de l'œdème pulmonaire se fait par la recherche de ses causes et par la radiographie du poumon.

Son traitement doit commencer par le maintien de l'oxygénation, et la meilleur moyen d'atteindre cet objectif est la ventilation à pression positive continue (CPPV). Cette manœuvre n'enlève pas l'eau du poumon (en réalité elle peut l'augmenter légèrement) mais elle améliore l'oxygénation en ventilant des alvéoles déjà remplies de liquide. Cette amélioration de l'oxygénation nous permet de temporiser en attendant une thérapeutique appropriée à la cause selon la loi de Starling.

L'état actuel de nos connaissances ne nous permet pas de traiter l'hyperperméabilité capillaire autrement qu'en abolissant sa cause: il ne nous est pas possible non plus de réduire la pression osmotique des colloïdes tissulaires, ni d'augmenter la pression hydrostatique des fluides contenus dans le tissu pulmonaire ou la pression colloïde intracapillaire ou encore le flux lymphatique. Il ne nous reste donc pour traiter l'œdème pulmonaire que deux manœuvres: soit l'augmentation de la pression osmotique des colloïdes intracapillaires soit la diminution de la pression hydrostatique pulmonaire. Mais l'infusion de colloïdes peut constituer un danger lorsque la compliance ventriculaire gauche est diminuée par l'augmentation du volume intravasculaire qui s'ensuit, ce qui aura pour effet d'élever la pression hydrostatique capillaire pulmonaire et d'aggraver l'œdème. Si c'est l'augmentation de perméabilité capillaire qui est en cause, il s'en suivra une fuite vers l'espace extra-vasculaire de colloïdes avec entraînement d'eau. Si on fait abstraction du traitement causal, la thérapeutique la plus importante de l'œdème pulmonaire devient donc la réduction de la pression capillaire hy-

drostatique. D'après la cause de l'œdème et la valeur du débit cardiaque, la pression capillaire pulmonaire peut être réduite en diminuant la pré-charge ventriculaire gauche, en augmentant la contractibilité ou par une association de ces deux manœuvres.

Les implications pour l'anesthésiste sont que les réserves de Starling sont vastes et que l'œdème pulmonaire ne devrait pas survenir chez le sujet normal. A la période pré-opératoire, chez le malade atteint d'œdème pulmonaire ou d'une réserve cardiopulmonaire basse, tous les efforts doivent être tentés pour optimiser les forces de Starling avant d'induire l'anesthésie dans des conditions qui risquent de devenir catastrophiques.