Pulmonary circulatory arrest

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According to Gibbon (1959), pulmonary complications have contributed most to the morbidity of open heart surgery performed with the help of a pump oxygenator during cardiopulmonary bypass. Dodrill (1958) has estimated their incidence to be 15 to 25%. An indication of their frequency and importance may be found in the reports of experience with intermittent positive pressure respiration (Norlander, Björk, Crafoord, Friberg, Holmdahl, Swensson, and Widman, 1961 ; Gilston, 1962). In some cardiac surgical units the treatment of respiratory inadequacy has been accepted as an inevitable part of post-operative management in open heart surgery when an artificial oxygenator is used. This contrasts with the infrequent need of respiratory resuscitation after cardiovascular operations which do not require cardiopulmonary bypass. The characteristic post-bypass clinical picture was described by Dodrill (1958) as follows : 'The respiratory rate is increased and although ventilation appears adequate, there is variable cyanosis. There are usually few radiological signs. The condition if untreated becomes progressively worse and death occurs on the second or third day. Post-mortem examination shows pulmonary collapse of a non-segmental distribution *without* pulmonary oedema. Histological examination shows distortion and fragmentation of the elastic fibres of the alveoli.'

Osborn, Popper, Kerth, and Gerbode (1962) described the clinical features of this lesion in similar fashion and also attributed it to diffuse non-segmental pulmonary collapse which may not be apparent on radiological examination.

The sudden death syndrome sometimes associated with cyanosis described by Kirklin, McGoon, Patrick, and Theye (1958) may have been of respiratory origin. In the past, many factors have been held responsible, such as the effects of bilateral thoracotomy, raised pulmonary vascular resistance, or alveolar desiccation due to the ventilation of unperfused lung.

More likely causes are the following:

(1) A raised left atrial pressure due to arrested or inadequate left ventricular action during cardio-pulmonary bypass. The pathology of this complication is parenchymal haemorrhage or pulmonary oedema, unlike the alveolar changes described after cardiopulmonary bypass (Kolff, Effler, and Groves, 1960 ; Muller, Littlefield, and Dammann, 1958). The pulmonary congestion can be controlled by a left-sided vent, and this particular complication is seen less frequently now that its cause is understood.

(2) The use of an artificial oxygenator. Penido, Swan, and Kirklin (1957) showed that increased oxygen tension may occur in the blood after passage through an oxygenator, and Kolff *et al.* (1960) suggested that this might be a cause of alveolar damage.

It is possible that small emboli of air, thrombi, or antifoam substance could produce pulmonary insufficiency, but there is no direct evidence that this occurs.

Schramel, Chapman, Weiffenbach, and Creech (1961) produced alveolar haemorrhage in dogs who had prolonged veno-venous perfusions using an artificial oxygenator. They were unable to explain the lung lesions that occurred.

Prolonged perfusion may be an important factor since the incidence of pulmonary lesions seems to increase with the length of perfusion (Osborn *et al.*, 1962). This may be related to damage of blood elements (Kontaxis, Tomin, Wittles, Neville, and Clowes, 1961 ; Lee, Krumhaar, Derry, Sachs, Lawrence, Clowes, and Maloney, 1961 ; Lee, Krumhaar, Fonkalsrud, Schjeide, and Maloney, 1961).

(3) Pulmonary circulatory arrest. This factor has received scant attention as a possible reason for pulmonary complications. Pulmonary circulatory arrest occurs during cardiopulmonary bypass, and the lungs are then wholly dependent on the bronchial circulation for protection against ischaemia. As long ago as 1856, Virchow studied the effects of pulmonary ischaemia. More recent work has been reported by Blades (1954) and by Blades, Beattie, Hill, and Thistlethwaite (1952), Blades, Pierpont, Samadi, and Hill (1953), Hankinson and Edwards (1959), and Lewis, Demos, Connaughton, and Poticha (1961). These

experiments were done with temporary total ischaemia. Few studies have been made on the effects of temporary pulmonary artery occlusion with an intact bronchial circulation, although Long, Folkman, Neptune, and Sudduth (1962) have shown a marked increase in pulmonary vascular resistance and a decrease in anti-atelectatic factor after prolonged occlusion of the pulmonary artery.

Whatever the part played by the factors that have been described, a technique for open heart surgery which avoided them all should show a low incidence of pulmonary complications. This, in fact, has been our experience using the technique of profound hypothermia (Drew, Keen, and Benazon, 1959) in which (a) the left atrial pressure is never allowed to rise; (b) the patient's own lungs are used to oxygenate the blood; and (c) pulmonary circulatory arrest occurs only at a very low temperature.

This paper is concerned with the effect of pulmonary circulatory arrest in a series of acute experiments on 15 dogs in which pulmonary artery occlusion was carried out under varying conditions.

METHOD

Mongrel dogs weighing between 10 and 20 kg. were used. The following procedure was employed in all animals.

They were anaesthetized with intravenous thiopentone and succinyl choline followed by tracheal intubation. Intermittent positive pressure respiration was maintained by a Manley ventilator (Manley, 1961) using nitrous oxide and oxygen from a Boyle's machine.

A bilateral thoracotomy was performed and both pulmonary arteries were mobilized and taped outside the pericardium.

Heparin, 4 mg./kg., was given. The central aortic pressure was recorded by a catheter in one femoral artery via a Southern Instruments capacitance manometer and a Siemens Ediswan oscillograph.

The arterial oxygen saturation was continuously monitored by a Kipp CC oximeter (Zijlstra, 1958) placed in a femoral arteriovenous loop through which there was a slow, continuous flow of blood (Fig. 1).

Three different types of experiment were conducted on groups of five dogs. The arterial oxygen saturation was determined on 20% and on 100% oxygen (usually 95% and 99% respectively) at the beginning of each experiment.

GROUP 1 In five animals the oxygen saturation was maintained between 95% and 99%. Each pulmonary artery was clamped in turn for one hour and both lungs were ventilated.

The animals were then observed for a further period of one hour. During this time the lungs appeared normal and the arterial oxygen saturation remained at the original level.

GROUP 2 In five animals the arterial oxygen saturation was lowered to 75% by reducing the amount of oxygen in the anaesthetic mixture (usually to 12%). This was maintained for two hours without occlusion of the pulmonary arteries. The oxygen in the anaesthetic gas mixture was then increased to 20% and the arterial oxygen saturation promptly rose to 95%.

During the next hour there was no fall in oxygen saturation and no change in the gross appearance of the lungs.

GROUP 3 In the third series of five animals the pulmonary arteries were clamped for one hour as in the first group, but with arterial desaturation as in the second group.
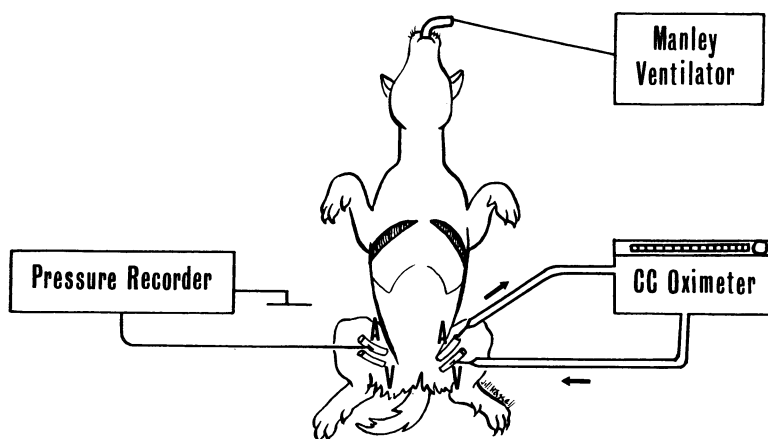

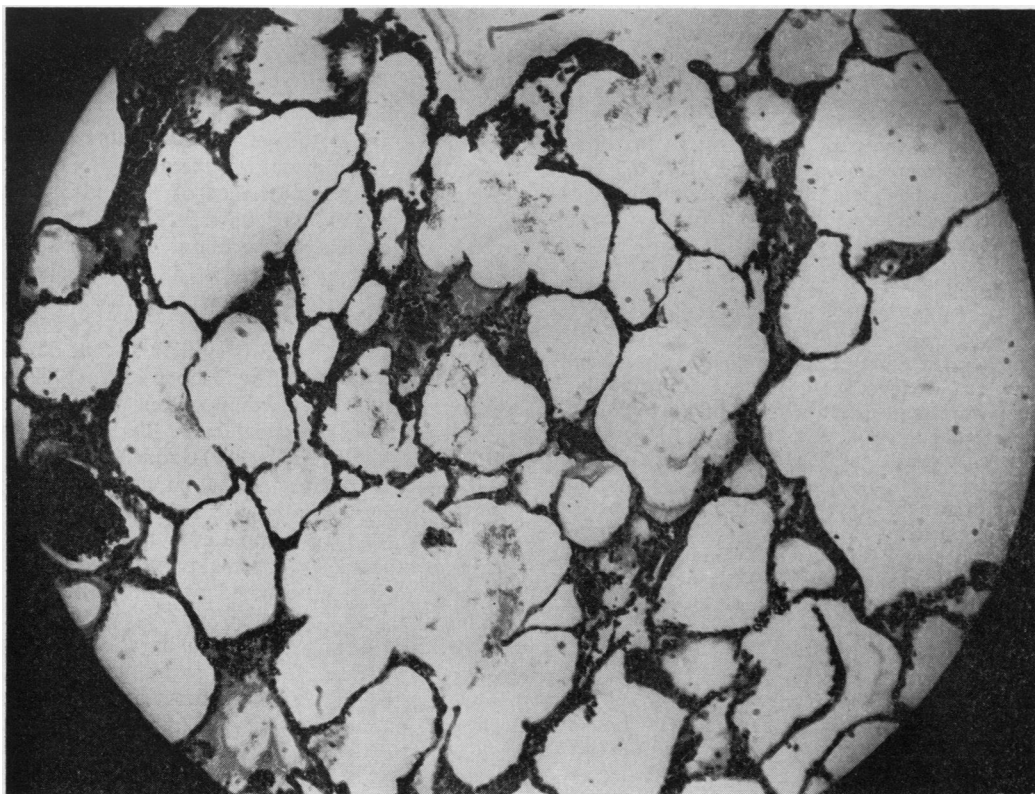FIG. 1. *Shows the method used to monitor systemic arterial oxygen saturation.*

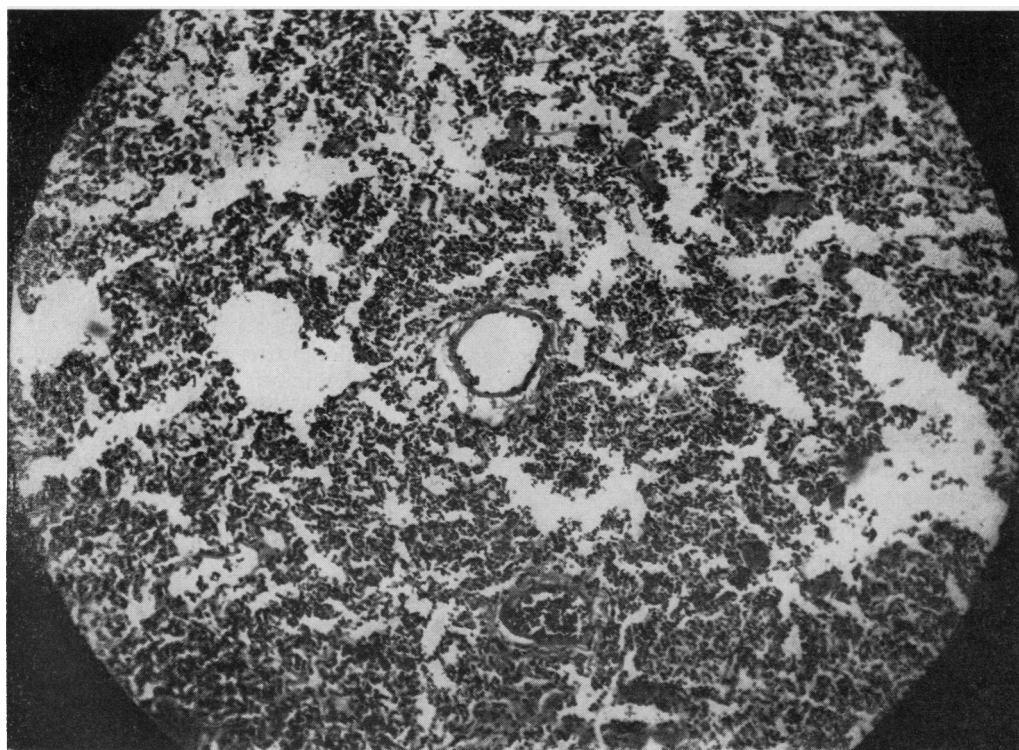**FIG. 2.** *Section of lung from animal in group 2. There is no obvious abnormality.* ×120.

FIG. 3. *Section of lung from animal in group 3. There is alveolar collapse and thickening of the alveolar membrane.* ×120.

At the end of the period of occlusion the original anaesthetic mixture was restored.

In four animals the oxygen saturation returned immediately to its pre-operative level, but during the next half hour a striking series of changes was observed.

The arterial oxygen saturation gradually fell and eventually could not be maintained above 90% on 100% oxygen, and above 75% on 20% oxygen. The lungs showed a marked and progressive tendency to collapse, and frequent periods of increased ventilation pressure were required to control this, without effect on the arterial oxygen saturation.

These changes did not become apparent until after the second pulmonary artery had been released, implying that the damaged lung could support the animal for up to an hour while the second pulmonary artery was occluded. However, in one animal, oxygen in the anaesthetic mixture had to be increased to maintain the arterial oxygen saturation at 75% during the period of occlusion of the second pulmonary artery.

In all experiments the central aortic blood pressure in each animal remained constant.

The animals were sacrificed at the end of the period of observation and the lungs were removed before death.

Figure 2 shows a section from a lung of an animal which had suffered arterial desaturation, and Figure 3 shows a section from one which had suffered both arterial desaturation and pulmonary occlusion. In the first there is no obvious abnormality, but in the other there is alveolar collapse with marked thickening of the alveolar walls. The bronchi are empty and there is no pulmonary oedema.

DISCUSSION

From these experiments it seems that occlusion of the pulmonary artery of a dog for one hour in the presence of systemic arterial desaturation is always followed by severe alveolar damage.

These experiments do not reproduce the situation in cardiopulmonary bypass, as the total cardiac output is delivered through one lung while the contralateral pulmonary artery is occluded. However, the situation was the same for both groups 2 and 3, and the only factor which consistently produced lesions in the lung was a reduction in systemic arterial saturation in addition to pulmonary artery occlusion.

The animals were observed for only one hour after pulmonary circulatory arrest, so that in those with a normal systemic arterial saturation, as in group 1, a lesser degree of pulmonary damage might have occurred.

It might be said that 75% oxygen saturation is too low for blood delivered from a pump

oxygenator, but this may occur quite often if a high flow at normal temperature is employed according to the experience of Nixon, Grimshaw, Catchpole, Snow, and Lawrence (1960).

The lung changes were not dependent on the cardiac output as there was little or no change in the systemic arterial pressure throughout each experiment.

The lesion produced is similar to that described by Dodrill (1958) and by Osborn *et al.* (1962), who remarked that the cardiac output was normal or increased in their clinical cases. Blades *et al.* (1952, 1953) and Blades (1954) concluded that 30 minutes' complete bronchial and pulmonary arterial occlusion was the safe limit. Hankinson and Edwards (1959) and Lewis *et al.* (1961) found that up to one hour was permissible, and pulmonary oedema occurred after two hours' total ischaemia.

The results might seem to be at variance with ours. However, in the experiments of these workers, the test for lung function was a contralateral pneumonectomy performed after the animals had survived for several weeks.

It is likely that the lesion is recoverable if it affects one lung only, as the damage appears to be confined to the alveolar wall with alveolar collapse, and clinical evidence shows that patients can recover after treatment by intermittent positive pressure ventilation.

CONCLUSIONS

We submit that pulmonary circulatory arrest is an important factor in the incidence of pulmonary complications following cardiopulmonary bypass. This can be overcome by using very high flows of fully saturated blood, and this is not always possible with the artificial oxygenators in current use. Perfusion is never perfect even if the output from the pump oxygenator is high, because the blood enters the femoral artery in a retrograde direction and the smaller vessels are probably inadequately perfused (Gibbon, 1959). The bronchial circulation suffers from this diminished flow.

The use of hypothermia with cardiopulmonary bypass should theoretically reduce the incidence of pulmonary complications.

SUMMARY

The effect of pulmonary circulatory arrest has been observed under varying conditions in dogs.

It appears that during pulmonary circulatory arrest, bronchial flow is only adequate to main-

tain lung function if the systemic arterial flow and oxygen saturation are high.

We suggest that pulmonary circulatory arrest may be a factor in the production of pulmonary complications following cardiopulmonary bypass and one reason why these complications are rare when profound hypothermia with lung perfusion is used.

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