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Pulmonary Shunt and Cardiovascular Responses to CPAP during Nitroprusside-induced Hypotension

Michael R. Hodges, Theodore H. Stanley, M.D.,† Richard K. Johansen‡*

The effects of continuous positive airway pressure (CPAP) on cardiovascular dynamics and pulmonary shunt ($\dot{Q}_S/\dot{Q}_T$) were investigated in 12 dogs before and during sodium nitroprusside infusion that decreased mean arterial blood pressure 40–50 per cent. Before nitroprusside infusion, 5 cm H_2O CPAP significantly, $P < .05$, decreased arterial blood pressure, but did not significantly alter heart rate, cardiac output, systemic vascular resistance, or $\dot{Q}_S/\dot{Q}_T$. Ten cm H_2O CPAP before nitroprusside infusion produced a further decrease in arterial blood pressure and significantly increased heart rate and decreased cardiac output and $\dot{Q}_S/\dot{Q}_T$. Nitroprusside caused significant decreases in arterial blood pressure and systemic vascular resistance and increases in heart rate, but did not change cardiac output or $\dot{Q}_S/\dot{Q}_T$. Five cm H_2O CPAP during nitroprusside did not further alter any of the above-mentioned variables. However, 10 cm H_2O CPAP decreased arterial blood pressure, cardiac output, and $\dot{Q}_S/\dot{Q}_T$. These data indicate that nitroprusside infusion rates that decrease mean arterial blood pressure by 40–50 per cent do not change cardiac output or $\dot{Q}_S/\dot{Q}_T$. During nitroprusside infusion low levels of CPAP do not markedly alter cardiovascular dynamics, but high levels of CPAP (10 cm H_2O), while decreasing $\dot{Q}_S/\dot{Q}_T$, produce marked decreases in arterial blood pressure and cardiac output. (Key words: Anesthetic techniques, hypotension, induced; Ventilation, CPAP, shunting; Lung, shunting; Blood pressure; Heart, cardiac output.)

SODIUM NITROPRUSSIDE-INDUCED hypotension is being used to decrease blood loss during operation[1–3] and to decrease myocardial afterload during and after anesthesia. Continuous positive airway pressure (CPAP) is also used during these periods to decrease pulmonary shunting ($\dot{Q}_S/\dot{Q}_T$) and increase arterial oxygen tension.[4,5] The influence of CPAP on cardiovascular dynamics and $\dot{Q}_S/\dot{Q}_T$ during nitroprusside administration is unknown and was, therefore, investigated in this study.

Methods

Twelve fasted, unpremedicated mongrel dogs, average weight 15 kg (range 12–20 kg), were studied. Each animal had an intravenous infusion of lactated Ringer's solution started in a foreleg prior to anesthesia. Anesthesia was induced with sodium thiopental, 12–15 mg/kg, and succinylcholine, 1.5 mg/kg, and after tracheal intubation was maintained with alpha-chloralose, 75–100 mg/kg, intravenously. Respirations were controlled with 100 per cent oxygen at tidal volumes of 8–12 ml/kg and rates of 8–14 breaths/min necessary to maintain arterial carbon dioxide tension (Pa_{CO_2}) at 30–35 torr, as measured in arterial blood every 15 minutes. Additional muscle relaxants were not necessary.

Immediately after intubation, a Teflon catheter was implanted in a femoral artery. A quadruple-lumen thermodilution catheter was placed in an external jugular vein and threaded into the right or left pulmonary artery. An Edwards model 9510 thermodilution cardiac output computer was used to measure cardiac output. Stroke volume was determined by dividing cardiac output by heart rate. Pulmonary-artery wedge pressure, mean right atrial pressure and mean arterial pressure were measured utilizing Statham model P23Db pressure transducers. Systemic vascular resistance was calculated from the equation:

$$\text{Systemic vascular resistance} = \frac{\text{mean arterial pressure} - \text{mean right atrial pressure}}{\text{cardiac output}} \times 80$$

$\dot{Q}_S/\dot{Q}_T$ was calculated from the modified shunt equation:

$$\dot{Q}_S/\dot{Q}_T = \frac{(P_{A_{O_2}} - Pa_{O_2} \times 0.0031}{(Ca_{O_2} - C\bar{v}_{O_2}) + (P_{A_{O_2}} - Pa_{O_2}) \times 0.0031}$$

where:

$P_{A_{O_2}}$ = partial pressure of oxygen in alveolar air;
Pa_{O_2} = partial pressure of oxygen in arterial blood;
Ca_{O_2} = content of oxygen (ml) in 100 ml of arterial blood;
$C\bar{v}_{O_2}$ = content of oxygen (ml) in 100 ml of mixed venous (pulmonary artery) blood.

After a 20-minute equilibration period, control cardiovascular data were obtained. Then CPAP, 5 cm H_2O, was added to the expiratory limb of the respirator via an underwater device and 30 minutes later measurements were repeated. CPAP was then changed to 10 cm H_2O, and after 30 minutes data

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* Technical Research Supervisor.

† Associate Professor of Anesthesiology/Surgery.

‡ Research Assistant.

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Address reprint requests to Dr. Stanley.

TABLE 1. Cardiovascular and $\dot{Q}_S/\dot{Q}_T$ Responses to CPAP before and during Nitroprusside-induced Hypotension (Mean ± SD)

	Before Nitroprusside			During Nitroprusside			
	Control	CPAP 5 cm H_2O	CPAP 10 cm H_2O	Control	No CPAP	CPAP 5 cm H_2O	CPAP 10 cm H_2O
Stroke volume	27 ± 9	22* ± 9	17† ± 6	24 ± 10	12† ± 7	14† ± 4	11† ± 7
Heart rate (beats/min)	118 ± 15	124 ± 14	131* ± 11	126 ± 16	162* ± 15	171* ± 11	159* ± 14
Cardiac output (l/min)	2.8 ± 0.5	2.4 ± 0.4	1.9* ± 0.5	2.7 ± 0.4	2.4 ± 0.3	2.7 ± 0.3	1.7†§ ± 0.5
Mean arterial blood pressure (torr)	144 ± 15	138* ± 16	125† ± 13	145 ± 16	99† ± 14	91† ± 14	80‡§ ± 20
Mean right atrial pressure (torr)‖	5 ± 3	7* ± 2	11† ± 2	6 ± 3	4 ± 2	8§ ± 2	13†¶ ± 2
Pulmonary wedge pressure (torr)‖	9 ± 2	11* ± 2	14† ± 2	9 ± 2	7* ± 2	9§ ± 2	15*¶ ± 2
Systemic vascular resistance $\left(\frac{\text{dynes-sec}}{\text{cm}^{-5}}\right)$	4,828 ± 736	4,791 ± 681	4,937 ± 572	4,602 ± 799	3,080† ± 541	2,563† ± 684	2,810† ± 710
Pa_{O_2} (torr)	366 ± 29	368 ± 36	334 ± 31	353 ± 20	339 ± 28	347 ± 22	332 ± 29
$P\bar{v}_{O_2}$ (torr)	60 ± 4	58 ± 4	54* ± 3	59 ± 3	60 ± 4	60 ± 3	56 ± 4
$\dot{Q}_S/\dot{Q}_T$ per cent	13.8 ± 2.1	14.0 ± 2.0	10.9* ± 1.7	14.7 ± 1.8	15.0 ± 1.6	15.6 ± 1.5	11.4*§ ± 1.9

* $P < 0.05$, † $P < 0.01$, ‡ $P < 0.001$, Student's t test for paired data, compared with control.
§ $P < 0.05$, ¶ $P < 0.01$, Student's t test for paired data compared with nitroprusside + no-CPAP values.
‖ These data represent actual recorded values, *i.e.*, they are not corrected for CPAP.

were collected again.§ Following termination of CPAP and recollection of control data 20 minutes later, sodium nitroprusside (0.005 per cent in 5 per cent dextrose in water) was infused intravenously so that mean arterial blood pressure was decreased 40–50 per cent. Five and 10 cm H_2O CPAP were then added as before and data recollected 30 minutes after each change.

Data obtained with CPAP before nitroprusside infusion and data obtained with nitroprusside infusion with and without CPAP were compared with control values using Student's t test for paired data for determination of statistical significance. P values of 0.05 or less were regarded as significant.

Results

Before sodium nitroprusside administration, 5 cm H_2O CPAP significantly decreased stroke volume and mean arterial blood pressure and increased pulmonary-artery wedge pressure and mean right atrial pressure (table 1). Five cm H_2O CPAP did not significantly alter heart rate, cardiac output, systemic vascular resistance, arterial or mixed venous (pulmonary arterial) oxygen tension, or $\dot{Q}_S/\dot{Q}_T$ before nitroprusside administration (table 1). Ten cm H_2O CPAP before nitroprusside produced further decreases in stroke volume and mean arterial blood pressure, increases in pulmonary-artery wedge pressure and, in addition, significantly increased heart rate and decreased cardiac output, mixed venous oxygen tension and $\dot{Q}_S/\dot{Q}_T$.

Nitroprusside caused marked decreases in stroke volume, systemic vascular resistance, and mean arterial blood pressure, and also decreased pulmonary-artery wedge pressure. Heart rate was increased by nitroprusside, but right atrial pressure, cardiac output, arterial and mixed venous oxygen tensions, and $\dot{Q}_S/\dot{Q}_T$ remained unchanged by the compound. Five cm H_2O CPAP during nitroprusside infusion did not further alter any variable except pulmonary-artery wedge pressure and mean right atrial pressure, which were increased. Ten cm H_2O CPAP produced significant decreases in cardiac output, mean arterial blood pressure, and $\dot{Q}_S/\dot{Q}_T$ and further increased pulmonary-artery wedge pressure and right atrial pressure. Correlation of $\dot{Q}_S/\dot{Q}_T$ and $\dot{Q}_T$ changes with 10 cm H_2O CPAP before and during nitroprusside infusion was high, r = .98.

Discussion

Elective hypotension induced with ganglionic blocking agents or high concentrations of halo-

§ In four animals the sequence of addition of CPAP was reversed (10 cm H_2O followed by 5 cm H_2O). Since the sequence of CPAP addition did not appear to influence the results, addition of CPAP was not randomized throughout the remainder of the study, and values obtained at a given CPAP were combined irrespective of the sequence of application.

thane is frequently associated with significant decreases in cardiac output[6,7] and arterial oxygen tension (Pa_{O_2})[8] and increases in pulmonary dead-space[8] and shunt ($\dot{Q}_S/\dot{Q}_T$).[9] A number of recent reports have shown that sodium nitroprusside-induced hypotension does not decrease cardiac output.[3,10,11] The findings of this study demonstrate that hypotension with nitroprusside preserves not only cardiac output but also Pa_{O_2} and $\dot{Q}_S/\dot{Q}_T$. Furthermore, our data document that CPAP produces the same changes in cardiovascular dynamics and Pa_{O_2} and $\dot{Q}_S/\dot{Q}_T$ during nitroprusside-induced hypotension as it does before infusion of the compound.

In a recent report, Stone and co-workers[12] showed that a decrease in mean arterial blood pressure of 37 per cent with either sodium nitroprusside or deep halothane anesthesia did not significantly change Pa_{O_2} or $\dot{Q}_S/\dot{Q}_T$ in young patients in good general health. Cardiac output was slightly increased in their patients given nitroprusside but not changed in those receiving high concentrations of halothane. In contrast, Fahmy and Lappas (unpublished data) demonstrated that hypotension produced by trimethaphan was associated with a significant increase in $\dot{Q}_S/\dot{Q}_T$ and decrease in cardiac output. In our study nitroprusside-induced hypotension did not change $\dot{Q}_S/\dot{Q}_T$ or cardiac output before or during 5 cm H_2O CPAP, but produced significant and highly correlated decreases in both variables during 10 cm H_2O CPAP. These data suggest that preservation of $\dot{Q}_S/\dot{Q}_T$ and Pa_{O_2} during nitroprusside-induced hypotension may be related to an unchanged cardiac output.

Stanley *et al.*[13] recently showed that calcium produced significant increases in $\dot{Q}_S/\dot{Q}_T$ that were strongly correlated with corresponding increases in cardiac output. Positive correlation of changes in $\dot{Q}_S/\dot{Q}_T$ with simultaneous changes in cardiac output has also been found after administration of digoxin (Lunn J, unpublished data), isoproterenol,[14,15] norepinephrine,[14] ephedrine, and metaraminol (Stanley, unpublished data). In another study, Stanley and co-workers[16] demonstrated that $\dot{Q}_S/\dot{Q}_T$ may be significantly increased by a decrease as well as an increase in cardiac output. They suggested that during any metabolic state there is an ideal range of cardiac output that minimizes $\dot{Q}_S/\dot{Q}_T$, and that changes of cardiac output within the ideal range do not alter $\dot{Q}_S/\dot{Q}_T$. On the other hand, increases or decreases of cardiac output outside of the ideal range produce significant increases in $\dot{Q}_S/\dot{Q}_T$. Although the exact mechanism(s) is unknown, preliminary data (Stanley, unpublished data) suggest that pulmonary venous pressure and changes induced in this variable through alterations in left atrial or left ventricular dynamics have a profound influence on $\dot{Q}_S/\dot{Q}_T$ and secondarily affect Pa_{O_2}, and may be one of the means by which cardiac output influences these variables. Unfortunately, further elucidation of the relationship of $\dot{Q}_S/\dot{Q}_T$, cardiac output, and pulmonary venous pressure from analysis of the data from this study is not possible, since pulmonary venous pressure was not measured and pulmonary-artery wedge pressure, a reasonable reflection of pulmonary venous pressure during most situations, is notoriously unreliable during conditions of increased airway pressure.

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