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Intraoperative Ventilator-induced Right-to-left Intracardiac Shunt

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The inadvertent introduction of air into the venous system during surgery is believed to be fairly common but is of limited clinical significance because of the typically

small volumes involved and because of the filtering capacity of the lungs. However, even a small volume of air entering the left side of the heart (paradoxical embolization) has the potential to obstruct portions of the cerebral or coronary circulations with possibly disastrous consequences.¹

Paradoxical embolization is believed to occur most commonly through the foramen ovale, which is known from autopsy studies to be probe-patent in up to 34% of the adult population.² Provocative maneuvers such as coughing or Valsalva's maneuver are known to cause rapid changes in intrathoracic pressure associated with reversal of interatrial pressure gradients.³ Transthoracic echocardiographic studies using these maneuvers performed in normal subjects and in patients before surgical procedures reported a 6-10% incidence of patent foramen ovale

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(PFO).⁴⁻⁶ Thus, the potential for paradoxical embolization is present in a small but significant number of patients presenting for surgery, and any intraoperative events that can cause right-to-left flow through a probe-PFO should be of particular interest to the anesthesiologist.

We now report the occurrence of cyclic right-to-left shunt flow through a PFO induced by mechanical ventilation in an otherwise healthy patient anesthetized for noncardiac surgery. This finding was seen during an ongoing study using transesophageal echocardiography (TEE) during general anesthesia in healthy patients (ASA physical status 1 or 2).

CASE REPORT

The patient was a healthy, physically active 45-yr-old, 80-kg, 170-cm man, ASA physical status 1, scheduled for outpatient left elbow arthroscopy. The patient refused regional anesthesia. General anesthesia was induced with thiopental, and vecuronium was used to facilitate tracheal intubation. Anesthesia was maintained with isoflurane, nitrous oxide, and oxygen. With the patient supine, the lungs were mechanically ventilated using a Narcomed[®] 2B ventilator. Intraoperative monitoring included an electrocardiogram, blood pressure cuff, pulse oximeter, and capnograph.

As part of an ongoing study on the incidence of and the factors affecting interatrial shunt flow during noncardiac surgery (with the approval of the Stanford Human Subjects Committee and the patient's prior consent), the TEE probe was introduced into the esophagus with the transducer facing anteriorly. All ultrasound recordings were obtained using a Hewlett-Packard ultrasonograph (model Sonus 500, Andover, MA) with a 5-MHz transducer mounted at the tip of a 14-mm adult gastroscope (model 21362A echoscope, Hewlett-Packard). Tomographic planes were obtained in the usual fashion by translating and rotating the echoscope within the esophagus while observing the ultrasonic image for reference.⁷ Modified four-chamber views were used to allow optimal visualization of the interatrial septum and of the left and right atria. To verify the existence of a flow-PFO, 10 ml normal saline agitated with air (producing microbubble echo targets) and from which macroscopic bubbles were excluded was injected *via* the intravenous catheter located in the back of the right hand.

While the lungs were ventilated with a tidal volume of 1,200 ml (inspiratory:expiratory ratio 1:2.5 and respiratory rate 7 breaths per min), producing a maximum airway pressure of 37 cmH₂O, echo targets were observed crossing the interatrial septum and entering the left atrium coincident with early inspiration. In addition, target injections were done after equilibration at 0, 5, 10, 15, and 19 cmH₂O positive end-expiratory pressure (PEEP). A minimum of 30 s was allowed to elapse after each PEEP adjustment to permit pressure equilibration. At 15 cmH₂O PEEP, echo targets were seen to cross the interatrial septum from right to left, independent of the ventilator cycle. Arterial hemoglobin oxygen saturation as measured by pulse oximetry was 100% throughout the procedure.

At the completion of surgery, neuromuscular blockade was reversed and the patient's trachea extubated without incident in the operating room. The patient was discharged home 3 h later without any sequelae.

DISCUSSION

This is the first report of shunt flow through a PFO in an otherwise healthy patient induced as a result of intra-

operative mechanical ventilation. This case may represent a mechanism whereby paradoxical embolization could be induced intraoperatively. Traditionally, patients undergoing surgical procedures while in the sitting position have been considered to be at high risk for venous air embolism; however, venous air embolism has also been reported during procedures in patients in the supine position, including craniectomy,⁸ hip replacement,⁹ and cesarean section.¹⁰ The incidence of venous air embolism in the latter three studies was 66, 30, and 50%, respectively.

Previous studies have shown that intraoperative TEE is advantageous for diagnosing PFO after induction of anesthesia or during the surgical procedure.⁶ Echocardiographic studies for detection of PFO usually are performed using provocative maneuvers, either Valsalva's maneuver or cough in the awake patient or PEEP in the anesthetized patient.⁴⁻⁶ With conventional transthoracic echocardiography, only 64% of patients known to have a flow-PFO could be detected with these provocative maneuvers.¹¹ In contrast, TEE should easily detect even minimal shunting through a PFO, because it allows optimal imaging of the interatrial septum and atria, particularly the left. However, the possibility of a false-negative contrast study should be considered. Indeed, Black *et al.*⁶ reported preoperative right-to-left shunting in 6 of 101 patients studied using transthoracic echocardiography during a Valsalva's maneuver. Subsequent intraoperative TEE during the release of 20-cmH₂O PEEP detected right-to-left shunting in only 4 of these 6 patients, confirming potential problems associated with the sudden release of high levels of PEEP as a provocative procedure for the detection of PFO.

As a persistent anatomic consequence of fetal circulation, venous return to the heart *via* the superior vena cava is directed away from the foramen ovale, while blood entering *via* the inferior vena cava is directed at the foramen ovale. In the case reported above, since the echo contrast material entered the circulation through a vein in the upper extremity, the concentration of echo targets was likely to be less near the foramen ovale initially, thus decreasing the likelihood that transient shunting could be detected from its onset. Hence, in this patient, it is possible that shunt flow was occurring earlier in the respiratory cycle than we were able to detect.

Also worthy of note in this patient was the occurrence at a PEEP of 15 cmH₂O of a continuous right-to-left shunt across the PFO. This shunt flow was independent of phase of respiration and thus was independent of transient intrathoracic pressure gradients. An earlier study reported that 10-cmH₂O PEEP caused right atrial pressure to increase by an average of 5.3 mmHg and to exceed pulmonary artery wedge pressure (and thus, by inference, to exceed left atrial pressure) in 7 of 11 anesthetized patients studied while in the sitting position.¹² This obser-

vation is supported by reports of TEE-demonstrated shunt flow in seated anesthetized patients.^{4,13} More recently, however, both animal¹⁴ and human¹⁵ studies have been unable to demonstrate any effect of PEEP up to 10 cmH₂O on the interatrial pressure gradient in either supine (right atrial pressure increased by 3.4 mmHg) or sitting (right atrial pressure increased by 2.4 mmHg) positions.

In a study of pigs after balloon atrial septoplasty, it was suggested that the incidence of paradoxical air embolism was not affected by positive pressure ventilation with or without PEEP when compared to spontaneous ventilation.¹⁶ Paradoxical air embolism occurred regardless of the direction of the mean right-to-left atrial pressure gradient. In all cases of paradoxical embolism where mean left atrial pressure exceeded mean right atrial pressure, there were transient reversals of this gradient during each cardiac cycle. The authors concluded that in the presence of an atrial septal defect, there is a persistent risk of paradoxical embolization regardless of mean interatrial pressure gradient or pattern of ventilation.

The extrapolation of the latter results¹⁶ to the human may be somewhat difficult, in that this animal model lacks the flap valve characteristics of a normal human PFO. However, there are two case reports^{17,18} describing patients with large interatrial openings in which catheters were passed into both right and left atria, permitting simultaneous pressure measurements. Interestingly, in both of these patients the interatrial pressure gradient was right to left, and, in the first report,¹⁷ the gradient was diminished and reversed during mechanical inspiration, although increasing levels of PEEP did appear to increase the mean right-to-left gradient. In the second report,¹⁸ the right-to-left pressure gradient also increased with increasing PEEP, but no measurements were reported during mechanical ventilation. Again, extrapolation of these data to the normal heart would be difficult.

In conclusion, the current case report demonstrates two other means whereby a right-to-left intracardiac shunt, which may permit paradoxical embolization, could be induced during general anesthesia: as a result of either 1) mechanical ventilation or 2) the steady application of PEEP. A complete understanding of the mechanisms underlying these observations must await experimental studies. It is noteworthy, however, that both PEEP and the inspiratory phase of positive pressure ventilation may be associated with an increase in pulmonary vascular resistance that could produce a reversal of the normal left-to-right interatrial pressure gradient. Regardless of the physiologic mechanism, this report should serve to emphasize the importance of scrupulous attention to detail in the prevention of venous embolization in all patients in whom mechanical ventilation or moderate levels of PEEP during general anesthesia are used.

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