Patterns of ventilation

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Postoperative disturbances of pulmonary function were common when open heart surgery was first undertaken. Attempts to restore spontaneous ventilation postoperatively usually failed and a policy of elective mechanical ventilation for virtually all patients was established in most centers. Now that the factors contributing to pulmonary complications are understood more clearly, many can be avoided. At the same time, the emphasis in cardiac surgery has changed from valvular to ischemic heart disease, so fewer patients are likely to suffer from notable pulmonary disease as a result of their cardiac condition.

The reduction in pulmonary morbidity has prompted a reevaluation of the need for mechanical ventilation as a routine after open heart surgery. A policy of early extubation with the resumption of unassisted spontaneous ventilation is receiving growing support. Prakash et al[1] reported extubation within 3 hours of operation in 123 of 142 adult patients after open heart surgery; five subsequently required reintubation. They proposed criteria for selecting suitable patients based on common variables that are usually monitored routinely (*Table*).

Alternative criteria in common use are vital capacity per kilogram of body weight and maximum inspiratory force. Figures of at least 15 ml/kg vital

Table. Criteria for early extubation

Systolic blood pressure	>80 mm Hg
Left atrial pressure	<20 mm Hg
Arterial oxygen saturation	>90% } on F_IO_2
Mixed venous saturation	>60% } 40% in N_2
Arterial carbon dioxide tension	<55 mm Hg
Toe temperature	> 30 C
Absence of 'clinical indications for IPPV', e.g., dysrhythmia, hemorrhage	
Successful trial of spontaneous ventilation (end-tidal carbon dioxide, 5.5%)	

IPPV = intermittent positive pressure ventilation.
Reproduced with permission of Prakish et al.[1]

capacity (VC), and −28 cm H_2O maximum inspiratory force (MIF) are quoted by Hilberman et al,[2] who carried out an extensive computer-based study of the predictive value of many physiological variables in cardiac surgical patients. In other circumstances, lower values have often been regarded as acceptable, e.g., VC, 10 to 15 ml/kg; and MIF, −20 cm H_2O.

Although early extubation and a successful return to unassisted spontaneous respiration can often be achieved, many would still question whether this represents optimal management. In a recent roentgenographic study of pulmonary abnormalities after open heart surgery, pleural effusion was reported as the most common lesion (72%), but some type of atelectasis was present in 64% of patients. These figures are high but the authors point out that the roentgenographic abnormalities were rarely associated with significant clinical disturbance. In all but 2 of 50 patients, the arterial oxygen tension was maintained easily at more than 100 mm Hg, albeit with oxygen enrichment of the inspired air. In another recent report, a combined clinical and roentgenographic study of patients after upper abdominal surgery revealed a 75% incidence of pulmonary complications, a reminder that changes in the lungs are not unique to open heart surgery. Although at one time cardiopulmonary bypass was considered to contribute to postoperative disturbances of pulmonary function, this is now questionable. For at least a decade, some authors have claimed there is little if any clinical evidence that extracorporeal circulation has a specific adverse effect on the lungs, and that changes in pulmonary function after open heart surgery differ little from those that occur after major surgery not involving cardiopulmonary bypass, unless there is antecedent pulmonary disease.

Indications for different patterns of mechanical ventilation after open heart surgery must be considered in light of these observations and two questions can be posed: (1) Is there a role for mechanical ventilation as a prophylaxis against complications that are not unique to open heart surgery and that can be managed by simpler means? (2) What pattern of ventilation should be chosen when pulmonary function is more grossly deranged, either as a result of preoperative pulmonary disease or a consequence of the cardiac condition and its treatment?

Prophylaxis—*the role of PEEP*

Terminology is important in any discussion of airway pressure during either controlled or spontaneous ventilation. In this paper, the term positive end-expiratory pressure (PEEP) is used to refer to the maintenance of a pressure greater than atmospheric during expiration in patients who are receiving mechanical ventilation, be this continuous or intermittent. The term continuous positive airway pressure (CPAP) is used to refer to the spontaneous breathing of patients in whom the airway pressure exceeds atmospheric throughout the respiratory cycle.

The most important effect of PEEP is the increase of functional residual capacity. If there is extensive airway closure and atelectasis, PEEP can improve the distribution of ventilation and so decrease the shunt effect caused by the perfusion of unventilated or poorly-ventilated air spaces; the arterial oxygen tension will increase, as will pulmonary compliance. At the same time, the increase in intrathoracic pressure impedes cardiac filling and the cardiac output, already lower during controlled than during spontaneous respiration, is likely to fall even further. However, this reduction in cardiac output is small after cardiopulmonary bypass when patients are virtually always either normovolemic or hypervolemic.[3, 4]

Extrathoracic effects of PEEP are important in some patients. Glomerular filtration rate and sodium excretion are decreased and, if the intracranial pressure is elevated abnormally, it will rise even further when PEEP is used. The risks of pulmonary barotrauma cannot be ignored and it has even been suggested that pulmonary overdistension leads to the release of a myocardial depressant factor.

Thus, the desirability of promoting good expansion of the lungs by postoperative mechanical ventilation with added PEEP for patients with no specific pulmonary disability after cardiac surgery must be judged against these disadvantages.

Neither continuous mechanical ventilation nor intermittent mandatory ventilation without PEEP are effective in preventing atelectasis during the first 24 hours after open heart surgery.[5] Alternative techniques have been proposed which aim to retain the benefits of PEEP, but eliminate disadvantages that include CPAP, intermittent mandatory ventilation with PEEP, or spontaneous ventilation with a positive pressure during expiration only.

Most of the adverse effects of continuous mechanical ventilation with PEEP are attributable to the increase in mean intrathoracic pressure that results. By comparison with spontaneous respiration, there is an inevitable increase in intrathoracic pressure with CPAP, although it is less than the change occurring during continuous mechanical ventilation with PEEP. The transition from continuous mechanical ventilation with PEEP to CPAP after open heart surgery results in an increase in arterial carbon dioxide tension and systemic oxygen transport, with a small increase in cardiac output in some studies.[3, 4] By comparison with CPAP, there is an increase in respiratory work during spontaneous respiration with a positive pressure during expiration only; the cardiac output is higher than during CPAP, but this can be interpreted as the undesirable effect of an increased demand provoked by the increase in respiratory work.

It has been suggested that intermittent mandatory ventilation with PEEP is preferable to continuous mechanical ventilation with PEEP because there is less depression of cardiac output, but this may reflect the cardiovascular effects of the higher arterial carbon dioxide tension, which is usual during intermittent mandatory ventilation, rather than any mechanical effect. In one experimental study, spontaneous ventilation with intermittent mandatory ventilation did not protect against the fall in cardiac output induced by PEEP but the pressures studied were very high. The possibility that less sedation is required during spontaneous ventilation with intermittent mandatory ventilation than during continuous mechanical ventilation was not confirmed by Sladen and Jenkins.[5] Finally, it must be remembered that much of our effort in the management of patients with ischemic heart disease is directed towards the avoidance of unnecessary myocardial work.[6] Viewed in this context, the reduction in cardiac output that accompanies mechanical ventilation may be beneficial.

For patients with normal lungs preoperatively, who fulfill criteria such as those proposed by Prakash et al,[1] there is much to be said for the simplicity of management permitted by early extubation. Attention to humidification during anesthesia, to the management of the lungs during the period of bypass itself, and good postoperative care should prevent serious postoperative complications.

The therapeutic role of PEEP

The physiological sequelae of PEEP, which have been listed, are of greater value when there is extensive atelectasis, the lungs are congested or edematous, pulmonary compliance is poor, and a high inspired oxygen concentration is required to correct arterial hypoxemia. Such disturbances can precede operation or develop during surgery and are often associated with poor left ventricular function. This provides some protection against the adverse effects of a raised intrathoracic pressure because there is little change in the output of a failing heart in response to a reduction in filling pressure (*Fig. 1*). At the same time, the increase in intrathoracic pressure displaces blood from the pulmonary into the systemic circulation; this impedes the formation of pulmonary edema, reduces overdistension of the heart and so can improve myocardial oxygenation. If continuous mechanical ventilation rather than intermittent mandatory ventilation is chosen, the work of breathing is also eliminated, and, when this is excessive because pulmonary compliance is poor and airway resistance high, any decrease in cardiac output that occurs during mechanical ventilation may be more than offset by the reduction in oxygen consumption.

It must not be assumed, however, that all patients with low pulmonary compliance and arterial hypoxemia will benefit from a sustained increase in intrathoracic pressure. Thus, in patients with chronic mitral valve disease, Trichet et al[7] demonstrated that the chief effect of PEEP was to improve the ventilation of atelectatic basal areas that were poorly perfused because of pulmonary vascular disease. As a result, the ratio of dead space to tidal volume increased and there was no decrease in the shunt fraction. The effect on cardiac output depended on whether there was also ventricular failure and whether the intrathoracic pressure was significant by comparison with both the arterial and venous pressures in the pulmonary circulation. However, in a series of children 1 to 8 years old reported by Colgan and Stewart,[8] the response of those with pulmonary vascular disease was the same as in those without. This might be because the pulmonary vascular changes in congenital heart disease are distributed more uniformly than in long-standing mitral stenosis.

Continuous positive airway pressure

This technique is of particular value in infants who often settle poorly during continuous mechanical ventilation. Closing volume is close to functional residual volume in normal infants and airway closure can occur during tidal ventilation, particularly if the mucosa is engorged. Any reduction in functional residual capacity, as is inevitable after thoracotomy, will exacerbate hypoxemia caused by perfusion of underventilated air spaces. Gregory et al,[9] and Pick et al,[10] have demonstrated an increase in functional residual capacity during CPAP as compared with spontaneous respiration after palliative or corrective cardiac surgery in infants and small children. The arterial oxygen tension rose in both studies, although the change in cyanotic infants in the series of Gregory et al[9] was only 4%; pulmonary compliance increased in six of ten cases in the second study. On the limited evidence available both groups concluded that the cardiovascular changes caused by CPAP were trivial, but Pick et al,[10] and Colgan and Stewart,[8] in a comparable study in older children,[8] recommended that CPAP should be reserved for patients in whom there is a positive indication—known or suspected pulmonary congestion, impaired compliance, and a large intrapulmonary shunt.

Variation in the pattern of inspiration

The effects of varying both the duration and pattern of inspiration during mechanical ventilation have been reviewed extensively and studied experimentally by Baker et al.[11–13] In their studies in dogs, the reversed ramp or decelerating inspiratory flow pattern resulted in the lowest ratio of dead space to tidal volume and arterial carbon dioxide tension, and the highest arterial oxygen tension and pulmonary compliance. Both airway and esophageal pressures were higher with the reversed ramp than with the ramp or accelerating flow pattern, but the changes in cardiac output between the two wave forms were small and the alveolar-arterial oxygen tension difference was unchanged. Shortening the inspiratory time caused deterioration in most indices of pulmonary function and gas exchange, but mean airway and esophageal pressures fell.

An end-inspiratory pause has been advocated to promote more even distribution of ventilation in patients with regional differences in airway resistance. The results of at least two studies have shown that this decreases the ratio of dead space to tidal volume and improves elimination of carbon dioxide, but neither demonstrated significant improvement in oxygenation in a miscellaneous group of patients with various pathologic findings. Extrapolating from these findings, one would anticipate that an end-inspiratory pause is only likely to benefit patients after open heart surgery if they have disease of the small airways such as occurs in those with long-standing mitral stenosis or pulmonary hypertension secondary to pulmonary plethora. Some patients with poor pulmonary compliance and a large shunt effect show an increase in arterial oxygen tension as well as a reduction in carbon dioxide tension and, subjectively, this pattern of ventilation is often tolerated particularly well.

High frequency positive pressure ventilation

The advantages claimed for high frequence positive pressure ventilation are that at constant alveolar ventilation, cardiac output, stroke volume, and systemic oxygen transport are higher, and that peak and mean airway pressures and systemic vascular resistance are lower than during conventional continuous mechanical ventilation. Advocated some years ago for endoscopic procedures on the upper respiratory tract, a recent report has claimed benefit in patients with acute respiratory insufficiency.[14] The role of this technique in the management of patients after open heart surgery has yet to be defined, and a note of caution should be added because considerable intrapulmonary gas-trapping is a hazard, particularly in patients with increased airway resistance.

Intermittent mandatory ventilation

Intermittent mandatory ventilation was first introduced to assist weaning from continuous mechanical ventilation. Advantages claimed were that the arterial carbon dioxide tension would be much closer to normal than during continuous mechanical ventilation, that the cardiac output and cerebral blood flow would improve, that there would be a rightward shift of the hemoglobin-oxygen dissociation curve, that there would be improved compliance and reduced airways resistance, and that there would be a diminution in right-to-left intrapulmonary shunting.

Its role in the management of most cardiac surgical patients is questionable. It was no more successful than continuous mechanical ventilation at preventing atelectasis unless PEEP was added too.[5] Claims that intermittent mandatory ventilation makes PEEP feasible with fewer deleterious side-effects have not been supported experimentally and, for reasons outlined above, continuous mechanical ventilation is preferable to intermittent mandatory ventilation when PEEP is required therapeutically, provided care is taken to ensure normocapnia.

Many variants of intermittent mandatory ventilation have been introduced in recent years; patients with prolonged respiratory disability after cardiac surgery, e.g., those with cardiac cachexia and chronic pulmonary disease, may be helped by one or other of these techniques. However, the consistency and patient comfort provided by a patient-triggered device may still be preferable if smooth weaning from mechanical ventilation cannot be achieved without assistance.

There have been many advances in the management of mechanical ventilation during the past 25 years and much that is known of the physiological sequelae has been learned by studying patients after open heart surgery. At the same time, the improved prognosis for these patients has lessened their need for sophisticated ventilatory support, and it is important that the availability of a technique does not mean that its use becomes routine.

References

1. Prakash O, Jonson B, Meij S, et al. Criteria for early extubation after intracardiac surgery in adults. Anesth Analg 1977; **56:** 703–8.
2. Hilberman M, Kamm B, Lamy M, Dietrich HP, Martz K, Osborn JJ. An analysis of potential physiological predictors of respiratory adequacy following cardiac surgery. J Thorac Cardiovasc Surg 1976; **71:** 711–20.
3. Askitopoulou H, Sykes MK, Young C. Cardiorespiratory effects of increased airway pressure during controlled and spontaneous breathing after cardiac surgery. Br J Anaesth 1978; **50:** 1203–9.
4. Vuori A, Jalonen J, Laaksonen V. Continuous positive airway pressure during mechanical and spontaneous ventilation; effects on central haemodynamics and oxygen transport. Acta Anaesthesiol Scand 1979; **23:** 453–61.
5. Sladen RN, Jenkins LC. Intermittent mandatory ventilation and controlled mechanical ventilation without positive end-expiratory pressure following cardio-pulmonary bypass. Can Anaesth Soc J 1978; **25:** 166–72.
6. Hamilton WK. Do let the blood pressure drop and do use myocardial depressants! Anesthesiology 1976; **45:** 273–4.
7. Trichet B, Falke K, Togut A, Laver MB. The effect of pre-existing pulmonary vascular disease on the response to mechanical ventilation with PEEP following open-heart surgery. Anesthesiology 1975; **42:** 56–67.
8. Colgan FJ, Stewart S. PEEP and CPAP following open-heart surgery in infants and children. Anesthesiology 1979; **50:** 336–41.

9. Gregory GA, Edmunds LH Jr, Kitterman JA, Phibbs RH, Tooley WH. Continuous positive airway pressure and pulmonary and circulatory function after cardiac surgery in infants less than three months of age. Anesthesiology 1975; **43:** 426–31.
10. Pick MJ, Hatch DJ, Kerr AA. The effect of positive end expiratory pressure on lung mechanics and arterial oxygenation after open heart surgery in young children. Br J Anaesth 1976; **48:** 983–8.
11. Baker AB, Babington PCB, Colliss JE, Cowie RW. Effects of varying inspiratory flow waveform and time in intermittent positive pressure ventilation. I. Introduction and methods. Br J Anaesth 1977; **49:** 1207–20.
12. Baker AB, Colliss JE, Cowie, RW. Effects of varying inspiratory flow waveform and time in intermittent positive pressure ventilation. II. Various physiologic variables. Br J Anaesth 1977; **49:** 1221–33.
13. Baker AB, Cowie RW, Colliss JE. Effects of varying inspiratory flow waveform and time in intermittent positive pressure ventilation. III. Blockade of the autonomic nervous system. Br J Anaesth 1977; **49:** 1235–7.
14. Carlon GC, Klain M, Kalla R, Turnbull AD, Kahn RC. High frequency positive pressure ventilation; applications in acute respiratory failure. Crit Care Med 1979; **7:** 128.