Cardiovascular Pressures With Venous Gas Embolism And Decompression

B. D. BUTLER, Ph.D., R. ROBINSON, M.D., T. SUTTON, P.A., and G. B. KEMPER, Ph.D.

VENOUS GAS EMBOLISM (VGE) is commonly reported with decompression to lowered ambient pressures, as experienced by divers, astronauts, and aviators. These circulating bubbles ultimately become trapped within the lungs where they are excreted via the airways or dissolved in the blood. Although decompression-induced venous bubbles may be associated with

From the Department of Anesthesiology, The University of Texas Medical School, Houston, TX and Armstrong Laboratory (AFMC), Brooks AFB, TX.

This manuscript was received for review in March 1994. It was revised in June and August 1994. It was accepted for publication in August 1994.

Address reprint requests to B. D. Butler, Ph.D., Department of Anesthesiology, University of Texas Medical School, 6431 Fannin, MSB 5.020, Houston, TX 77030.
mine at what point the left to right atrial pressure gradients were likely to reverse.

MATERIALS AND METHODS

Venous Gas Infusions

Surgery: Twenty-two mongrel dogs (22 ± 6 kg) of both sexes were fasted for 24 h, anesthetized with pentobarbital sodium (25 mg • kg⁻¹ IV) and maintained with 10 mg • h⁻¹. The dogs were intubated and mechanically ventilated with air at a tidal volume (~15 ml • kg⁻¹) and frequency (~10–14 breaths • min⁻¹) adequate to maintain baseline arterial carbon dioxide (Paco₂) tensions between 30–45 mm Hg. Polyvinyl catheters were placed into the abdominal aorta via the left femoral artery for measurement of mean arterial blood pressure (MAP), in the right atrium (RAP), and the pulmonary artery via the right jugular vein (PAP), the right ventricle via the right carotid artery for left ventricular end-diastolic pressure (LVEDP), as an indirect measure of left atrial pressure (LAP), and the inferior vena cava via the left femoral vein for venous access. Airway pressure was measured from the proximal end of the endotracheal tube. The catheters, excepting the airway, were fluid-filled with degassed heparinized saline and connected to calibrated pressure transducers, zero referenced at the right atrial level. Cardiac output (Q) was measured using thermodilution techniques. Arterial blood gases were measured at baseline and hourly thereafter. End-tidal carbon dioxide (PETCO₂) and arterial oxygen saturation (Sao₂) were continuously measured (Nellcor, N-1000, Pleasanton, CA).

Gas infusions: Following stabilization (30–45 min) and collection of baseline data, air was infused into the right atrium for 180 min using a volume-controlled reciprocating servo pump (Harvard, South Natick, MA). The dogs in the gas infusion studies were subdivided into three experimental groups (n = 6 each), depending upon the gas infusion dose and one control group (n = 4). The three gas doses were 0.025, 0.05 and 0.15 ml • kg⁻¹ • min⁻¹. Hemodynamic measurements were collected throughout the gas infusion and for a 60 min post infusion period. Q and blood gases were measured every 60 min. Each dog received the VGE infusion for 180 min only once. The hearts were inspected post mortem for the presence of an ASD. Arterialization of the VGE was not examined in any of the experimental groups.

Hyperbaric Decompression

Six dogs were prepared as previously described with the addition of placement of an ultrasonic Doppler probe around the inferior vena cava via laparotomy to detect VGE that formed as a result of the decompression. The probe signal was range gated to maximize the reflected audible signal representing bubble recordings. Decompression bubble signals were evaluated semi-quantitatively according to Grades 1–4 using a modified Spencer code (29) which consisted of periodic audio sampling at resting conditions and following passive deep knee bends, with the bubble score recorded as the peak value obtained in the two conditions. Although passive knee bends do not fully simulate their active counterpart, in all cases significant bubble showers were detected by Doppler. In some cases, the signals were recorded on cassette for playback analysis or digitized directly for computer-assisted evaluation. The instrumented animals were placed in the experimental compression chamber, ventilation was switched to a pneumatic-driven time cycled ventilator (Bird, Mark 14, Palm Springs, CA) and compressed to 2.84 bar (60 ft of sea water, fsw) at 0.37 bar • min⁻¹ (12 fsw • min⁻¹) for 120 min, then decompressed to sea level at 0.92 bar • min⁻¹ (30 fsw • min⁻¹). The animals were then immediately removed from the chamber and monitored post dive for 90 min.

Altitude Studies

Six dogs were prepared as previously described, including the vena caval Doppler probe. LVEDP was measured with a non fluid-filled transducer-tipped catheter (Millar Instr., Houston, TX). Tetanic muscle stimulation was used while at altitude to release venous bubbles trapped within the capillary beds of the left hind limb for the Doppler detection. The dogs were placed into the altitude chamber and all pressure and Doppler monitors connected to through-pass devices for continuous recordings. Following baseline data collection the dogs were decompressed to 40,000 ft (4,000 ft • min⁻¹) for 180 min. The animals were ventilated with room air to 20,000 ft and then switched to 100% oxygen thereafter. No oxygen pre-breathing was administered. The animals were then recompressed to sea level at 10,000 ft • min⁻¹. Monitoring was continued throughout the altitude simulation and until no further VGE could be detected by the Doppler, usually not exceeding 45 min. The breathing gas was switched back to air at 20,000 ft during decent.

All procedures were approved by The University of Texas-Houston Animal Care and Use Committee, and the animals were handled in accordance with the National Institutes of Health "Guide for the Care and Use of Laboratory Animals."

Statistics

Data are expressed as mean ± SEM. Data were analyzed using analysis of variance (ANOVA) with post-hoc comparisons made using Bonferroni-corrected Student's t test; p < 0.05 was considered statistically significant.

RESULTS

Venous Gas Infusions

The hemodynamic data from the VGE studies are given in Tables I–III. Fig. 1 shows the time course of changes for PAP and RAP in both the VGE and altitude simulated decompression. PAP increased significantly with each gas dose, beginning within the first 5 min of the infusion and remaining elevated for the 180 min period. Peak increases were dose dependent with the maximum value reaching 104% above baseline (0.15 ml • kg⁻¹ • min⁻¹). RAP values were unchanged at the 0.025 dose, decreased (nonsignificant) with the 0.05
Table 1. Venous Gas Infusion Air Dose: 0.025 ml • kg\(^{-1}\) • min\(^{-1}\).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>60 Min</th>
<th>120 Min</th>
<th>180 Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAP (mm Hg)</td>
<td>165 ± 7</td>
<td>157 ± 6</td>
<td>155 ± 5</td>
<td>148* ± 6</td>
</tr>
<tr>
<td>PAP (mm Hg)</td>
<td>13.1 ± 1.2</td>
<td>16.3* ± 1.7</td>
<td>16.5* ± 1.3</td>
<td>17.3* ± 1.5</td>
</tr>
<tr>
<td>RAP (mm Hg)</td>
<td>1.3 ± 1.0</td>
<td>2.7 ± 1.4</td>
<td>2.0 ± 0.8</td>
<td>1.5 ± 0.6</td>
</tr>
<tr>
<td>LVEDP(_m) (mm Hg)</td>
<td>4.7 ± 1.2</td>
<td>4.6 ± 0.7</td>
<td>4.4 ± 0.6</td>
<td>5.1 ± 1.0</td>
</tr>
<tr>
<td>LVEDP(_s) (mm Hg)</td>
<td>5.0 ± 1.4</td>
<td>5.6 ± 1.1</td>
<td>5.8 ± 1.1</td>
<td>5.7 ± 1.0</td>
</tr>
<tr>
<td>RVP (mm Hg)</td>
<td>8.0 ± 0.5</td>
<td>10.0 ± 1.9</td>
<td>8.4 ± 1.1</td>
<td>8.9 ± 1.3</td>
</tr>
<tr>
<td>RVP(_p) (mm Hg)</td>
<td>20.3 ± 1.7</td>
<td>22.2 ± 2.9</td>
<td>20.8 ± 1.8</td>
<td>21.5 ± 1.6</td>
</tr>
<tr>
<td>LVEDP-RAP(_m) (mm Hg)</td>
<td>1.6 ± 0.5</td>
<td>2.3 ± 1.1</td>
<td>1.8 ± 0.5</td>
<td>2.2 ± 0.7</td>
</tr>
<tr>
<td>LVEDP-RAP(_s) (mm Hg)</td>
<td>3.7 ± 0.8</td>
<td>2.8 ± 1.2</td>
<td>3.8 ± 0.9</td>
<td>4.2 ± 0.7</td>
</tr>
<tr>
<td>CO (L • min(^{-1}))</td>
<td>217 ± 43</td>
<td>310 ± 21</td>
<td>395* ± 30</td>
<td>441* ± 38</td>
</tr>
<tr>
<td>PVR (dyn • s • cm(^{-1}))</td>
<td>4150 ± 276</td>
<td>4334 ± 365</td>
<td>5192 ± 525</td>
<td>5487 ± 609</td>
</tr>
</tbody>
</table>

Pressure units are mm Hg.
* p < 0.05 vs. baseline.
† LVEDP and RAP values taken at peak inspiration.
m = mean; s = systolic; d = diastolic; p = peak.

Arterial \(P_{O_2}\) was decreased (significant) with the 0.05 and 0.15 ml • kg\(^{-1}\) • min\(^{-1}\) dose and \(P_{CO_2}\) was elevated with each dose, 0.025 and 0.15 ml • kg\(^{-1}\) • min\(^{-1}\) groups achieving significance.

Hyperbaric Decompressions

MAP and HR values were not significantly changed with hyperbaric decompression (Table IV). PAP values increased to a peak 30 min post decompression (nonsignificant), and returned to baseline values over the next 60 min; RAP values were unchanged (Fig. 1). LVEDP decreased within the first 10 min post decompression (nonsignificant) and remained slightly decreased. RVP pressures were slightly decreased (nonsignificant). \(Q\) steadily decreased, reaching significance 90 min post dive. PVR increases reached peak values at 30 min post dive (155%) and remained elevated throughout the 90 min. SVR increased progressively over the 90 min post dive period. The LVEDP-RAP mean gradient decreased post decompression while never achieving a reversal in the direction of the normal gradient (Fig. 2). Arterial \(P_{O_2}\) was elevated post decompression and \(P_{CO_2}\) was unchanged. \(P_{ETCO_2}\) was decreased (significant) at 90 min, and \(S_{AO_2}\) was unchanged.

Doppler detected venous bubbles were first recorded 12.3 ± 4 min (10–18 min, range) post decompression and persisted for up to 120 min. Spontaneous bubbles were detected at a peak Grade of 2 in two dogs and Grade 3 and 4 in one dog each. Grade 4 bubbles were detected in three dogs with deep knee bends.

Altitude Simulations

The hypobaric decompression data are presented in Table V. MAP increased at 20,000 ft, possibly due in part to the systemic vasoconstriction associated with the switch to 100% oxygen ventilation, and returned to lower than baseline values upon return to sea level pressures. PAP increased progressively (significant) to 20,000 ft, decreased momentarily with the switch to oxygen ventilation then continued to rise to a peak value (106%) 180 min into the simulated flight. RAP decreased during the decompression to altitude, then increased after 60 min at 40,000 ft. RAP values at 120 and 180 min increased.
were decreased, although clotting of the venous pressure lines occurred in several incidences and were not corrected until descent (Fig. 1). RVP values increased upon ascent and remained elevated throughout the decompression. LVEDP increased over the duration of the simulated flight and during the period of maximal venous bubbling (non-significant) then returned towards baseline upon return to sea level. The LVEDP-RAP peak gradient increased throughout the decompression, returning towards baseline with recovery (Fig. 2). The LVEDP-RAP mean was never reversed, although one dog had a transient reversal upon arrival at a simulated altitude of 40,000 ft. Q was slightly decreased post decompression while PVR was increased (significant) as was SVR (non-significant). PaO₂ and PaCO₂ values were increased post decompression. Venous gas bubbles were recorded at Grades 2–4 during the simulated flights.

No animals from any of the experimental or control groups had an ASD detected at autopsy.

DISCUSSION

The results of this study demonstrated that the normal mean pressure gradient across the atria of the heart (LAP > RAP, using LVEDP as a measure of LAP) was not reversed with venous gas infusions of 0.025, 0.05 and 0.15 ml kg⁻¹ min⁻¹, or with hypo- or hyperbaric decompressions in anesthetized dogs with an intact atrial septum. Examining peak gradient changes throughout individual respiratory and cardiac cycles revealed three incidences (3%) with momentary reversals occurring during the experimental gas infusions or decompressions, out of a total of 92 recorded measurements.

This relatively low rate for atrial pressure gradient reversal with VGE or decompression is consistent with reported findings that patients with a PFO who have VGE do not appear to be symptomatic of arterial embolism at rates predictable from the incidence rates of PFO’s in the general population (12). The incidence of PFO’s in individuals with no history of cardiac disease has been demonstrated at autopsy to be 27–35% (17). Using preoperative precordial ultrasound, the detection rate has been reported from 10–30% (16, 20). Failure to demonstrate a PFO with echocardiography can still occur as a result of improper contrast technique, poor image resolution or inability to produce flow through the defect because of inadequate atrial pressure changes. An inadequate degree of sensitivity of precordial echocardiography can, for example, result in failure to correctly identify surgical patients at risk of arterial embolization (26), examples of which are reported where actual embolization did subsequently oc-
cardiac pressures with VGE—Butler et al.

...circulation may represent other factors influencing flow reversal through a PFO. In fact, Mehta et al. (22) reported that rapid bolus injections of air (0.5-1.5 ml · kg⁻¹) into the right atria of dogs with intact atrial septa did not cause a pressure reversal, but that 2.0 ml · kg⁻¹ did. This dose was 13.3 times the dose in the present study and far exceeded that normally seen with decompression (27). Vik et al. (31), reported arterial bubbles in anesthetized pigs receiving venous air infusions as small as 0.05 ml · kg⁻¹ · min⁻¹, and who had PFO's detected by transesophageal echocardiography. Further, in their study the size of the PFO's (4.5 ± 3.1 mm dia.) were not related to the occurrence of the arterial bubbles and although RAP was elevated (non-significantly), they did not report left atrial values.

In the present study, MAP decreased with each VGE dose, and although statistically significant for the 0.025 and 0.15 ml · kg⁻¹ · min⁻¹ doses, these values never exceeded 17% of baseline. ECG changes reported with VGE, such as S-T segment depression or T-wave inversion, have been associated with reductions in cardiac output and myocardial contractility (8). MAP was not significantly affected by the altitude or hyperbaric decompressions, although the decrease in heart rate likely contributed to the decrease in cardiac output. PAP was increased in a dose response fashion for the three VGE doses and closely approximated the hypobaric decompression values. These responses have been previously reported over a wider range of gas doses (7,9) and are likely attributable to increased mechanical obstruction, shunt, reflex vasoconstriction, and release of vasoactive mediators. These combined effects on the pulmonary microcirculation account for the significant elevations in pulmonary vascular resistance and to some degree the increase in peripheral vascular resistance as well. RVP values (mean, systolic, and diastolic) increased with VGE due to the increased pulmonary vascular resistance. This finding was previously reported by Powell, et al. (27), who correlated RVP values with decompression-induced venous gas loads to the pulmonary circulation based on an algorithm that was determined from calibrated venous gas infusions.

Arterial oxygen tensions and saturation values decreased with each VGE dose (significant at the larger doses) due largely because of the development of physiological shunt by obstruction of pulmonary vessels by the gas bubbles. Further explanations reported earlier include: a) changes associated with lung injury that cause diffusion impairment such as edema or atelectasis; b) changes in the ventilation-perfusion ratio; or c) opening of pulmonary shunts (25). Obstruction of pulmonary vessels reduces the CO₂ tensions in the exhaled gases (PₐCO₂), thereby increasing the values in the arterial blood (PₐCO₂).

Certain conclusions drawn from the present study depend to some degree on the degree of confidence that can be placed in the approximation of LAP by LVEDP. Braunwald, et al. (6), reported that in normal individuals LVEDP exceeds LAP mean by an average of only 0.2 mm Hg. They further suggested that although atrial systole increased the ventricular filling rate, it did not cause LVEDP to further increase above LAP mean.
TABLE IV. HYPERBARIC DECOMPRESSION.

| TABLE V. ALTITUDE DECOMPRESSION. |
|-------------------------------|-------------------|-------|-------------------|
| **Baseline**                  | **0 Min**         | **60 Min** | **180 Min** | **Post Flight** |
| MAP                           | 138 ± 4          | 144 ± 5  | 133 ± 3        | 134 ± 4       | 136 ± 5   |
| PAP                           | 9.6 ± 1.1        | 14.9* ± 1.4  | 17.6* ± 2.6  | 19.6* ± 2.7  | 19.8* ± 3.0  | 11.5 ± 1.9  |
| RAP_m                        | 2.5 ± 0.7        | 2.3 ± 1.3  | 2.9 ± 0.9      | 1.8 ± 1.3   | 1.0 ± 0.9  | 2.5 ± 0.4  |
| LVEDP_m                      | 3.1 ± 0.5        | 5.5 ± 0.1  | 4.5 ± 0.5      | 5.0 ± 0.2   | 4.3 ± 0.3  | 4.1 ± 0.2  |
| LVEDP_p                      | 4.7 ± 0.8        | 6.5 ± 1.7  | 7.1 ± 1.4      | 6.3 ± 1.6   | 5.3 ± 1.7  | 6.0 ± 1.8  |
| RVP_m                        | 6.7 ± 1.7        | 8.2 ± 2.8  | 9.2 ± 2.5      | 10.2* ± 2.1 | 9.8* ± 2.0 | 5.9 ± 1.8  |
| RVP_p                        | 23.5 ± 1.7       | 27.0 ± 3.7  | 28.0 ± 6.6     | 37.5* ± 2.2 | 29.8 ± 3.9 | 21.3 ± 1.9  |
| RVP_s                        | -0.1 ± 0.9       | -0.4 ± 1.8 | 1.4 ± 2.6      | 5.1* ± 0.9  | 4.4 ± 1.4 | -0.1 ± 1.4 |
| LVEDP-RAP_m                  | 3.5 ± 1.2        | 6.0 ± 1.2  | 4.3 ± 1.7      | 3.9 ± 1.7   | 3.7 ± 1.4  | 4.2 ± 1.6  |
| LVEDP-RAP_p                  | 2.2 ± 0.9        | 4.2 ± 1.8  | 3.4 ± 2.8      | 3.8 ± 1.8   | 2.9 ± 1.3  | 3.4 ± 1.8  |
| CO (L min⁻¹)                 | 2.2 ± 0.5        |           |               |               |           | 1.84* ± 0.5  |
| PVR (dyn s cm⁻²)             | 333 ± 62         |           |               |               |           | 505* ± 115  |
| SVR (dyn s cm⁻²)             | 6145 ± 1096      |           |               |               |           | 7088 ± 1231 |

Legend same as Table I.

Another study, Braunwald, et al. (5), reported little difference between LAP mean, LAP z-wave (atrial pressure at onset of left ventricular contraction) and LVEDP. Additionally, the LAP a-wave peak (atrial contraction) was the same as the left ventricular a-wave which represents the transmission of the atrial contractile wave into the left ventricle (6). The tallest wave in the LAP pulse is the V-wave, which is the pressure at the time that the mitral valve opens. Although the apparent differences in LVEDP (obtained in a closed chested animal) and LAP (principally V waves, obtained by thoracotomy) pose some interpretative limitations on the determination of the atrial gradients, the relative advantage of using a closed-chested versus open-chested preparation presents a compelling argument for its use. Although mean LVEDP-RAP was not reversed in the present study, transient pressure changes during a cardiac or ventilation cycle need to be considered as well (4). Of the total number of VGE or decompression measurements in the present study, 3% showed transient reversals in the atrial pressure gradient. These data may also be affected by exaggerated respiratory maneuvers.

When any reversal of the atrial pressure gradient occurs during VGE in the presence of a PFO, the subject is at risk for arterial embolization with subsequent cerebral complications if the bubbles circulate into the brain. This risk factor has been previously recognized in hyperbaric decompression illness (23). In a later retrospective study of 90 divers, Moon et al. (24) found a statistically significant relationship between PFO and serious DCI. For the individuals with a resting PFO (i.e., Valsalva maneuver or cough was not required to provoke venous contrast transmission through the septal defect) they reported a five-fold increase in risk for serious DCI. Valsalva-induced shunts were not significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with an increased risk of DCI. Further, no data were reported on the incidence of neurologic DCI and with precordial bubble Grade and PFO. Wilmshurst, et al. (32), studied 61 divers with DCI and reported that the incidence of neurologic DCI and with precordial bubble Grade and PFO was significantly correlated with a

**Aviation, Space, and Environmental Medicine** • May 1995
CARDIAC Pressures with VGE—Butler et al.

study that the amount of gas phase present in the venous circulation is likely to be an important factor influencing a reversal of the atrial pressure gradient. Earlier studies have also suggested a relationship between PFO’s and fatal hypobaric decompression illness (1), although in review of these cases, Fryer (14) emphasized that a disparity remains between the incidence rates of PFO’s and decompression collapse.

CONCLUSION

It has been established that VGE may pose a significant risk to people undergoing decompression, and has been further postulated that a PFO may increase that risk factor. Reversal of the normal atrial pressure gradient can occur, at least transiently, with a release of a Valsalva maneuver, cessation of positive pressure breathing, cessation of the L-I or M-I anti-G straining maneuver, Müller maneuver, negative pressure breathing or even a cough (2,3,15). Further, pulmonary hypertension resulting from hypoxic pulmonary vasoconstriction as a consequence of altitude exposure (15) or following mediator release caused by VGE may also elevate RAP above LAP and contribute to an atrial pressure gradient reversal.

Altitude decompression resulting in the formation of venous bubbles and decompression illness has occurred for many years and is likely to continue as aircraft altitude capability increases. Continued exposure of individuals with a PFO to these environments requires a better understanding of their hemodynamic consequences.

ACKNOWLEDGMENTS

The authors wish to thank Mrs. Tina Little, for her technical assistance in this investigation, and Mrs. Caroline Buggs-Warner for manuscript preparation. This work was supported in part by SCEE CF F33615-90-D0606,0014 and NASA NAG 9-215.

REFERENCES