

Anesthesiology
64:541-545, 1986

Transesophageal Echocardiography and Transcutaneous O₂ and CO₂ Monitoring for Detection of Venous Air Embolism

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The sensitivities of current monitoring methods for detection of air embolism were compared in eight anesthetized dogs. Air was infused at controlled rates of 0.001 and 0.005 ml · kg⁻¹ · min⁻¹ for 1 min; 0.01, 0.05, 0.1, 0.2, and 0.4 ml · kg⁻¹ · min⁻¹ for 6 min; and 5 ml · kg⁻¹ bolus injection. Based on the mean quantity of air infused to elicit a positive response, the monitors could be placed into three significantly different sensitivity groups. Transesophageal echocardiography (TEE) and precordial Doppler ultrasound were the most sensitive monitoring methods detecting 0.19 and 0.24 ml · kg⁻¹ of air, respectively. TEE detected air during six infusions in which the Doppler failed to do so. The next most sensitive group of monitoring methods included pulmonary artery pressure (PAP), end-tidal CO₂ (PETCO₂), arterial oxygen tension (PaO₂), and transcutaneous oxygen tension (PtcO₂). The mean quantity of air infused to elicit a positive response in this group of monitors ranged from 0.61 to 0.76 ml · kg⁻¹. The response of PtcO₂, PaO₂, PETCO₂, and PAP equally reflected the quantity of air infused. The least-sensitive group of methods included arterial and transcutaneous carbon dioxide tension and systemic arterial blood pressure. These data indicate that TEE is more sensitive than Doppler ultrasound and that PAP, PETCO₂, and PtcO₂ are equally sensitive in detecting venous air embolism in the dog. (Key words: Carbon dioxide: transcutaneous. Embolism: air. Monitoring: carbon dioxide; echocardiography; oxygen. Oxygen: transcutaneous.)

MONITORING FOR AIR EMBOLISM is an important component of anesthetic care of patients in the sitting position. The combination of a Doppler ultrasound and either end-tidal carbon dioxide (PETCO₂) measurement or mean pulmonary artery pressure (PAP) monitoring has become a standard monitoring approach for detecting air embolism. The sensitivities of these routinely used monitoring methods for detecting air embolism were previously com-

pared in dogs by English *et al.*¹ Since that work, transesophageal echocardiography (TEE), transcutaneous oxygen (PtcO₂), and transcutaneous carbon dioxide (PtcCO₂) monitoring have become available for use in the operating room and each has been shown clinically to detect venous air embolism or the accompanying physiologic changes.^{2,3}

The following study was designed to evaluate the monitoring methods currently available to detect venous air embolism, determining the sensitivity of each method and its ability to reflect the volume of air infused. The newer methods (TEE, PtcO₂, and PtcCO₂) were compared with methods currently used clinically (Doppler ultrasound, PETCO₂, and PAP).

Methods

Subjects were eight mongrel dogs weighing 15.2–23.5 kg (mean 17.2 kg). Anesthesia was induced with pentobarbital 30 mg · kg⁻¹ iv and maintained with pentobarbital 5 mg · kg⁻¹ as needed. Following tracheal intubation the lungs were ventilated with a volume-cycled ventilator at a tidal volume of 10 ml · kg⁻¹. Respiratory rates of 8–12 cycles · min⁻¹ were used to maintain baseline arterial carbon dioxide (PaCO₂) tension between 35–45 mmHg. Muscle paralysis was achieved with pancuronium 0.1 mg · kg⁻¹, which was repeated as necessary. Four dogs received 50% oxygen in nitrogen, and four dogs received 100% oxygen. All dogs remained in a supine position throughout the study and were heparinized.

A 7-Fr balloon-tipped catheter was placed into the pulmonary artery *via* the right external jugular vein and an 18-g Teflon® catheter was placed in the femoral artery. Both catheters were connected to calibrated Gould-Statham P23ID® transducers. Systemic arterial and pulmonary artery pressures were recorded on a multichannel recorder. A calibrated infrared CO₂ analyzer (Beckman Instruments, Inc., Fullerton, CA) was used to measure PETCO₂ from a sample catheter placed just proximal to the endotracheal tube.

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Received from the Department of Anesthesiology, Mayo Clinic, 200 First Street SW, Rochester, Minnesota 55905. Accepted for publication November 11, 1985. Supported in part by NIH grant NS-7507 from the National Institutes of Health, Public Health Service.

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The chest was shaved and the skin was cleansed with a detergent followed by alcohol. Transcutaneous O₂ and CO₂ electrodes were placed on the chest following two-point calibration. The Ptc_{CO₂} monitor automatically divided the actual Ptc_{CO₂} value by a 1.6 correction factor, and the corrected values are reported in this study. The 1.6 correction factor is based on the observed difference between transcutaneous and arterial carbon dioxide values obtained from the literature and our previous experience.³ A Doppler ultrasonic flow transducer (Medasonics, Mountain View, CA) was positioned over the right heart chambers so that a 10 ml agitated saline injection delivered to the right atrium would produce an audible change in frequency. A 3.5 MHz TEE echocardiographic probe (Diasonic, Inc., Milpites, CA) interfaced with a 3400 Diasonics® phased array sector ECHO instrument was positioned to view the right ventricular outflow tract. Arterial blood oxygen tension (Pa_{O₂}) and Pa_{CO₂} were measured with an Instrumentation Laboratory 1303® blood gas analyzer.

During air infusion, the monitoring methods compared included: precordial Doppler ultrasound, TEE, PAP, Pa_{O₂}, Pa_{CO₂}, Ptc_{O₂}, Ptc_{CO₂}, PET_{CO₂}, and mean systemic arterial pressure (MAP). Real-time TEE and Doppler changes were monitored by blinded, experienced observers at the start of each infusion. Air was infused into the superior vena cava or right atrium at controlled rates by a Harvard® infusion pump through the proximal port of the pulmonary artery catheter. Initial rates were 0.001 ml · kg⁻¹ · min⁻¹ and 0.005 ml · kg⁻¹ · min⁻¹ for 1 min. Arterial samples were not obtained with these infusions because physiologic changes were not expected to occur at such low doses. The order of the subsequent rates were randomly chosen and included 0.01, 0.05, 0.1, 0.2, and 0.4 ml · kg⁻¹ · min⁻¹ for 6 min. A bolus of 5 ml · kg⁻¹ was given at the termination of the study in seven of eight dogs. Arterial blood gas samples were obtained prior to each infusion and 1, 3, 6, and 12 min after the start of each infusion. Ptc_{O₂}, Ptc_{CO₂}, PAP, and MAP were continuously recorded and PET_{CO₂} was tabulated at each 15-s interval. All variables were allowed to return to baseline levels before a subsequent infusion was begun.

Positive responses were arbitrarily defined prior to the start of the study and consisted of an increase in PAP of ≥3 mmHg; a decrease in MAP of ≥10 mmHg; a decrease in Pa_{O₂} or Ptc_{O₂} of ≥5 mmHg; a decrease in PET_{CO₂} of ≥3 mmHg; and an increase in Pa_{CO₂} or Ptc_{CO₂} of ≥3 mmHg. A positive response on Doppler ultrasound was the presence of an unmistakable audible change in frequency and on TEE was the visualization of densities consistent with air bubbles in the right cardiac chambers or outflow tract.

Skin preparation and transcutaneous electrode application were more difficult in dogs than in humans. Because

of poor electrode-skin contact, the Ptc_{O₂} erroneously drifted downward on occasion. The Ptc_{O₂} was labeled as malfunctioning if the Ptc_{O₂} did not reach a baseline prior to air infusion or if following an air infusion it continued to drift downward without returning toward baseline. Ptc_{O₂} data from that injection were eliminated from data analysis, and the Ptc_{O₂} electrode was repositioned.

The quantity of air infused to elicit a positive response for each monitoring method was summed for all 6-min infusions. A mean was calculated and used as a measure of a monitor's sensitivity in detecting air embolism. Differences between monitoring methods in the quantity of air producing a positive response were tested by a one-way analysis of variance and least significant difference procedure.⁴ Differences between those dogs receiving 50% oxygen and those dogs receiving 100% oxygen were tested by Student's *t* test for independent samples. The maximum response of each numerically quantitated monitoring method at each air infusion was calculated. The relationship of the dose of air to the magnitude of the monitor response in each subject was analyzed with simple linear regression and trend analysis.⁵ The relationship between arterial and transcutaneous gas tension values was analyzed with simple linear regression and correlation analysis. A *P* value < 0.05 was considered significant. Means ± SD are given.

Results

The air injection rates at which the different monitors developed a consistently positive response are presented (table 1). To allow a statistical comparison of the monitoring methods, the mean quantity of air infused to elicit a positive response was calculated for each monitor (table 2). Based on the mean quantity of air infused to elicit a positive response, the monitors could be placed into three significantly different sensitivity groups: TEE and Doppler demonstrated the greatest sensitivity; PAP, PET_{CO₂}, Pa_{O₂}, and Ptc_{O₂} demonstrated intermediate sensitivity; and Pa_{CO₂}, MAP, and Ptc_{CO₂} were least sensitive.

TEE and Doppler detected 0.19 and 0.24 ml · kg⁻¹ of air, respectively. TEE detected air during six infusions ranging from 0.001 to 0.01 ml · kg⁻¹ · min⁻¹ in which the Doppler failed to do so. There were no infusions in which the Doppler was positive and the TEE was not. The smallest amount of air detected by TEE was 0.02 ml over 1 min, and the smallest amount of air detected by Doppler was 0.12 ml over 40 s.

Among the next most-sensitive group of monitoring methods, the mean quantity of air infused to elicit a positive response ranged from 0.61 to 0.76 ml · kg⁻¹. While Ptc_{O₂} and Pa_{O₂} had more positive responses than PAP and PET_{CO₂} at 0.05 ml · kg⁻¹, Ptc_{O₂} and Pa_{O₂} did not become consistently positive until 0.4 ml · kg⁻¹ · min⁻¹.

TABLE 1. Percentage of Dogs Showing Positive Response (n = 8)

Monitoring Method and Positive Test Criteria	Volume of Air Infused						
	<0.005*	0.01†	0.05‡	0.1‡	0.2‡	0.4‡	5.0‡
Transesophageal echocardiography§	14	57	86	71	100	100	100
Precordial Doppler ultrasound	0	25	62	75	100	100	100
PAP ≥ 3 mmHg	0	12	12	75	100	100	100
PET _{CO₂} ≥ 3 mmHg	0	0	38	63	100	100	100
Pa _{O₂} ≥ 5 mmHg	—	0	50	50	75	100	100
Ptc _{CO₂} ≥ 5 mmHg¶	0	0	50	67	80	100	100
Pa _{CO₂} ≥ 3 mmHg	—	0	25	25	62	100	100
MAP ≥ 10 mmHg	0	0	0	12	50	75	100
Ptc _{CO₂} ≥ 3 mmHg	0	0	0	25	50	75	100

PAP = pulmonary artery pressure; PET_{CO₂} = end-tidal CO₂ tension; Ptc_{CO₂} = transcutaneous oxygen tension; MAP = mean arterial pressure; Ptc_{CO₂} = transcutaneous carbon dioxide tension.
* ml · kg⁻¹ for 1 min.

† ml · kg⁻¹ · min⁻¹ for 6 min.
‡ ml · kg⁻¹ bolus.
§ n = 7.
¶ n = 6 to 8.

There was not a significant difference in the mean quantity of air infused to elicit a positive response in Pa_{O₂} or Ptc_{CO₂} between the dogs receiving 50% oxygen and those receiving 100% oxygen.

Among the least-sensitive group of monitoring methods, the mean quantity of air infused to elicit a positive response ranged from 1.15 to 1.54 ml · kg⁻¹. Pa_{CO₂} became consistently positive at the 0.4 ml · kg⁻¹ · min⁻¹ infusion, while MAP and Ptc_{CO₂} did not become consistently positive until the 5 ml · kg⁻¹ bolus injection.

Ptc_{CO₂} malfunctioned in 11 of 47 air infusions, and the Ptc_{CO₂} data from these infusions were excluded from data analysis. There was a significant correlation between Ptc_{CO₂} and Pa_{O₂} for all observations (r = 0.92). The maximum Ptc_{CO₂} response during each infusion significantly correlated with the maximum Pa_{O₂} response (r = 0.89).

Ptc_{CO₂} correlated significantly with Pa_{CO₂} (r = 0.66), and the maximum Ptc_{CO₂} response during each infusion significantly correlated with the maximum response in Pa_{CO₂} (r = 0.87). Onset of changes in Ptc_{CO₂} usually followed the corresponding change in Pa_{CO₂}.

There was a direct incremental relationship between volume of air infused and magnitude of response of each numerically quantitated monitor. Among the more sensitive monitors, the response of Ptc_{CO₂}, Pa_{O₂}, PET_{CO₂}, and PAP equally reflected the volume of air infused (figure 1, table 3). However, PET_{CO₂} and PAP often defined the magnitude of a response sooner than Ptc_{CO₂}, particularly following the 5 ml · kg⁻¹ bolus air injection. Trend analysis indicated the relationships depicted in figure 1 were highly significant (P < 0.001) for all four monitoring methods. Regression analysis of the maximum monitor response

TABLE 2. Sensitivity of Air Embolism Monitoring Methods

Sensitivity	Monitoring Method	Mean Quantity of Air to Elicit Positive Response (±SD) (ml · kg ⁻¹)
Greatest*	Transesophageal echocardiography	0.19 ± 0.25
	Precordial Doppler ultrasound	0.24 ± 0.33
Intermediate	PAP	0.61 ± 0.37
	PET _{CO₂}	0.63 ± 0.23
	Pa _{O₂}	0.71 ± 0.54
	Ptc _{CO₂}	0.76 ± 0.58
Least	Pa _{CO₂}	1.15 ± 0.76
	MAP	1.16 ± 0.76
	Ptc _{CO₂}	1.54 ± 0.70

See table 1 for abbreviations.

* All three groups are significantly different (P < 0.05) by one-way analysis of variance and least significance difference analysis.

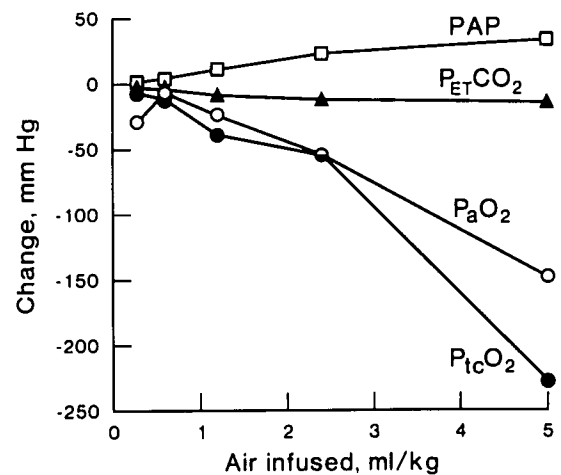


FIG. 1. Maximal response of pulmonary artery pressure (PAP), end-tidal CO₂ (PET_{CO₂}), arterial oxygen tension (Pa_{O₂}), and transcutaneous oxygen tension (Ptc_{CO₂}) to air infusion.

TABLE 3. Maximal Change in Monitoring Method Induced by Air Infusion

Monitoring Method (mmHg)	Rate of Air Infusion (ml · kg ⁻¹ · min ⁻¹ for 6 min)					5 ml · kg ⁻¹ Bolus
	0.01	0.05	0.1	0.2	0.4	
PAP	0.5	0.4	3.1	11.6	22.1	32
PET _{CO₂}	0	2.1	4.7	9.2	12.4	15.9
Pa _{O₂}	0	28.1	5.4	23.8	54.2	148
Ptc _{CO₂}	0	7.2	12.5	39.6	54.4	226

See table 1 for abbreviations.

versus dose of air for each dog provided consistently positive slopes for PAP and consistently negative slopes for PET_{CO₂}, Ptc_{CO₂}, and Pa_{O₂} (fig. 2). There was considerable variation in Ptc_{CO₂} and Pa_{O₂} response to a given volume of air. There was not a significant difference in magnitude of response in Pa_{O₂} or Ptc_{CO₂} between the dogs receiving 50% oxygen and those receiving 100% oxygen.

The time required for each monitor to return to baseline values following air injection was not specifically studied. However, PET_{CO₂} and PAP usually approached baseline values sooner than Ptc_{CO₂}. Twelve minutes following the 5 ml · kg⁻¹ bolus injection, PET_{CO₂}, PAP, and Ptc_{CO₂} had returned to within 23%, 31%, and 47% of baseline values. A typical response following the cessation of air infusion is depicted in figure 3.

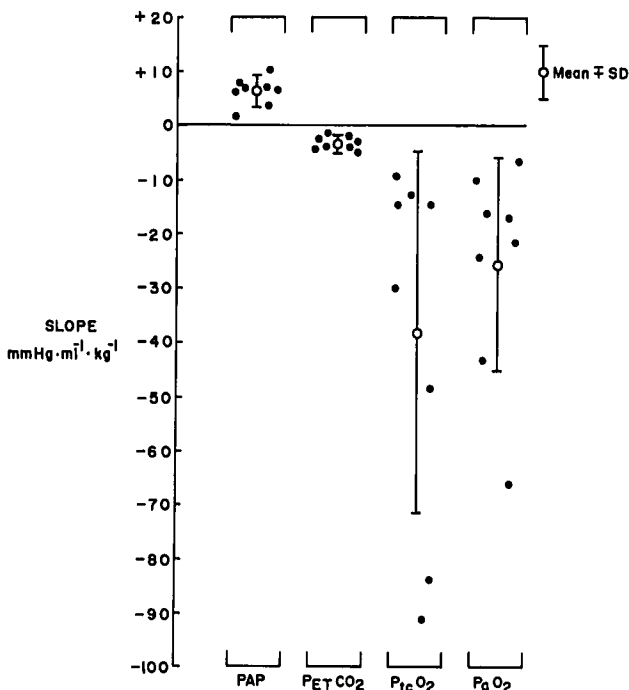


FIG. 2. Slopes (mmHg · ml⁻¹ · kg⁻¹) from regression analysis of the maximum monitor response versus dose of air for each dog.

PAP, mm Hg	17	33	32	26	24
P _{ET} CO ₂ , mm Hg	27	9	15	17	24

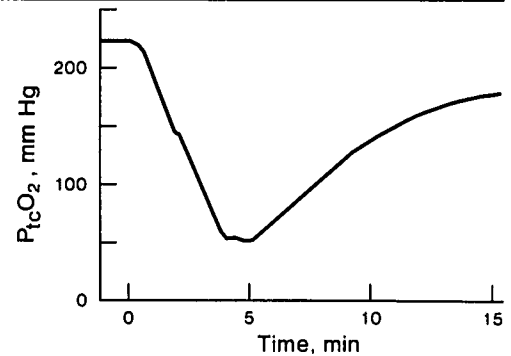


FIG. 3. Relationship of mean pulmonary artery pressure (PAP), end-tidal CO₂ (PET_{CO₂}), and transcutaneous O₂ (Ptc_{O₂}) following a 5 ml · kg⁻¹ bolus of air. PAP and PET_{CO₂} values are noted at baseline and 1, 3, 6, and 12 min following air injection. Ptc_{O₂} is a continuous tracing.

Discussion

Clinical venous air embolism generally occurs as air enters an open vein at a slow rate until significant physiologic changes occur.^{6,7} The pathophysiology of slow air infusion has been shown to be different from that of a rapid bolus of air.⁷ Methods monitoring the accompanying physiologic changes might, therefore, be expected also to show a different response. To simulate the usual clinical course of air embolism, slow continuous air infusions were used in our study. This differs from the previous work of English *et al.*,¹ who used a more rapid rate of air injection (1 ml · s⁻¹).

Criteria for positive monitor responses were chosen to be in close agreement with the criteria used by English *et al.* except for Pa_{O₂}. A decrease of 25 mmHg in Pa_{O₂} was defined as a positive response in their study. Ptc_{CO₂} allowed continuous assessment of Pa_{O₂}, and we found in both the operating room and the animal laboratory that a decrease of 5 mmHg reliably indicated a change in baseline oxygenation. For this reason, a 5-mmHg decrease in Pa_{O₂} or Ptc_{CO₂} was defined as a positive response.

In spite of differences in methodology, our statistically significant grouping of the monitoring methods was quite similar to the four groups of monitoring methods outlined by English *et al.* An exception was the increased sensitivity of Pa_{O₂} likely due to the differences in criteria for a positive response. Adding TEE, Ptc_{CO₂}, and Ptc_{CO₂} to the monitoring method grouping places TEE as the most sensitive detector of air embolism.

TEE has been used in the clinical setting and is at least as sensitive as Doppler ultrasound in detecting air embolism.² Our data confirmed that TEE was more sensitive than Doppler ultrasound when both were used simulta-

neously to detect known quantities of injected air. Because both units detected small quantities of air prior to physiologic changes, the difference in sensitivities between TEE and Doppler may not be clinically important. However, TEE offers the additional advantage of detecting left-sided cardiac air. It is possible that the early detection of paradoxical air embolism may help prevent morbidity or mortality from systemic arterial air embolism.

TEE, as well as the Doppler, cannot quantitate the size of the air embolism. Likewise, neither monitor can reliably detect the cessation of air entry into the venous system. A continued positive response of TEE and Doppler commonly occurred following discontinuation of the air infusion. Air bubbles could be seen on TEE for 6 to 8 min following the 0.2 and 0.4 ml · kg⁻¹ · min⁻¹ infusions. Air was likely trapped in the superior vena cava or right atrial appendage and intermittently escaped from these sites. Martin *et al.* have demonstrated similar detainment and entrapment of air for 3 to 24 min following air injection.^{8,9}

Our data showed that Ptc_{O₂} was as sensitive as PAP and PET_{CO₂} in detecting air infusion and equally reflected the quantity of air infused. All three methods detected air infusion well before changes in MAP occurred. Following larger doses of air (5 ml · kg⁻¹), which presumably decreased cardiac output, the Ptc_{O₂} decrease was disproportionately greater due to a presumed decrease in peripheral perfusion. The duration of positive response for a given air infusion was usually longer for Ptc_{O₂} than for either PAP or PET_{CO₂}, suggesting that altered pulmonary physiology persists even after PAP and PET_{CO₂} return to normal.

Ptc_{O₂} has been shown to be useful in detecting venous air embolism in the clinical setting, decreasing early during the course of air embolism.³ Advantages of Ptc_{O₂} monitoring for the detection of air embolism include: 1) it is noninvasive; 2) it provides the most relevant information about the degree of immediate physiologic threat to the patient; and 3) it provides continuous assessment of oxygenation. Disadvantages of Ptc_{O₂} monitoring include the requirement for calibration every 4–6 h and its technical complexity compared with PET_{CO₂} monitoring. Ptc_{CO₂} can reliably reflect the changes in Pa_{CO₂} during air embolism. However, the relatively slow response time of Ptc_{CO₂} prevents it from being useful as an early indicator of air embolism.

The ideal monitor for detecting air embolization should: 1) be sensitive and specific; 2) quantitate the size of the air embolism; 3) detect early physiologic changes secondary to the air embolism; and 4) provide information on the cessation of air entrapment. No single monitor

meets these requirements. TEE and Doppler are the most sensitive monitors but lack the ability to quantitate the amount of air or detect physiologic changes. PAP, PET_{CO₂}, and Ptc_{O₂} are equally able to quantitate the size of the air embolism and provide information on the cessation of air entrapment. This study did not address specificity of the monitoring techniques. Clinical settings other than air embolism can alter PAP, PET_{CO₂}, or Ptc_{O₂}. Changes in these values must be interpreted in light of changes in the TEE or Doppler to prevent false positive diagnosis of air embolism. Therefore, a combination of two or more monitors should be used to detect air embolism. Our data would suggest that TEE or Doppler along with PAP, PET_{CO₂}, or Ptc_{O₂} would provide the proper combination of monitoring to detect air embolism. This combination of monitors would be exquisitely sensitive, quantitate the size of the air embolism, detect early physiologic changes, and provide information regarding the cessation of air entrapment.

We conclude that TEE and Ptc_{O₂} are reliable and sensitive detectors of air embolism. TEE is both more sensitive than Doppler in detecting air and offers the advantage of detecting left-sided cardiac air. Ptc_{O₂} will reflect the decrease in Pa_{O₂} that accompanies air embolism and can be used as a monitor for detecting venous air embolism.

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