Incidence of Venous Air Embolism during Craniectomy for Craniosynostosis Repair

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Background: Investigations to determine the incidence of venous air embolism in children undergoing craniectomy for craniosynostosis repair have been limited, although venous air embolism has been suspected as the cause of hemodynamic instability and sometimes death. A precordial Doppler ultrasonic probe is an accepted method for detection of venous air embolism and is readily available at most institutions.

Methods: A prospective study was conducted using a precordial Doppler ultrasonic probe in children undergoing craniectomy for craniosynostosis repair. The Doppler signal was continuously monitored intraoperatively for characteristic changes of venous air embolism. A recording was made of the precordial Doppler probe pulses, which was later reviewed by a neuroanesthesiologist, blinded to the intraoperative events. This information was correlated with the intraoperative events and episodes of venous air embolism were graded.

Results: Twenty-three patients were enrolled in the study during the 2-yr study period. Nineteen patients (82.6%) demonstrated 64 episodes of venous air embolism; six patients (31.6%) had hypotension associated with venous air embolism. Thirty-two episodes of hypotension were demonstrated in eight patients (34.7%). None of the patients developed cardiovascular collapse.

Conclusion: The incidence of venous air embolism in our study of 23 children undergoing craniectomy for craniosynostosis was 82.6%. Though most episodes of venous air embolism during craniosynostosis repair are without hemodynamic consequences, the preemptive placement of a precordial Doppler ultrasonic probe is a noninvasive, economic, and safe method for the detection of venous air embolism. Prompt recognition may allow for the early initiation of therapy, thereby decreasing morbidity and mortality rates related to venous air embolism.

(Key words: Children; hypotension; intervention; precordial Doppler ultrasonic probe.)

INVESTIGATIONS to determine the incidence of venous air embolism (VAE) in children undergoing cranietomy for craniosynostosis repair have been limited. A few case reports have suggested VAE as the cause of hemodynamic instability and sometimes death in these surgical patients.1–3 Recent advances in the surgical management of craniosynostosis and the potential for greater blood loss with the more involved surgical procedures may further predispose these children to VAE.5,6 The anatomic and physiologic characteristics of younger surgical patients may make VAE more likely and the consequences even more devastating.7–9

A precordial Doppler ultrasonic probe is an accepted method for the detection of VAE and is readily available at most institutions.10,11 The routine placement of a precordial Doppler probe in patients undergoing craniectomy allows continuous monitoring for characteristic changes that suggest VAE. Identification of VAE in children undergoing craniectomy for craniosynostosis allows better perioperative care in this subset of surgical patients.

Methods

After institutional review board approval and parental consent, 23 children undergoing surgical repair for craniosynostosis from August 1, 1996, through October 1, 1998, were enrolled in this prospective study. After induction of anesthesia, routine monitors and a precordial Doppler ultrasonic probe were placed. Anesthesia was maintained with isoflurane or halothane in oxygen and air. End-tidal carbon dioxide and nitrogen concentrations were monitored. However, because all patients...
received a mixture of oxygen and air, end-tidal nitrogen was not considered to be a sensitive monitor for VAE and was not recorded. Placement of an arterial catheter, a central venous line, or both was at the discretion of the attending anesthesiologist. The patients were positioned supine, prone, or modified prone as determined by the surgical procedure (table 1). After final operative positioning, the Doppler probe was secured with a clear adhesive, and correct placement was verified by rapid intravenous injection of 5–10 ml of agitated saline peripherally and the subsequent observation of characteristic Doppler tones. The precordial Doppler tones were monitored continuously during the operative procedure. Injection of fluids, blood products, or medications was designated on the audio recording by the verbal communication of the anesthesiologist. Episodes of VAE were diagnosed by characteristic changes in Doppler tones and with continuous audio recording.

The audio recording of the Doppler tones was later reviewed by an experienced neuroanesthesiologist blinded to the intraoperative events. The timing of the episode of VAE relative to the operative course was noted and correlated with data regarding blood pressure and end-tidal carbon dioxide concentration. The severity of VAE was graded according to the following scale: grade I, Doppler tone changes only; grade II, Doppler tone changes plus decreases in end-tidal carbon dioxide concentration greater than 2 mmHg; and grade III, Doppler tone changes plus a 20% decrease from baseline (preoperative) systolic arterial pressure, with or without a change in end-tidal carbon dioxide concentration. Neither anesthetic or surgical plans were altered because of a patient’s inclusion in this study.

Several therapeutic maneuvers were used simultaneously intraoperatively with the detection of hemodynamically significant air. The maneuvers used to treat VAE were administration of fluid, often packed erythrocytes; application of bone wax; and flooding the surgical field. Procedures such as lowering the surgical field and the aspiration of air from a right atrial catheter were not performed.

**Table 1. Percentage of Patients Undergoing Different Surgical Procedures for Craniosynostosis**

<table>
<thead>
<tr>
<th>Suture</th>
<th>% of Patients (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal</td>
<td>47.8 (11)</td>
</tr>
<tr>
<td>Bicornal</td>
<td>26 (6)</td>
</tr>
<tr>
<td>Metopic</td>
<td>13 (3)</td>
</tr>
<tr>
<td>Coronal</td>
<td>8.6 (2)</td>
</tr>
<tr>
<td>Lambdoidal</td>
<td>4.3 (1)</td>
</tr>
</tbody>
</table>

**Statistical Analysis**

Episodes of hypotension, VAE, or both are designated as median values with a measure of variance (25–75% percentiles).

**Results**

Evidence of VAE was demonstrated in 19 patients (82.6%), of whom 6 (31.5%) developed hypotension associated with VAE. There were 64 total episodes of VAE, with hypotension occurring in 10 (15.6%) of the episodes (fig. 1). Hypotension was demonstrated in eight (34.7%) patients, with a total of 32 episodes (fig. 2). Ten episodes of hypotension (31%) were associated with VAE. None of the patients developed cardiovascular collapse. The median number of VAE episodes per surgical procedure was 2.0 (range 0–8), and the median number of hypotension episodes per surgical procedure was 0.0 (range 0.0–1.7).

**Discussion**

The incidence of VAE in our study (82.6%) was greater than previously reported (66%) and greater than that reported with suboccipital craniotomy in children (33%). Intraoperative hypotension in our study associated with VAE (31.5%; 6/19 patients with VAE) was less frequent than previously reported in children (69%) but similar in frequency to adult patients (36%). Interestingly, only one third of the total episodes of intraoperative hypotension were associated with VAE. Clinical factors predisposing children to VAE such as age, weight,
estimated blood loss, and suture involvement could not be determined from this study. However, large blood losses are inevitable with the surgical repair of craniosynostosis and are the likely cause for most episodes of hypotension.

Venous air embolism may occur during any operative procedure in which the operative site is above the level of the heart and noncollapsible veins are exposed to air. With the operative site above the level of the heart, a pressure gradient may develop that favors air entry rather than bleeding if a vein is opened. A 5-cm gradient is sufficient to entrain air in a patient undergoing a neurosurgical procedure.\(^{13}\) VAE occurs in approximately 10–17% of craniotomies performed in the prone position and is a more common complication in the sitting position (42%).\(^{11,13,14}\)

Children undergoing craniectomy in the supine position may be more predisposed to VAE compared with adults for several reasons. When infants are supine, their larger heads relative to their weights unintentionally may be positioned above the heart. Because of the highly vascular nature of the infant scalp, rapid hemorrhage is not unusual.\(^{7,8}\) Rapid blood loss can lead to a decrease in central venous pressure and the development of a pressure gradient between the right atrium and the surgical site favoring entrainment of air. Thus, hypotension associated with blood loss may precede VAE. Hypotension with VAE may be more pronounced in children because the volume of entrained air is greater in comparison to their cardiac volume. The persistence of a patent foramen ovale in 50% of children younger than 5 yr of age may increase the potential for paradoxic air embolism.\(^{9,15}\)

Several monitors have been used to detect VAE: transesophageal echocardiography, precordial Doppler probe monitoring, end-tidal nitrogen concentration, end-tidal carbon dioxide concentration, transcutaneous oxygen saturation, central venous pressure monitoring, and esophageal stethoscope monitoring. The most sensitive monitors are the transesophageal echocardiogram and the precordial Doppler probe.\(^{10,11,14,16}\) Precordial Doppler monitoring is inexpensive, noninvasive, and very sensitive, but not specific, in the detection of VAE. Continued experience in using the precordial Doppler probe and increased familiarity with the changes in Doppler tones has allowed early detection of VAE.

Routine use of the precordial Doppler probe in procedures such as posterior fossa craniotomy in the sitting position resulted in an increased incidence of VAE detection.\(^{14}\) Also, a dramatic reduction in the morbidity rate related to VAE and near elimination of deaths resulting from VAE resulted from the routine use of a precordial Doppler probe in these patients. Before routine use of precordial Doppler probes during sitting posterior fossa craniotomy, the incidence of VAE was reported as 1–15%, with a mortality rate of 0–73% and major morbidity rate of 25%.\(^{16}\) With the routine use of a precordial Doppler probe, VAE is detected in 43–45% of patients, with major morbidity and mortality rates reported as 0–1%.\(^{14}\) It is likely that the same is true with craniosynostosis repair. Routine use of a precordial Doppler probe could be expected to result in a significant increase in

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**Fig. 2.** Number of hypotension and venous air embolism (VAE) episodes according to cranial suture involved in surgical repair (mean ± SEM). The cranial suture involved in surgical repair is designated on the x-axis. Proceeding from left to right for each cranial suture is the median number of episodes of VAE per hour, total number (median) of VAE episodes, the median grade of VAE, the median number of hypotension episodes (with or without VAE) per hour, and the total number of hypotension episodes (with or without VAE).
diagnosis of VAE, allowing for prompt treatment before the development of clinical signs of VAE. This would in turn be expected to result in the reduction of morbidity and mortality rates related to VAE.

Venous air embolism might have been the cause of fewer than one third of the hypotensive episodes in our study. Craniosynostosis is associated with a large blood loss and frequent hypotensive episodes. Consequently, VAE might be overlooked as a possible cause of intraoperative hypotension in these patients if precordial Doppler monitoring is not utilized. Volume replacement for suspected hypovolemia is only one of the appropriate treatments if VAE is occurring; elimination of air entrainment by the surgeon is crucial. Without precordial Doppler monitoring, VAE might not be recognized.

Venous air embolism is common in the surgical repair of craniosynostosis. VAEs can be quickly detected with the preemptive placement of a precordial Doppler probe. Early detection of VAE can expedite therapeutic maneuvers, such as elimination of the source of VAE and replacement of intravascular volume. Interventions such as these potentially attenuate the incidence of hemodynamic instability in this subset of surgical patients.

References