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The Incidence of Ventilator-induced Pulmonary Barotrauma in Critically Ill Patients

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Pulmonary barotrauma (pneumothorax, pneumomediastinum or subcutaneous emphysema) reportedly occurs in 10 per cent (range 4–18 per cent) of patients who need mechanical ventilation with or without the use of positive end-expiratory pressure (PEEP). To document the impression that the incidence of pulmonary barotrauma was lower than those in previously reported series, the authors retrospectively examined the charts of 200 consecutive critically ill patients for pulmonary barotrauma and evaluated those factors that might have contributed to its occurrence.

The patients ranged in age from 18 to 95 years. Central venous pressure catheters had been used in 168 patients, and 178 patients were ventilated with a volume-cycled ventilator. Durations of ventilation averaged six days. The highest peak inspiratory pressures averaged 38 ± 12 (1 SD) cm H_2O, although in 60 patients, peak inspiratory pressures exceeded 40 cm H_2O. Mean dynamic compliance was 29.6 ± 13.8 ml/cm H_2O. Many patients needed more than 40 hours of ventilation with 3–> 12 cm H_2O PEEP.

While 22 of these patients showed evidence of barotrauma at some time during hospitalization, barotrauma was definitely unrelated to mechanical ventilation in 16, and probably unrelated in five more patients. In only one case was there a definite relationship between the use of mechanical ventilation and the development of pulmonary barotrauma, for an overall incidence of 0.5 per cent. (Key words: Complications: pneumothorax. Lung: compliance; damage; function. Ventilation: continuous positive airway pressure; continuous positive-pressure breathing; mechanical, positive end-expiratory pressure.)

PULMONARY BAROTRAUMA may be defined as the development of pneumothorax, pneumomediastinum, or subcutaneous emphysema in patients receiving respiratory therapy. Several reports have implicated positive-pressure ventilation with or without positive end-expiratory pressure (PEEP) as an important cause of pulmonary barotrauma in patients needing mechanical ventilation.[1–5] These reports suggest incidences of barotrauma ranging from 4 to 18 per cent, depending on type of ventilator used, level of PEEP, the patient population, and the disease process. Meanwhile, those who advocate the use of "high-level PEEP" (more than 18 torr) report an incidence of pneumothorax of 7 or 14 per cent, claiming that this incidence is no greater than that associated with mechanical ventilation with or without conventional PEEP.[6,7]

The frequency of occurrence of pulmonary barotrauma seemed to be exceedingly low in our intensive care unit. To document this impression and to provide a basis for comparison with other studies, we retrospectively reviewed our experience with a large group of critically ill patients.

Methods

Two hundred critically ill patients admitted consecutively to the Recovery Room–Acute Care Unit between September 1974 and September 1976 who needed mechanical ventilation with or without PEEP or continuous positive airway pressure (CPAP) for more than 24 hours were studied. Using the Therapeutic Intervention Scoring System (TISS), we defined these patients as Class IV, the most critically ill group seen in our intensive care unit, about whom much descriptive information has been published.[8,9] Such patients averaged 43 ± 1 (1 SE) TISS points, compared with Class III patients, who averaged 23 ± 1 points.[10]

Roentgenograms of the chest were obtained daily or every other day for all patients. These were routinely reviewed by the clinical staff of the intensive care unit, the team of primary surgeons, the radiology resident, and the radiology staff, and the findings recorded. When pneumothorax, pneumomediastinum, or subcutaneous emphysema was reported, the patient's chart was searched in detail for statements concerning the circumstances of barotrauma. For every patient, we recorded the following: age, presence of pre-existing cardiovascular disease, chronic obstructive pulmonary disease, pneumonia, a surgical procedure in the chest, tracheotomy, pleural tap, chest tube, presence of an endotracheal tube or tracheotomy tube, presence and location of central invasive catheters, and current diagnoses and hospital course. In addition, the following ventilatory data were obtained for each day of positive-pressure ventilation: length of time ventilated, mode

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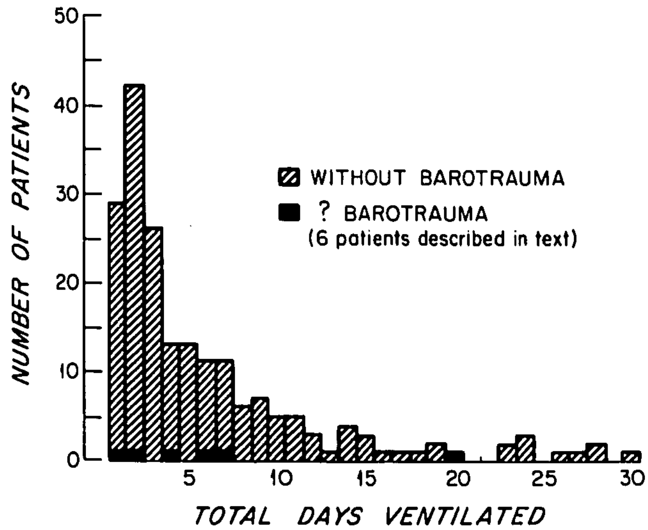

FIG. 1. Frequency histogram, showing the numbers of patients who needed one or more days of mechanical ventilation. The mean number of days of ventilation was 6 ± 6 (1 SD). The only patient (Patient 6) (see text) in whom barotrauma developed secondary to mechanical ventilation was ventilated for 20 days.

used (control, assist, intermittent mandatory ventilation, continuous positive airway pressure), amount of PEEP, respiratory rate, tidal volume, peak inspiratory pressure, inspired oxygen concentration, Pa_{O_2}, Pa_{CO_2}, and pH. The numbers of hours at three levels of PEEP, 3–7, 8–12, and more than 12 cm H_2O, were calculated. The patients' later medical course was obtained from the chart.

Results

All patients ranged in age from 18 to 95 years. The patients' primary disease categories are listed in table 1; their distribution follows that in the previous study of Class IV patients. Endotracheal tubes only were used in 146 patients, four patients needed immediate tracheotomy, while 50 patients initially needed endotracheal intubation, which was later converted to a tracheotomy. Central venous pressure catheters were used in 168 patients and pulmonary-artery catheters in 100 patients. Twenty-one patients received pressure-cycled ventilation, 178 patients, volume-cycled ventilation, and one patient received only continuous positive airway pressure. The mean number of days of ventilation was 6 ± 6 (1 SD) (fig. 1). The lowest tidal volumes averaged 866 ± 169 ml (1 SD): highest tidal volumes averaged 1,049 ± 179 ml. The lowest peak inspiratory pressures recorded for all patients averaged 28 ± 8 cm H_2O (1 SD), and the highest peak inspiratory pressures averaged 38 ± 12 cm H_2O. Sixty patients received peak inspiratory pressures of more than 40 cm H_2O without suffering pulmonary barotrauma (fig. 2). The lowest Pa_{O_2} values recorded for all patients averaged 240 ± 109 torr (1 SD), while the highest Pa_{O_2} values averaged 384 ± 90 torr, both at FI_{O_2} of 1.0. The lungs of many patients were ventilated for more than 48 hours at 3–7, 8–12, or more than 12 cm H_2O PEEP without development of pulmonary barotrauma (fig. 3). Mean dynamic compliance was 29.6 ± 13.8 ml/cm H_2O (1 SE) (fig. 4), but 69 patients had dynamic compliances of less than 25 ml/cm H_2O, yet only one had pulmonary barotrauma.

Pneumothorax, pneumomediastinum, or subcutaneous emphysema developed in 22 patients (11 per cent), but in 16, the complications were definitely not related to mechanical ventilation. Of these 16 patients, six had pneumothoraces that occurred after chest-tube insertion to drain pleural effusions, four had pneumothoraces after trauma to the chest and rib fractures secondary to motor vehicle accidents; two had pneumothoraces after thoracic surgical procedures with chest tubes placed intraoperatively; one had pneumothorax after a ruptured esophagus, cardiac arrest, and cardiopulmonary resuscitation; one had pneumothorax immediately after subclavian placement of a central venous pressure catheter; one had subcutaneous emphysema and pneumothorax after necrosis of the skin flap covering remaining trachea following a reconstructive operation on the neck for carcinoma of the larynx; one had pneumothorax immediately after tracheotomy. Pulmonary barotrauma in these patients did not develop from mechanical ventilation, and new instances of pulmonary barotrauma did not develop when their lungs were mechanically ventilated.

Of the other six patients, five had pulmonary barotrauma resulting from causes probably unrelated to mechanical ventilation, while barotrauma in one patient (Patient 6) was definitely related to mechanical ventilation. These six patients are briefly described.

TABLE 1. Classification of Patients by Disease Process Categories*

1. Elective operation for malignant disease	19
2. Massive trauma not treated by neurosurgery	16
3. Neurosurgical procedure or trauma to the head	29
4. Major vascular operation—emergency	28
5. Major vascular operation—elective	32
6. Unexpected major complications with elective operation	11
7. Emergency operation—gastrointestinal bleeding, cirrhosis, portal hypertension	30
8. Emergency operation, major abdominal catastrophes, nonbleeding	35

* The eight disease process categories listed are those used in a previous classification of critically ill Class IV patients.[7]

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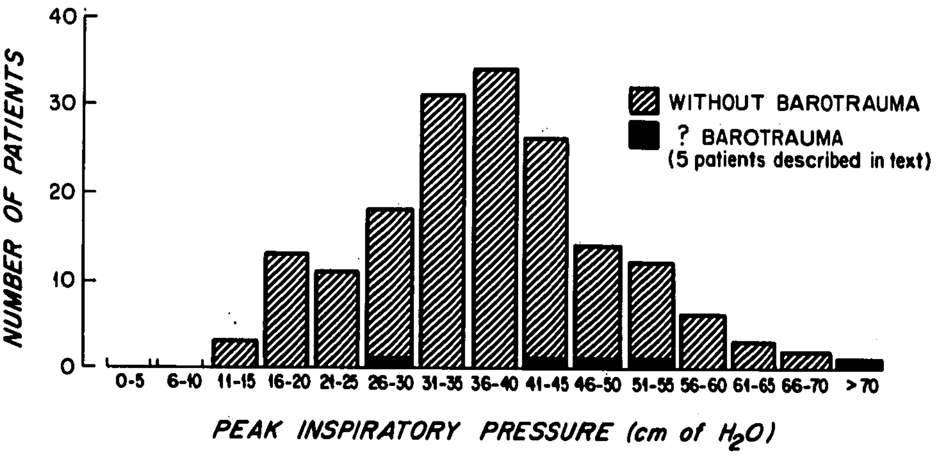

FIG. 2. Highest recorded peak inspiratory pressures. Frequency histogram, showing the numbers of patients who needed peak inspiratory pressures of 11–15 cm H_2O or more. The only patient (Patient 6) in whom barotrauma developed secondary to mechanical ventilation needed the highest peak inspiratory pressure, >70 cm H_2O.

REPORT OF SIX CASES

In Patient 1, right paratracheal air and subcutaneous emphysema developed within a few hours following insertion of a right subclavian catheter. The lungs were ventilated with a volume-cycled ventilator set to provide 15 cm H_2O PEEP, peak inspiratory pressure 54 cm H_2O, tidal volume 1,500 ml, and respiratory rate 10/min. The patient had had similar ventilatory settings for the preceding four days, without difficulty.

Patient 2 had a left subclavian catheter placed preoperatively. During the procedure (cholecystectomy), crepitus in the left neck was noticed. Several hours later, left pneumothorax was seen on a roentgenogram of the chest.

Patient 3 had a pharyngeal perforation, acute feculent posterior mediastinitis, endocarditis, numerous small pulmonary infarcts, bilateral bronchopneumonia, and bilateral pneumothoraces.

In Patient 4, subcutaneous emphysema about the neck developed a day after evacuation of a left subdural hematoma that had resulted from trauma to the head sustained in a motor vehicle accident. Roentgenograms of the chest did not show rib fractures or pneumothorax. Chest tubes were not placed. The patient was paralyzed and respiration was controlled with an Engström ventilator set at 5 cm H_2O PEEP, 12 breaths/min, tidal volume 1,000 ml, and peak inspiratory pressure 44 cm H_2O. A bronchial tear was suspected but not established. The patient subsequently needed controlled, then assisted, ventilation, with use of 3–5 cm H_2O PEEP for several more days without placement of chest tubes and without progression of subcutaneous emphysema.

In Patient 5 a 20 per cent right pneumothorax developed following insertion of a pulmonary-artery catheter through the right internal jugular vein. A chest tube was placed and subsequently was removed on the fifth postoperative day, without difficulty. Approximately a month and a half later, a right subclavian line was inserted with difficulty for purposes of hyper-

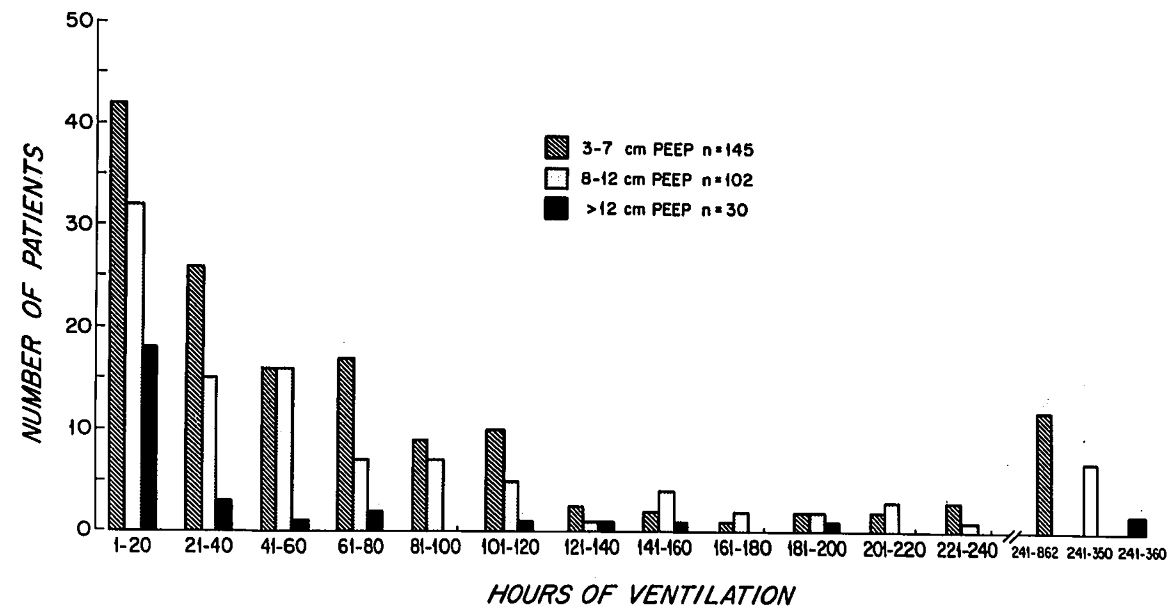

FIG. 3. PEEP hours (numbers of hours at three levels of PEEP). Frequency histogram, showing the numbers of patients who needed positive end-expiratory pressure (PEEP) and the numbers of hours during which they needed PEEP of 3–7, 8–12 or more than 12 cm H_2O.

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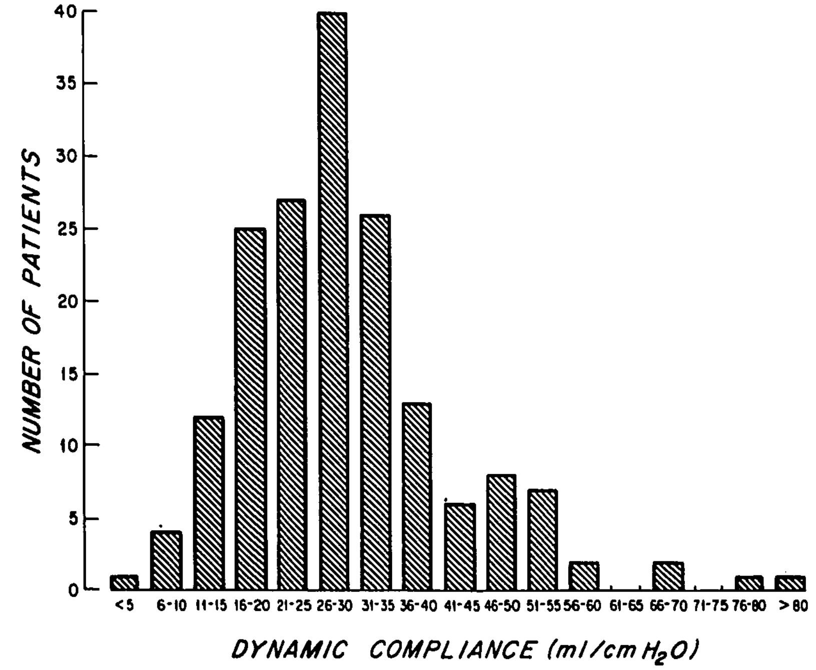

FIG. 4. Frequency histogram, showing the dynamic compliance distribution. Mean dynamic compliance was 29.6 ml/cm H_2O; 69 patients had values of less than 25 ml/cm H_2O.

alimentation. The trachea was not intubated at this time, but again, a large right pneumothorax was observed on the immediate post-insertion roentgenogram of the chest. A chest tube was placed and recovery was uneventful. Two years previously, the patient had fractured the right first rib in a motor vehicle accident.

Patient 6 had subcutaneous emphysema and pneumomediastinum 11 days after tracheal intubation and ventilation with peak inspiratory pressures as high as 76 cm H_2O. Chest tubes were not placed, and pneumothorax did not develop. Subcutaneous emphysema probably resulted from prolonged ventilation of a noncompliant lung, and occurred at a time when the patient was noticed to be struggling against the ventilator. Although chest tubes were not placed, and controlled ventilation with high peak inspiratory pressures was necessary for nine more days until her death, pulmonary barotrauma resolved spontaneously and did not contribute to her demise.

Thus, pulmonary barotrauma causally related to mechanical ventilation developed in one of 200 patients. The 95 per cent confidence limits estimated by binomial distribution are between zero and four cases of barotrauma. Although we could not exclude the other five cases from consideration, we do not believe that mechanical ventilation can be implicated as initiating pulmonary barotrauma in those cases.

Of the 200 patients, 116 died, and 39 of these underwent postmortem examination. Lung weights were twice normal (table 3). Twenty-two patients had pathologic evidence of pulmonary edema, and 19 had bronchopneumonia.

Discussion

In this group of critically ill surgical patients who needed mechanical ventilation for various lengths of time at different peak inspiratory pressures and levels of PEEP, only one had pulmonary barotrauma that was related to mechanical ventilation. Even this patient had been ventilated at a peak inspiratory pressure of 58–76 cm H_2O for the preceding two weeks, requiring 8–12 cm H_2O PEEP for almost 20 days. All these events followed two months of an extremely complicated hospital course of a patient who had severe multisystem failure. In the other five cases, pulmonary barotrauma was probably unrelated to mechanical ventilation.

Despite earlier reports of a 10 per cent incidence of pulmonary barotrauma in patients needing mechanical ventilation with or without PEEP,[1] or incidences as high as 39 per cent in patients receiving high-level PEEP,[6] our data show that the basal incidence of pulmonary barotrauma following mechanical ventilation over the ranges of peak inspiratory pressures and positive end-expiratory pressures reported here was 0.5 per cent. Since Class IV patients are by subjective[8] and objective[11] definitions critically ill, extremely unstable, and suffer a very high mortality rate, the use of mechanical ventilation with or without positive end-expiratory pressure and the use of whatever peak inspiratory pressures are deemed necessary are essential adjuncts to their medical care. Yet, the risk of pulmonary barotrauma need not be high.

Is it possible that our incidence of pulmonary barotrauma was erroneously low because numerous occurrences of barotrauma were missed? We believe not, because daily roentgenograms of the chests were viewed by several groups of physicians, including staff radiologists, who would always report the pres-

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ence of pneumothorax, pneumomediastinum, or subcutaneous emphysema. Even if evidence of barotrauma were missed on one occasion, it would be most unlikely to disappear without treatment before the next day's roentgenograms were obtained.

We can only speculate why our incidence of pulmonary barotrauma was one-twentieth that reported by Kumar *et al.* from a similar intensive care unit within the same hospital five years ago. More patients with chronic obstructive pulmonary disease were included in Kumar's series than in ours. Ventilatory practices have been refined; patients are more effectively sedated and when necessary, paralyzed in order to facilitate mechanical ventilation. Conversely, the use of intermittent mandatory ventilation allows patients to receive some ventilatory support while they still breathe spontaneously at will without fighting the ventilator. One disease process not seen in our series of patients was acute respiratory distress syndrome secondary to viral pneumonia. This is associated with progressively severe hypoxemia, decrease in compliance, pulmonary fibrosis, and ultimately, disruption of the pulmonary parenchyma. Since these patients need high levels of PEEP and high peak inspiratory pressures, and are also undergoing a destructive process of the pulmonary parenchyma, their incidence of barotrauma may be considerably higher than that in our series. Our patients were equally ill, but respiratory failure was usually secondary to other disease processes and was not the primary reason for their hospitalization. When Fleming reported a 15 per cent incidence of pneumothorax, all his patients' lungs were being ventilated via tracheotomy tubes, and 17 of the 19 had necrotizing pneumonia. Pneumonia (though not necessarily necrotizing) developed clinically in 60 of our patients during their critical illnesses, but pulmonary barotrauma was rare. Almost half the patients so examined had pathologic evidence of bronchopneumonia at postmortem examination. The doubling of lung weight and other pathologic findings at autopsy further suggested the extensive disease involvement in these patients' lungs.

Several factors have been implicated in the causation of pulmonary barotrauma. High-level positive end-expiratory pressure is used to expand lung units and improve functional residual capacity, oxygenation, and compliance, and to decrease intrapulmonary shunt. However, if overdistention were to rupture some lung units, pulmonary barotrauma could occur. Indeed, Kirby *et al.*[7] reported that pneumothorax developed in 14 per cent (4 of 28) of their patients who had PEEP greater than 18 torr. More recently, Downs and Chapman reported a 7 per cent incidence of pneumothorax, a 35 per cent incidence of pneumomediastinum, and a 39 per cent incidence of subcutaneous emphysema in patients needing positive end-expiratory pressures greater than 20 torr.[6] Thirty patients in our series were ventilated with PEEP greater than 12 cm H_2O, yet none had barotrauma (table 2). Thomas, commenting on Steier's paper, stated a 20–30 per cent incidence of pneumothorax in patients sustaining trauma who needed prolonged mechanical ventilation and PEEP.[4] Further details were not given. Compared with the 10 per cent incidence of barotrauma reported by Kumar *et al.*,[1] the values of pneumothorax reported by these authors are perhaps comparable, but we believe they should now be compared with the baseline figure of less than 1 per cent reported here.

Patients who strain and cough vigorously against volume-cycled ventilators may also be more likely to sustain barotrauma. Steier *et al.*[4] and de Latorre *et al.*[5] reported 7 and 9 per cent incidences of pneumothorax, respectively, in patients being ventilated with volume-cycled ventilators. Since most of our patients received volume-cycled ventilation, our baseline incidence of barotrauma of less than 1 per cent helps to establish the safety of these ventilators.

Many investigators have suggested that high peak airway pressure relates to the development of pulmonary barotrauma, and indeed our one case of pulmonary barotrauma specifically related to mechanical ventilation occurred in such a patient. However, many of our patients' lungs were ventilated with peak

TABLE 2. Distribution of 30 Patients Who Received PEEP > 12 cm H_2O

PEEP (cm H_2O)	Number of Patients
13	1
14	3
15	22
18	1
20	3
	30

TABLE 3. Pathologic Diagnoses at Autopsy (n = 39)

Diagnosis	Number of Patients
Pulmonary edema	22
Interstitial fibrosis	6
Bronchopneumonia	19
Emphysema	7
Recent pulmonary emboli	13
Intrapulmonary abscess	4
Aspergillosis	2
Cor pulmonale	1

Right lung weight = 735 ± 38 g; mean ± 1 SE. Left lung weight = 680 ± 42 g.
Pleural effusion volume = 1,308 ± 253 ml.

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inspiratory pressures of more than 40 cm H_2O at one time or another during their critical illnesses without increasing the incidence of pulmonary barotrauma (fig. 2).

Duration of ventilation is thought to increase the likelihood of barotrauma. Data from Kumar *et al.* do not support this premise, since eight of 78 patients (11 per cent) whose lungs were ventilated for less than five days sustained pulmonary barotrauma, as did eight of 86 patients (10 per cent) whose lungs were ventilated for more than five days. The mean duration of ventilation in our series was six days, yet barotrauma was minimal.

Pulmonary barotrauma secondary to mechanical ventilation with or without PEEP was a rare event in this large series of consecutively admitted critically ill surgical patients. Perhaps prospective or cooperative multi-center studies would help ascertain the reason for such an extremely low incidence of pulmonary barotrauma.

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