CASE REPORTS

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Compliance and Capnography Monitoring during Independent Lung Ventilation: Report of Two Cases

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INDEPENDENT lung ventilation (ILV) has been applied in severe asymmetrical or unilateral lung injury to improve hypoxemia refractory to conventional mechanical ventilation and positive end-expiratory pressure.[1–6] The most commonly used approach is to deliver the same tidal volume (Vt) to each lung.[1,3,6–8] However, this setting produces higher plateau airway pressure (Pplat) in the more injured lung.[2–4,7]

We describe two patients with unilateral lung injury successfully treated using ILV. Unlike other cases reported, Vt was initially set in each lung at a value generating a Pplat less than or equal to 26 cm H_2O and then progressively reset on the basis of single-lung static compliance (Cst) variations. Capnography of each lung was continuously performed, and end-tidal carbon dioxide (ET_{CO_2}) was measured to follow the ventilation–perfusion (V/Q) matching.

Case Reports

Case 1

A 25-yr-old woman experienced thoracic trauma. Intubation was performed with use of an orotracheal tube, and the patient was transferred to the intensive care unit. Computed tomography showed left lung contusion. Major asymmetry in lung expansion was observed, with poor aeration of the left lung. The patient underwent ventilation using square wave flow, respiratory rate 16 breaths/min, Vt 700 ml, fractional inspired oxygen tension ($F_{I_{O_2}}$) 100%, and inspiratory–expiratory ratio 0.33. Pplat was 40 cm H_2O and Cst was 13 cm H_2O/ml. The capnogram wave had an irregularly shaped plateau with an ET_{CO_2} of 30 mmHg. Arterial oxygen saturation was 90%, arterial oxygen tension (Pa_{O_2}) was 50 mmHg, arterial carbon dioxide tension was 34 mmHg, and respiration (*p*H) was 7.47.

Independent lung ventilation was instituted *via* a double-lumen tube: each lung was initially ventilated with respiratory rate 16 breaths/min, Vt 350 ml, inspiratory–expiratory ratio 0.33, and $F_{I_{O_2}}$ 100%. A positive end-expiratory pressure of 5 cm H_2O was applied to the left lung. In the right lung, Pplat recorded 30 min later was 18 cm H_2O, Cst was 19.4 cm H_2O/ml, and the capnogram was regular, with ET_{CO_2} of 35 mmHg. On the left side, Pplat was 36 cm H_2O, Cst was 11.2 cm H_2O/ml, expiratory carbon dioxide waveform was irregular with a biphasic plateau, and ET_{CO_2} was 22 mmHg. Consequently, ventilatory settings for the right lung remained unmodified, whereas Vt to the left lung was decreased to 230 ml. With this setting, Pplat was 26 cm H_2O and Cst was 10.9 cm H_2O/ml. The capnogram remained irregular and ET_{CO_2} increased to 24 mmHg. Arterial oxygen saturation was 98%. Vt to the left lung was progressively increased and set to obtain a Pplat less than or equal to 26 cm H_2O, as shown in figures 1A–C. ILV was discontinued after 48 h, at which point there was no difference in Vt and, consequently, in Cst between the two lungs. At the same time, the capnogram of the left lung had a steady plateau, and there was no difference in ET_{CO_2}. After ILV was discontinued, the patient received ventilation *via* an orotracheal single-lumen tube and was transferred to the unit after mechanical ventilation was discontinued.

Case 2

A 59-yr-old man was admitted to the intensive care unit with multiple right-sided rib fractures, diffuse right lung contusion, and right arm fracture. The patient was intubated with an orotracheal monolumen tube and received ventilation with square wave flow, respiratory rate 16 breaths/min, Vt 850 ml, $F_{I_{O_2}}$ 100%, and inspiratory–expiratory ratio 0.33. Pplat was 46 cm H_2O and Cst was 18.4 cm H_2O/ml. The capnography wave was irregularly shaped with a positive slope, and ET_{CO_2} was 35 mmHg. Arterial oxygen saturation was 90%, Pa_{O_2} was 65 mmHg, arterial carbon dioxide tension was 38 mmHg, and respiration was 7.44.

Independent lung ventilation was instituted *via* an orotracheal double-lumen tube, and each lung was ventilated with respiratory rate 16 breaths/min, Vt 400 ml, inspiratory–expiratory ratio 0.33, and $F_{I_{O_2}}$ 100%. A positive end-expiratory pressure of 7 cm H_2O was applied to

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Key words: Barotrauma; plateau airway pressure; thoracic trauma; tidal volume.

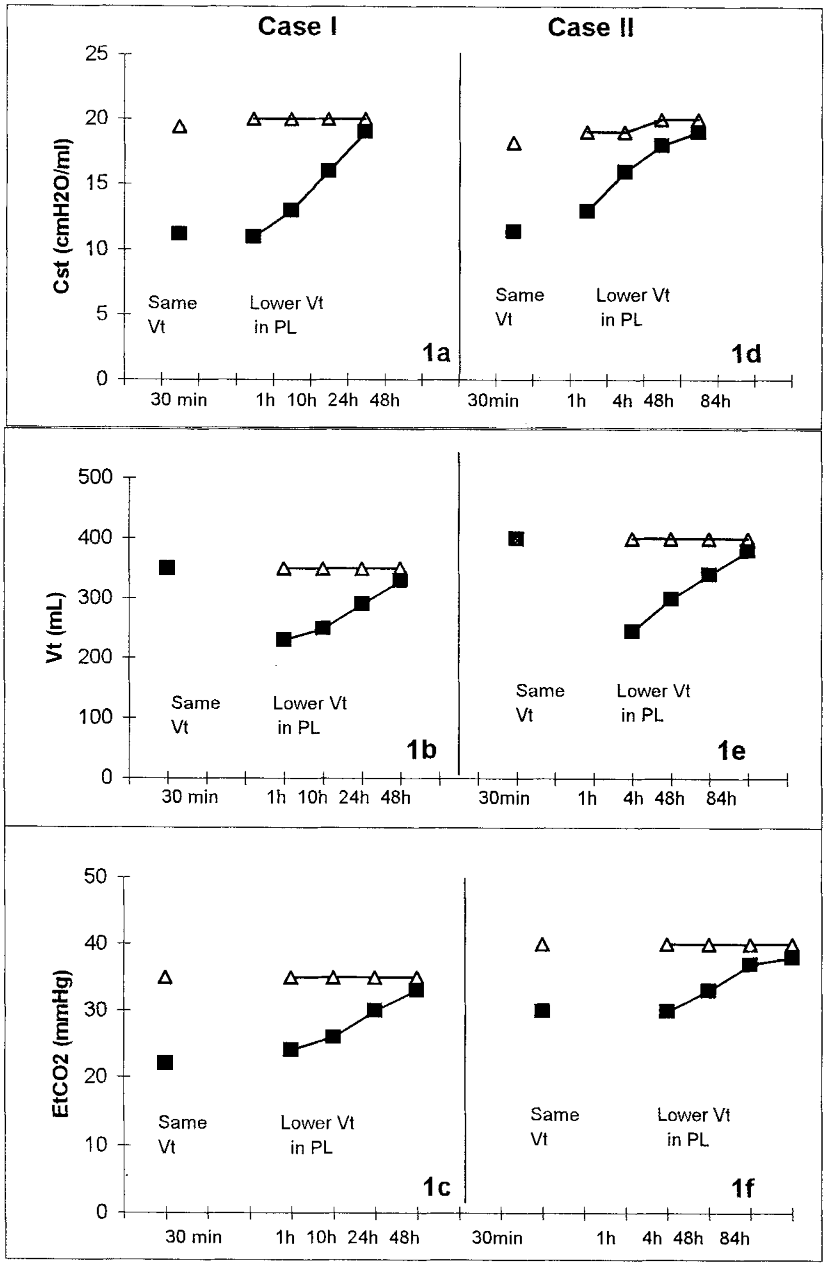

Fig. 1. (Open triangles) normal lung and (closed squares) diseased lung. Single points indicate values measured 30 min after setting independent lung ventilation with the same tidal volume on both lungs. Solid lines indicate values measured during ILV set with a lower tidal volume on the diseased lung. (*A–C*) case 1, (*D–F*) case 2. (*A* and *B*) static compliance, (*C* and *D*) tidal volume, and (*E* and *F*) end-tidal carbon dioxide of normal (open triangles) and diseased lung (closed squares) during independent lung ventilation.

the right lung. In the left lung, Pplat recorded 30 min later was 22 cm H_2O, Cst was 18.2 cm H_2O/ml, and the capnogram was regular, with an ET_{CO_2} of 40 mmHg. In the right lung, Pplat was 42 cm H_2O, Cst was 11.4 cm H_2O/ml, expiratory carbon dioxide waveform was irregular with a positive slope, and ET_{CO_2} was 28 mmHg. Ventilatory settings for the left lung remained unmodified, and Vt to the right lung was reduced to 245 ml. With this setting, Pplat was 26 cm H_2O, Cst was 12.9 cm H_2O/ml, the capnogram plateau did not change, and ET_{CO_2} was 30 mmHg. Pa_{O_2} was 85 mmHg, arterial carbon dioxide tension was 50 mmHg, and *p*H was 7.52. A Swann-Ganz catheter was inserted, and the measured Qs/Qt was 26%. Vt to the right lung was progressively increased and set to obtain a Pplat less than or equal to 26 cm H_2O, as shown in figures 1D, E, and F. ILV was discontinued after 84 h, at which point there was no difference in Vt and, consequently, in Cst between the two lungs. At the same time, the capnogram of the right lung had a steady plateau, and there was no difference in ET_{CO_2}. The measured Qs/Qt was 10%.

After ILV was stopped, the patient received ventilation *via* an orotracheal single lumen tube and was transferred to the hospital ward after mechanical ventilation was discontinued.

Discussion

The main aspect of unilateral lung injury is the development of asymmetric lung disease, producing differences in compliance between the two lungs.[1,2,5,6] As a consequence, during conventional lung ventilation, Vt is mostly diverted toward the more compliant lung, resulting in overinflation and increased ventilation–perfusion ratio (dead space).[2,3,8] Lung overdistension causes a Starling resistor mechanism on normal alveolar capillaries, with the diversion of blood flow toward the underventilated injured lung, increasing blood shunting.[1-7] During such conditions, ILV is indicated to ventilate the diseased lung while avoiding hyperinflation in the normal lung.[1-8]

The two patients described herein were treated by setting Vt in both lungs at a value generating a Pplat less than or equal to 26 cm H_2O and progressively increasing it on the basis of Pplat variations, and the patients were monitored using the continuous measurement of single-lung capnography.

Until now, equal Vt in the two lungs has been considered in most published studies to be the setting that produces the best oxygenation.[1,3-7] In an experimental study, East *et al.*[3] compared different Vt delivery patterns and found that the highest Pa_{O_2}:FI_{O_2} ratio was obtained when equal Vt was given in both lungs. However, this pattern led to levels of Pplat higher than 30 cm H_2O in the diseased lung, as also reported in a clinical study by Zandstra *et al.*,[7] because in unilateral lung injury, by definition, the contused lung is less compliant than the normal lung. This ventilatory strategy was based on the assumption that the aim of ILV is only to separate the ventilation of each lung, allowing the lung with contusion to receive its Vt. The angiographic data of Carlon *et al.*,[1] showing that the shunt fraction in the lung with contusion decreased considerably as soon as ILV was instituted, confirmed this hypothesis.

However, some data in the literature seem to show that a different ventilatory strategy, *i.e.*, to set for each lung ventilation modeled to its mechanical properties, can be applied with good results in terms of the Pa_{O_2}:FI_{O_2} ratio, avoiding additional lung injury caused by volutrauma.[2,8,9] Siegel *et al.*[2] proposed to measure the pressure–volume of each lung to set ventilation more appropriately. The pressure–volume curve measurement can be too complex to be performed many times a day, as would be necessary in such patients. Therefore, in our patients, mechanics of each lung were measured by the static compliance, and Vt was set at a value generating a Pplat less than 26 cm H_2O, which is the threshold level accepted by many authors to avoid additional volutrauma.[9] This ventilatory schema allowed a stable Pa_{O_2}:FI_{O_2} ratio in our two patients.

The second aspect to be outlined in these two patients is the expiratory capnograph monitoring. A few experimental and clinical studies showed that, during ILV, ET_{CO_2} is lower and the waveform is irregular in the lung with contusion.[2,3,8] The absence of a steady plateau on the capnogram may indicate intrapulmonary gas maldistribution, and an irregularly shaped plateau can reflect differences between the time constants of different alveolar regions.[10] The difference in carbon dioxide waveform and ET_{CO_2} value can be explained by the dyshomogeneity proper to lung injury, characterized by coexistence in the same lung of alveolar regions with different time constants.[10] A high Vt in the diseased lung probably accentuates this dyshomogeneity. These data were confirmed for our patients. During the course of ILV, in the lungs with contusion, together with improvement of the lung damage, the airway pressure developed by a given Vt was reduced, whereas ET_{CO_2} increased. Vt was increased stepwise until the Pplat was equal in both lungs, and by this time there was no difference in ET_{CO_2} between the two lungs. Moreover, in the patient in case 2, the measured shunt fraction was reduced from 26 to 10%.

We believe that the ventilatory setting used in these two cases could allow a stable Pa_{O_2}:FI_{O_2} ratio and that the ET_{CO_2} measurement could be a useful tool to monitor patients during ILV.

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The Rapid Infusion System: User Error in Tubing Connection Mimicking Severe Hemorrhage

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THE Rapid Infusion System (RIS) (Haemonetics, Braintree, MA) is a device used to infuse blood or other fluids at body temperature at rates up to 1.5 l/min.[1] The RIS infuses fluid *via* Y output tubing into two separate, large-bore intravenous cannulae to minimize resistance to flow and displays cumulative infusion output during use *via* a digital step-motor driving a roller pump. The knowledge of transfused fluid volumes may facilitate resuscitation by influencing the choice of subsequent blood component replacement during severe hemorrhage in anticipation of transfusion-related coagulation disorders. We present a case in which the use of a mechanically intact RIS during trauma resuscitation led to a gross overestimation of blood transfusion and estimated loss as a result of simple and unreported user error.

Case Report

A 64-yr-old man fell 7.6 m from a tree and had a left open forearm fracture with vascular compromise, a pelvic fracture, and serial rib fractures in the left side of the chest with flail chest and a widened mediastinum. He became hypotensive in the emergency room and received crystalloid resuscitation *via* two intravenous catheters. At arrival in the operating room, fluids were administered intravenously *via* a single limb of the RIS output into the existing femoral "trauma" catheter. The second limb of the RIS was not connected to the patient. Repeated acute fluid challenges and, finally, continuous infusion of 100-300 ml/min *via* the RIS were administered. The cumulative intraoperative fluid administration was 2,500 ml *via* a 16-gauge peripheral catheter, whereas the RIS indicated a cumulative 22-l transfusion of packed cells and crystalloid mixture after 90 min. Thoracic exploration was performed, which disclosed only moderate bleeding from a lacerated intercostal artery. This led to scrutiny of the extent of all visual-measurable hemorrhage, now suspected to be in gross discrepancy with the registered 26-l transfusion *via* the RIS output display. An RIS malfunction was excluded after the review of transfusion records indicated that only 7 l fluid was placed into the RIS. Closer evaluation revealed that, because only one of the two output infusion tubings was connected to the patient's intravenous catheters, the second output tubing had remained connected to the reservoir and unclamped after priming of the machine and tubing. This allowed the correctly measured RIS output *via* the Y tubing to predominantly recirculate into the reservoir as the path of least resistance.

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Discussion

The RIS can rapidly replace blood loss with fluids at body temperature, typically using two sites to minimize resistance to flow.[2,3] Only one limb of the RIS output was connected to the largest intravenous catheter, and this singular connection resulted in the registered output error *via* recirculation in the second limb as a deviation from routine application of the RIS during an urgent situation (fig. 1). Such single-limb use occurs possibly once or twice a year in our tertiary trauma center, which uses the RIS on a daily basis. The use of the RIS in trauma may benefit patients by minimizing lactate levels, coagu-