

# Hemodynamics of Increased Intra-abdominal Pressure:

## Interaction with Hypovolemia and Halothane Anesthesia

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The hemodynamic interaction of acute hypovolemia and halothane anesthesia in dogs with increased intra-abdominal pressure caused by intraperitoneal instillation of  $N_2$ ,  $N_2O$  and  $CO_2$  was studied. During normovolemia and just basal pentobarbital anesthesia, the response to increase of intra-abdominal pressure to 40 torr consisted of a 35 per cent decrease in cardiac output, which was equal to the decrease in magnitude of inferior vena caval blood flow. During basal pentobarbital anesthesia, the addition of halothane anesthesia (1 MAC) in combination with hypovolemia (15 per cent blood volume loss) depressed the pre-inflation cardiac output more than addition of halothane anesthesia alone or induction of hypovolemia alone. During each of these conditions, superimposition of increased intra-abdominal pressure to 40 torr caused a further 26-43 per cent decrease in cardiac output compared with the pre-inflation value. Therefore, the greatest cardiovascular depression occurred when the animals were both hypovolemic and anesthetized with halothane. There was no difference in the responses to increased intra-abdominal pressure with the different inflating gases at any time. These findings indicate that in the presence of halothane anesthesia or hypovolemia, induction of pneumoperitoneum may cause severe cardiovascular depression. (Key words: Anesthetics, volatile, halothane; Hemorrhage; Heart, cardiac output; Gases, nonanesthetic, nitrogen; Surgery, pneumoperitoneum; Surgery, laparoscopy.)

ACUTE INCREASES in intra-abdominal pressure in normovolemic animals obstruct inferior vena caval blood flow and increase cardiac afterload, and consequently decrease cardiac output.<sup>1,2</sup> Similarly, certain general anesthetics and hypovolemia decrease cardiac output. Because indications for diagnostic laparoscopy in man now include conditions that are likely to be associated with hypovolemia and decreased cardiac output (blunt and penetrating injuries to the abdomen, pancreatitis, and peritonitis<sup>3-5</sup>) and because general anesthesia may be needed, it is important that the interactions between anesthesia, hypovolemia, and intra-abdominal pressure with cardiac output be determined. Additionally, nitrous oxide ( $N_2O$ ) and carbon dioxide ( $CO_2$ ), when used as inflating gases,

could potentially exert hemodynamic effects after vascular absorption. The purpose of this investigation was to examine these relationships.

### Methods

Nineteen mongrel dogs, weighing 16-28 kg, were anesthetized with pentobarbital, 25 mg/kg, intravenously. The trachea of each was intubated with a cuffed endotracheal tube and the lungs were ventilated at a volume of 12 ml/kg with pure oxygen by a Harvard respirator. Catheters were placed in the carotid artery, femoral vein, and pulmonary artery. Following a median sternotomy, electromagnetic flow probes (Statham SP2202) were placed around the main pulmonary artery and thoracic inferior vena cava. Both flow probes had been calibrated *in vitro* with known blood flows through excised vessels. The main pulmonary-artery flow probe calibration was further confirmed by simultaneous thermal-dilution cardiac output measurements performed *in vivo*; the maximum deviation was less than 6 per cent. Prior to chest closure, catheters were also placed in the pleural space and left atrium. The chest was tightly closed in three layers and all catheters and cables were brought outside the chest through four separate intercostal sites and secured to the skin with airtight purse-string sutures. Finally, two rigid Teflon catheters were placed percutaneously into the abdominal cavity; one was used for pressure monitoring and the other for inflation of the abdomen. Blood loss during operation was minimal (<50 ml), and only maintenance amounts of crystalloid fluid were administered.

The variables measured during the experiment were mean arterial blood pressure (MAP), cardiac output ( $\dot{Q}_t$ ), inferior vena caval blood flow ( $\dot{Q}_{ive}$ ), right atrial pressure (RAP), left atrial pressure (LAP), intra-abdominal pressure (IAP), pleural pressure ( $P_p$ ), airway pressure ( $P_{airw}$ ), heart rate (HR), and end-tidal  $CO_2$  ( $ET_{CO_2}$ ) (Beckman LB-2) and end-tidal halothane (Beckman LB-2) concentrations. Calculated variables were stroke volume ( $SV = \dot{Q}_t/HR$ ) and systemic vascular resistance ( $SVR = MAP - RAP/\dot{Q}_t$ ). All pressure measurements were made utilizing HP1240 pressure transducers and were simultaneously recorded (HP 7788A). Body temperature and acid-

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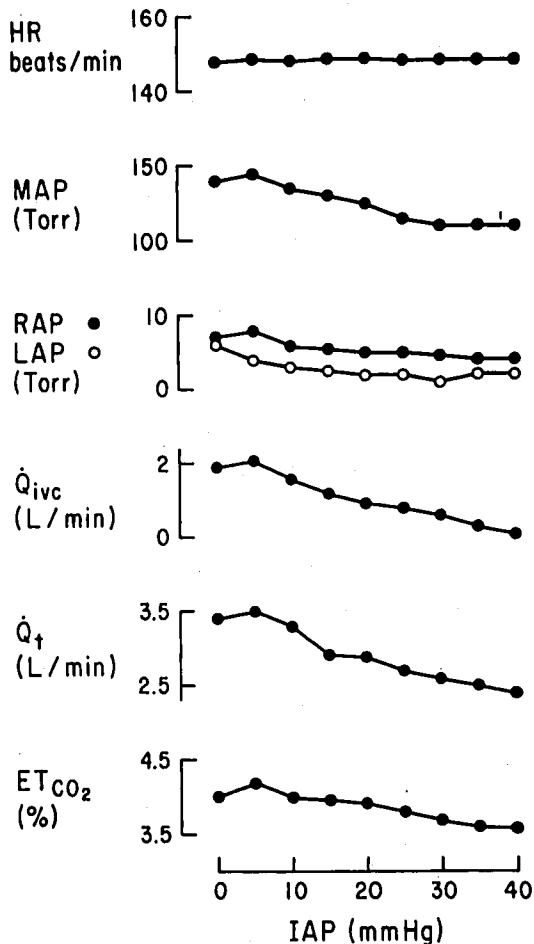


FIG. 1. Typical hemodynamic responses to increased intra-abdominal pressure caused by intraperitoneal insufflation of  $\text{CO}_2$  in a single dog with basal pentobarbital anesthesia and normovolemia. HR = heart rate, MAP = mean arterial pressure, RAP = transmural right atrial pressure, LAP = transmural left atrial pressure,  $\dot{Q}_{\text{ive}}$  = inferior vena caval blood flow,  $\dot{Q}_t$  = cardiac output,  $\text{ET}_{\text{CO}_2}$  = end-tidal  $\text{CO}_2$ , IAP = intra-abdominal pressure.

base balance (Radiometer BMS-3) were maintained within normal limits throughout each experiment.

Each dog was subjected to pneumoperitoneum caused by carbon dioxide ( $n = 7$ ), nitrous oxide ( $n = 5$ ) or nitrogen ( $n = 7$ ) during four induced conditions: Condition 1, pentobarbital anesthesia and normovolemia; Condition 2, pentobarbital anesthesia and hypovolemia; Condition 3, pentobarbital anesthesia with additional 1 MAC end-tidal halothane and normovolemia<sup>6</sup>; Condition 4, pentobarbital anesthesia with an additional 1 MAC halothane and hypovolemia. Following completion of test-gas pneumoperitoneum during Condition 1, temporal randomization of Conditions 2, 3 and 4 was achieved by performing them, in the different dogs for each test gas, in the six possible permutations of order.

Hypovolemia was achieved by bleeding each animal 15 per cent of its calculated blood volume (90 ml/kg).<sup>7</sup> The inflating gas was delivered at 800–1,000 ml/min, and when IAP = 40 torr, the pressure was maintained by gas inflow bleed until the animal's condition stabilized (3–5 minutes), and then the abdomen was passively deflated. The animal's condition was allowed to stabilize after conditions were changed (bleeding or reinfusion of blood, addition or subtraction of 1 MAC halothane) prior to the next pneumoperitoneum. Each animal, therefore, served as its own control. Throughout the experiment, anesthesia was maintained with pentobarbital when the dog showed signs of inadequate anesthesia. All data are reported as means  $\pm$  SE and were analyzed by Student's *t* test for paired data.

### Results

Irrespective of the type of inflating gas, a typical response to increased IAP during Condition 1 (pentobarbital plus normovolemia) consisted of small increases in  $\dot{Q}_{\text{ive}}$ ,  $\dot{Q}_t$ , and MAP at IAP = 5 torr, which were followed by progressively larger decreases in  $\dot{Q}_{\text{ive}}$  and  $\dot{Q}_t$  at IAP = 40 torr (fig. 1). SV decreased from 23.5 ml and SVR increased from 39.0 units, respectively, when IAP = 0 torr to 16.7 ml and 46 units, respectively, when IAP = 40 torr.  $\text{ET}_{\text{CO}_2}$  changed in the same manner as  $\dot{Q}_t$ , as expected, during constant minute ventilation (fig. 1). Transmural RAP (RAP -  $P_b$ ) and LAP (LAP -  $P_b$ ) decreased slightly, and heart rate increased slightly (fig. 1).

There was no significant difference in the responses to increasing IAP with the different inflating gases for each of the four conditions. We therefore added together for a single condition all responses to increased IAP caused by all the inflating gases (table 1). In order of decreasing magnitude, the initial  $\dot{Q}_t$ 's prior to increasing IAP were conditions 1, 3, 2, 4. Increases in  $\dot{Q}_t$  at IAP = 5 torr for all conditions were significant ( $P < 0.05$ ). The subsequent decreases in  $\dot{Q}_t$  as IAP equalled 40 torr were proportionally approximately the same (range 26–43 per cent decrease) for all conditions, and were highly significant compared with the initial  $\dot{Q}_t$ 's ( $P < 0.001$ ). Therefore,  $\dot{Q}_t$  at high IAP was lowest during Condition 4. During all conditions the decreases in  $\dot{Q}_t$  were essentially the same as the decreases in  $\dot{Q}_{\text{ive}}$ . The initial fractional  $\dot{Q}_{\text{ive}}/\dot{Q}_t$ 's prior to increasing IAP were the same for all conditions (range 45–55 per cent of  $\dot{Q}_t$ ). MAP and HR were lower and  $\dot{Q}_t$  higher during halothane anesthesia and normovolemia compared with basal pentobarbital anesthesia and hypovolemia initially ( $P < 0.02$ ). During the response to increased

TABLE 1. Hemodynamic Variables as a Function of Intra-abdominal Pressure during All Conditions\*

	Condition 1		Condition 2		Condition 3		Condition 4	
	Intra-abdominal Pressure 0 torr	Intra-abdominal Pressure 40 torr	Intra-abdominal Pressure 0 torr	Intra-abdominal Pressure 40 torr	Intra-abdominal Pressure 0 torr	Intra-abdominal Pressure 40 torr	Intra-abdominal Pressure 0 torr	Intra-abdominal Pressure 40 torr
Heart rate (beats/min)	145 ± 6	162† ± 5	159* ± 6	167† ± 5	127* ± 4	131 ± 6	130* ± 5	129 ± 5
Cardiac output (l/min)	2.60 ± 0.20	1.70††† ± 0.11	1.74** ± 0.19	1.29†† ± 0.09	2.09* ± 0.19	1.20††† ± 0.10	1.40*** ± 0.21	0.80††† ± 0.11
Stroke volume (ml)	17.9 ± 1.1	10.5††† ± 0.4	10.9** ± 0.5	7.7†† ± 0.3	16.5 ± 0.9	9.2††† ± 0.4	10.8 ± 0.5	6.2††† ± 0.3
Mean arterial pressure (torr)	118 ± 6	115 ± 6	102 ± 4**	95 ± 2	79 ± 4**	81 ± 3	59 ± 4***	61 ± 4
Inferior vena cava blood flow (l/min)	1.39 ± 1.1	0.59††† ± 0.10	0.89 ± 0.05	0.24†††† ± 0.04	0.94* ± 0.07	0.18†††† ± 0.05	0.70*** ± 0.10	0.08††† ± 0.04
Transmural right atrial pressure (torr)	5.3 ± 0.5	3.1†† ± 0.9	4.3 ± 0.5	6.1 ± 1.6	6.7 ± 0.4	7.2 ± 1.4	4.4 ± 0.5	0.3†† ± 0.4
Transmural left atrial pressure (torr)	5.2 ± 0.6	2.2†† ± 0.7	5.0 ± 0.8	7.5 ± 1.7	7.1 ± 1.0	7.7 ± 1.4	4.4 ± 0.6	0.8†† ± 1.0
Systemic vascular resistance (units)	43.3 ± 6.9	65.8††† ± 9.3	56.2** ± 7.3	68.9†† ± 9.4	34.6** ± 5.2	61.5††† ± 9.5	39.0 ± 5.9	75.9††† ± 10.1
End-tidal CO <sub>2</sub> (per cent)	4.6 ± 0.1	4.2†† ± 0.1	4.4 ± 0.2	3.7†† ± 0.2	4.5 ± 0.2	3.8††† ± 0.2	4.4 ± 0.2	3.4††† ± 0.2

\* Values represent means ± standard errors of the means of 19 experiments. Significance of change from condition 1 control values (0 torr):

- \*  $P < 0.05$
- \*\*  $P < 0.01$
- \*\*\*  $P < 0.001$

Significance of change from the initial value (0 torr) in each condition:

- †  $P < 0.05$
- ††  $P < 0.01$
- †††  $P < 0.001$

IAP, HR increased significantly during Conditions 1 and 2 ( $P < 0.05$ ) but there were no significant change in MAP for all conditions. Transmural RAP and LAP decreased significantly ( $P < 0.05$ ) during Conditions 1 and 4 only, and were statistically unchanged during Conditions 2 and 3.

### Discussion

The principal findings of this study were that both a potent inhalational anesthetic and intravascular volume depletion accentuate the deleterious hemodynamic effect of increased IAP, and that there was no difference in responses to increased IAP among different inflating gases. Before discussing these results, consideration should be given to possible sources of variability related to the methods used and the experimental model.

The major technical problem was reliability of the  $\dot{Q}_{ve}$  measurement. Guyton has shown that the inferior vena cava may actually collapse when IAP is increased.<sup>1</sup> Under these circumstances, the vessel wall would fall away from the flow probe and the resultant loss in contact invalidate the measurement. We do not know to what extent this occurred, but we are reassured by the fact that in the large majority of responses to increased IAP the decrease in  $\dot{Q}_{ve}$  was very close to the decrease in  $\dot{Q}_t$  (fig. 1 and table 1). Last, our results during Condition 1 were in good agreement with those of others who have used cannulating flow probes<sup>2</sup> or pump systems.<sup>1</sup>

The only data points obtained during hemodynamic stability were the first (IAP = 0 torr) and the last (IAP = 40 torr), because IAP was a continuously rising function in between. Although intermediate

dynamic readings may differ from steady-state readings,<sup>8</sup> the basic overall conclusions remain unaltered. In addition, constant inflation of the abdomen to a pressure end-point more closely mimics clinical practice.

It is possible that the extent of hypovolemia in our animals was less than 15 per cent due to neurally mediated splenic contraction.<sup>9,10</sup> However, our animals were well anesthetized, as indicated by failure of HR to increase substantially following bleeding in Condition 4 and induction of pneumoperitoneum in Conditions 3 and 4. Thus, it is likely that adequate anesthesia also inhibited splenic contraction.<sup>11</sup> The changes in  $\dot{Q}_t$ , SV and MAP induced by a 15 per cent decrease in blood volume were qualitatively similar to the changes previously observed for a 20 per cent decrease in blood volume.<sup>12</sup>

The change in HR was nonsignificant during pneumoperitoneum in Conditions 3 and 4, while significant increases in HR were found during Conditions 1 and 2 by us and during Condition 1 by others.<sup>2</sup> The reason for this difference in changes in HR may lie in a relatively greater depth of anesthesia during Conditions 3 and 4 compared with Conditions 1 and 2, due to additive effects of halothane and pentobarbital (Conditions 3, 4) and possibly hypovolemia (Conditions 2, 4).<sup>13</sup> Increased depth of anesthesia could inhibit neurally mediated increases in HR.<sup>11</sup>

The changes in  $\dot{Q}_t$ ,  $\dot{Q}_{lvc}$ , SVR, and HR during Condition 1 were similar to those found by Ivankovich<sup>2</sup> using a nearly identical experimental preparation. The only difference between these two studies was that we found no change in MAP during pneumoperitoneum during Condition 1, whereas Ivankovich found an increase of approximately 20 torr. The difference is only quantitative, not qualitative, for maintenance of MAP (our study) or an increase in MAP<sup>2</sup> while  $\dot{Q}_t$  decreased (both studies) resulted in increased SVR (both studies). It is possible that the quantitative difference was due to a prolonged period (25 minutes) of high IAP,<sup>2</sup> which permitted a vascular accommodation to the increased IAP (note beginning MAP increase in figure 1 as IAP approached 40 torr).

We did not find any significant difference in the responses to increased IAP for the different inflating gases, which is in agreement with previous findings.<sup>2</sup> Thus, with a short inflation time, the hemodynamic effects of the gases ( $N_2O$ ,  $CO_2$ ) were purely mechanical (the same as those of  $N_2$ ), and not pharmacologic. This is further confirmed by studies of laparoscopy performed with  $CO_2$  insufflation in man during general anesthesia and controlled ventilation<sup>14</sup> or local anesthesia.<sup>15</sup>

The mechanism by which increased IAP decrease  $\dot{Q}_t$  and SV has been previously explored<sup>2</sup> and is supported by our data. In summary, cardiac preload is decreased (decreased  $\dot{Q}_{lvc}$  and transmural cardiac pressures) and cardiac afterload is increased (increased SVR). In addition, during Conditions 2 and 3, maintenance of transmural RAP and LAP while SV decreased indicates a shift of the ventricular function curve to the right, perhaps due to the increase in cardiac afterload. Finally, our results re-emphasize that cardiac transmural pressures (relative to pleural pressure) and not directly measured pressures (relative to atmospheric pressure) should be used as the indicator of venous return to the heart.

We found that halothane anesthesia and hypovolemia (Condition 4) additively depressed cardiac output. Therefore, in terms of hemodynamics, Condition 4, which was disadvantaged, had the lowest initial  $\dot{Q}_t$ , and superimposition of increased IAP produced a proportionally equal decrease in  $\dot{Q}_t$  compared with Condition 1 and resulted consequently in more profound cardiovascular depression. The clinical implications of the latter finding may be significant in selected cases wherein diagnostic laparoscopy utilizing pneumoperitoneum is being performed in hypovolemic patients. In such cases it may be critical to re-expand depleted intravascular volume (increase preload). On the other hand, in patients with pre-existing heart disease in whom a shift in the ventricular function curve to the right may develop due to increased cardiac afterload, therapy should be directed toward improving contractility pharmacologically, as well as avoiding anesthetics that directly depress the heart. In addition, volume expansion and abdominal inflating pressure should be kept to a minimum.

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## References

1. Guyton AC, Adkins LH: Quantitative aspects of the collapse factor in relation to venous return. *Am J Physiol* 177: 523-527, 1954
2. Ivankovich AD, Miletich DJ, Albrecht RF, et al: Cardiovascular effects of intraperitoneal insufflation with carbon dioxide and nitrous oxide in the dog. *ANESTHESIOLOGY* 42: 281-287, 1975
3. Gomel V: Laparoscopy in general anesthesia. *Am J Surg* 131:319-323, 1976
4. Gazzaniga AB, Stanton WW, Bartlett RH: Laparoscopy in the diagnosis of blunt and penetrating injuries to the abdomen. *Am J Surg* 131:315-318, 1976
5. Robinson HB, Smith GW: Applications for laparoscopy in general surgery. *Surg Gynecol Obstet* 143:829-831, 1976

6. Eger EI II, Brandstater B, Saidman LJ, et al: Equipotent alveolar concentrations of methoxyflurane, halothane, diethyl ether, fluroxene, cyclopropane, xenon and nitrous oxide in the dog. *ANESTHESIOLOGY* 26:771-777, 1965
7. Gibson JC II, Keeley JL, Pijoan M: The blood volume of normal dogs. *Am J Physiol* 121:800-804, 1938
8. Richardson JD, Trumble JK: Hemodynamic and respiratory alterations with increased intra-abdominal pressure. *J Surg Res* 20:401-404, 1976
9. Guntheroth WG, Mullins GL: Liver and spleen as venous reservoirs. *Am J Physiol* 204:35-43, 1963
10. Folkow B, Neil E: Circulation, Gastrointestinal and Liver Circulations. Chapter 26. Oxford, Oxford University Press, 1971, pp 482-483
11. Whittenberger JL: Artificial respiration. *Physiol Rev* 35: 611-632, 1955
12. Morgan BC, Crawford EW, Guntheroth WG: The hemodynamic effects of changes in blood volume during intermittent positive pressure ventilation. *ANESTHESIOLOGY* 30:297-305, 1969
13. Eger EI II: MAC, Anesthetic Uptake and Action. Chapter 1. Baltimore, Williams and Wilkins, 1974, pp 9-13
14. Baratz RA, Karis JH: Blood gas studies during laparoscopy under general anesthesia. *ANESTHESIOLOGY* 30:463-464, 1969
15. Diamant M, Benumof JL, Saidman LJ: Laparoscopic sterilization with local anesthesia: Complications and blood gas changes. *Anesth Analg (Cleve)* 56:335-337, 1977

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