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The Young Lamb Can Increase Cardiovascular Performance during Isoflurane Anesthesia

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Cardiac output and myocardial blood flow decrease dramatically in a dose-dependent pattern in the young lamb during isoflurane anesthesia. This raises important questions about the ability of the young lamb to increase myocardial performance if oxygen delivery were compromised by a decrease in oxygen content during anesthesia and surgery. To investigate the ability of the young lamb to increase oxygen delivery during isoflurane anesthesia, the response to hypoxemia, which is known to increase myocardial performance, was studied in awake 1-week-old lambs. Mean systemic arterial pressure, heart rate, cardiac output, and regional distribution of blood flow were measured during three states: awake, 1.0 minimum alveolar concentration (MAC) of isoflurane in an $F_{I_{O_2}}$ of 1.0, and 1.0 MAC of isoflurane in an $F_{I_{O_2}}$ of 0.09. Stroke volume, total body and myocardial oxygen consumption, and fractional extraction of oxygen were calculated for the total body and for the myocardium. Isoflurane anesthesia decreased mean systemic arterial pressure (70 ± 8 mmHg), heart rate (222 ± 29 beats/min), and cardiac output (277 ± 72 $ml \cdot kg^{-1} \cdot min^{-1}$) significantly (43 ± 11 mmHg, 163 ± 20 beats/min, 191 ± 34 $ml \cdot kg^{-1} \cdot min^{-1}$). Hypoxemia returned heart rate to control (191 ± 23 beats/min), increased stroke volume (1.71 ± 0.2 ml/kg) above both control (1.23 ± 0.2 ml/kg) and 1.0 MAC isoflurane levels (1.19 ± 0.3 ml/kg), and increased cardiac output (325 ± 61 $ml \cdot kg^{-1} \cdot min^{-1}$) above the level during 1.0 MAC isoflurane. Isoflurane anesthesia also decreased myocardial blood flow, and, in parallel, myocardial oxygen consumption, but hypoxemia increased myocardial blood flow above the level during 1.0 MAC isoflurane and returned myocardial oxygen consumption to the control value. Myocardial oxygen extraction did not differ from control during either anesthetic state. Isoflurane caused no redistribution of cardiac output, but hypoxemia redistributed cardiac output to the adrenals, myocardium, and brain, similar to the pattern reported in the awake, hypoxic lamb. In summary, newborn lambs anesthetized with 1.0 MAC isoflurane decrease oxygen delivery when oxygen demand decreases, without diverting cardiac output from nonvital to vital organs. However, the anesthetized lamb is capable of increasing its cardiac output and oxygen delivery and decreasing oxygen consumption in response to stress. This ability of the heart to respond to hypoxemia during isoflurane anesthesia is vital in the clinical setting of cyanotic heart disease or when an acute systemic hypoxic insult occurs during surgery (*e.g.*, during repair of a congenital diaphragmatic hernia). (Key words: Anesthesia, pediatric: stressed newborn. Anesthetics, volatile: isoflurane. Heart, complications: hypoxia.)

DURING ISOFLURANE ANESTHESIA in the newborn lamb, cardiac output and myocardial blood flow decrease in parallel to the decrease in total body and myocardial oxygen consumption[1]; the decrease in oxygen delivery does not exceed the decrease in demand. This suggests that the decrease in cardiac output is due to a decreased metabolic demand, not to myocardial depression. If metabolic demand increases or if oxygen content decreases, oxygen delivery would only be preserved if cardiac output can increase. It is well known that the awake lamb increases cardiac output during acute hypoxemia.[2–7] Because anesthesiologists commonly encounter young infants with severe cyanotic congenital heart disease or infants predisposed to acute hypoxemia (*e.g.*, congenital diaphragmatic hernia, respiratory distress syndrome, tracheoesophageal fistula), it is important to investigate the ability of the young to adapt to acute hypoxemia during anesthesia. In addition, episodes of acute hypoxemia can occur in any infant undergoing surgery and anesthesia, and the short-term adaptation of the cardiovascular system is the primary mechanism to maintain oxygen delivery to vital organs.

At rest cardiac output[2–4,7] and oxygen consumption[2,4,7] in the newborn lamb are high, limiting the reserve to increase oxygen delivery during periods of stress. However, the young lamb is able to increase cardiac performance in response to hypoxemia[2,5–8]; cardiac output and heart rate increase and blood flow is redistributed toward the brain, heart, and adrenals and away from the carcass, kidney, and gut. To determine the cardiovascular response of the anesthetized young lamb to hypoxemia, we studied the response of five lambs to hypoxemia during 1.0 MAC isoflurane anesthesia. We studied the distribution of cardiac output and measured cardiac performance and myocardial and total body oxygen consumption simultaneously to correlate changes in performance and oxygen delivery with changes in oxygen consumption.

Methods

SURGICAL PREPARATION

After approval from our Committee on Animal Research, five lambs 6–10 days old were studied. General anesthesia was induced with halothane in oxygen deliv-

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ered by mask. The trachea of each lamb was then intubated, and the lungs were ventilated using a Harvard pump. After polyvinyl catheters were inserted into the hind limb artery and vein, a thoracotomy was performed and catheters were inserted through the fourth or fifth intercostal space into the ascending aorta *via* the internal thoracic artery, and directly into the left atrium, pulmonary artery, and coronary sinus. Because the hemiazygos vein in sheep drains into the coronary sinus, this vein was ligated distally and a catheter was inserted so that its tip was near the origin of the coronary sinus (the confluence of the hemiazygos and great cardiac veins). A precalibrated electromagnetic flow transducer (C & C Instruments, Culver City, California) was placed around the main pulmonary artery to allow continuous estimation of cardiac output during the studies. Because right-to-left shunting through the foramen ovale or the ductus arteriosus does not occur during acute hypoxemia in the young lamb, the ductus arteriosus was not ligated surgically.[2,7,9,10]

An 8-Fr polyvinyl catheter was placed in the pleural space to drain fluid or air. The chest was closed in layers, and all catheters and transducer cables were tunneled through the skin and protected in a bag sutured to the lamb's flank. Catheters were flushed with 0.9% NaCl and filled with heparin daily. Intramuscular penicillin (200,000 units) and streptomycin (250 mg) were administered for 5 days postoperatively. Lambs recovered for at least 3 days before any cardiovascular study.

Experimental Protocol

All lambs were 6–10 days old when studied. Each remained with its mother and was allowed to feed at will until approximately 1 h before study. Temperature was monitored with a rectal probe and maintained normal (39° C) by placing a heating pad under the lamb and/or an infrared lamp above.

Control measurements were taken while the lamb rested quietly. Aortic and pulmonary phasic and mean pressures were measured using Statham P23Db® transducers, pulmonary arterial blood flow with a Statham SP2202® flowmeter, and heart rate using a Beckman® cardiotachometer triggered by the aortic pressure signal. Data were recorded on a direct-writing Beckman® recorder. When the aortic, pulmonary arterial, and left atrial pressures and pulmonary arterial blood flow had been stable for 20 min, blood was drawn simultaneously from the aorta, pulmonary artery, and coronary sinus to measure hemoglobin concentration and oxygen saturation (Radiometer® hemoximeter) and blood gases (Corning® *p*H blood-gas analyzer, model 158). Then $1.0–2.0 \times 10^6$ 15-μ diameter radionuclide-labeled microspheres (57Co, 51Cr, 85Sr, 95Nb, 65Zn, 113Sn, 153Gd, 114In, or 54Mn) were injected into the left atrium as blood was withdrawn from the ascending and descending aorta for 1.25 min at a rate of 4 ml/min. Blood loss secondary to sampling was replaced with maternal blood after the microsphere injection.

General anesthesia was then induced with isoflurane in oxygen ($F_{I_{O_2}} = 1.0$) using a calibrated isoflurane vaporizer (Ohmeda®, Madison, Wisconsin) and fresh gas flows of 3–5 l/min delivered through an adult circle system and a mask. The trachea of each lamb was intubated and the lungs were ventilated using a Ventimeter® ventilator (Narco Medical Co., Warminster, Pennsylvania). No intravenous sedatives or muscle relaxants were administered. Ventilation was adjusted to maintain P_{CO_2} between 35 and 45 mmHg. Cardiovascular measurements and microsphere injections were repeated during 1.0 MAC isoflurane (1.6% isoflurane, end-tidal concentration)[1] after hemodynamic stability had been present for at least 20 min.

The $F_{I_{O_2}}$ was then decreased from 1.0 to 0.09 by mixing nitrogen and air to produce an inspired oxygen tension of 67–70 mmHg. Mechanical ventilation was continued to maintain a P_{CO_2} of 35–45 mmHg, the same level achieved during an $F_{I_{O_2}}$ of 1.0. Cardiovascular measurements and microsphere injections were repeated within the first 5–15 min of hypoxemia because cardiac output and heart rate increase maximally at this time.[2] Left ventricular output derived from left atrial injection of radionucleide-labeled microspheres is accurate in this study because there is no right-to-left shunting through either the foramen ovale or ductus arteriosus in the newborn lamb.[2,7,9,10]

Data Analysis

Blood oxygen content was calculated as the sum of the oxygen bound to hemoglobin [the product of hemoglobin concentration, oxygen saturation, and binding capacity (1.36 ml O_2 per g Hgb)] and dissolved oxygen (the product of P_{O_2} and 0.003). Oxygen consumption was calculated by multiplying the difference between aortic and pulmonary arterial oxygen contents times cardiac output. Oxygen delivery was calculated as the product of systemic arterial oxygen content and cardiac output. Systemic vascular resistance (SVR) was calculated by dividing mean systemic arterial pressure by cardiac output.

Eighty-eight per cent of blood flow to the left ventricular free wall drains into the coronary sinus[11] (smaller percentages of flow from the left atrium, septum, and right ventricle also drain into the coronary sinus). By multiplying the difference between the aortic and coronary sinus oxygen contents times blood flow (per 100 g) to the left ventricular free wall, left ventricular free wall oxygen consumption was approximated. Fractional extraction of

oxygen of the body and of the myocardium were calculated as the ratio of arteriovenous difference in blood oxygen content to arterial blood oxygen content.

Left ventricular output and its distribution were measured using the radionuclide-labeled microsphere technique with the least squares method.[12] Tissues were weighed, carbonized, and radioactivity counted along with all drawn blood samples in a scintillation counter (Searle Analytic, Inc.) connected to a 512-channel pulse height analyzer. Samples were divided into six organ and body groups: adrenal, brain, carcass (muscle, bone, skin), heart, kidney, and splanchnic bed (spleen, gut, liver). Blood flow determined for the liver signified only hepatic arterial flow because microspheres are injected only into the left atrium. The left ventricular free wall was divided evenly into the inner and outer layers to determine the flow to each area. The ratio of the flow to each layer is the inner-to-outer ratio.

Microsphere data are presented in two ways. First, total blood flow to each organ group is presented as milliliters per 100 g of tissue weight per minute to measure any absolute change in blood flow from control. Second, flow to each organ group is calculated as a per cent of the total cardiac output to evaluate redistribution of blood flow toward or away from any organ group.

Data were analyzed by analysis of variance using repeated measures and the Student-Newman-Keuls test, when the data were normally distributed. In some cases analysis was by the Mann Whitney U test if data were not normally distributed. A P value of less than 0.05 was considered significant.

Results

General Hemodynamics

Heart rate, mean systemic arterial pressure, and cardiac output decreased significantly from control during 1.0 MAC isoflurane in oxygen (table 1). Stroke volume, mean pulmonary arterial pressure, and systemic vascular resistance did not change. Fractional extraction of oxygen did not change because cardiac output and total body oxygen consumption were both at a similar per cent of control (fig. 1).

During hypoxemia plus isoflurane, oxygen delivery decreased to about 58% of the normoxic isoflurane value and to 42% of control value. This decrease was based on the decrease in oxygen saturation because cardiac output actually increased significantly to 170% of the value during isoflurane in oxygen ($P < 0.05$). During hypoxemia oxygen consumption decreased to 51% of control. Mean systemic arterial pressure remained significantly below the awake value. Heart rate returned toward control. Fractional extraction of oxygen increased to 124% of the value during isoflurane and oxygen.

Myocardium

Myocardial blood flow and oxygen consumption decreased in parallel during normoxic isoflurane anesthesia (table 2; fig. 2). Myocardial fractional oxygen extraction did not differ from control, and the inner-to-outer ratio of flow to the left ventricular wall remained in the normal range.

During hypoxemia plus isoflurane, myocardial blood flow increased above that during isoflurane alone. However, myocardial oxygen transport remained at control levels (table 2). Myocardial oxygen consumption increased to the control level. Neither myocardial fractional oxygen extraction nor the inner-to-outer ratio of flow to the left ventricular free wall differed from that during the awake or normoxic isoflurane states.

Regional Blood Flow

Blood flow to the kidney, adrenal, and splanchnic circulations decreased during isoflurane alone (table 3). The

TABLE 1. General Hemodynamics

	Awake	MAC 1.0	MAC 1.0 + Hypoxia
Mean systemic arterial pressure (mmHg)	70 ± 8	43 ± 11*	51 ± 7*
Mean pulmonary arterial pressure (mmHg)	22 ± 7	18 ± 4	33 ± 8†
Heart rate (beats/min)	222 ± 29	163 ± 20*	191 ± 23
Stroke volume (ml/kg)	1.23 ± 0.2	1.19 ± 0.3	1.71 ± 0.3*†
Systemic vascular resistance ($mmHg/ml \cdot kg^{-1} \cdot min^{-1}$)	261 ± 46	230 ± 47	164 ± 50*
Oxygen delivery ($ml \cdot kg \cdot min^{-1}$)	2,712 ± 541	1,967 ± 273	1,147 ± 563*†
Cardiac output ($ml \cdot kg^{-1} \cdot min^{-1}$)	277 ± 72	191 ± 34*	325 ± 61†
$\dot{V}_{O_2}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	13.4 ± 3.9	9.15 ± 1.3	6.86 ± 3.5*
Systemic % oxygen extraction	49.7 ± 12	47.3 ± 11	58.8 ± 6.4†
pH	7.41 ± .06	7.42 ± .07	7.39 ± .08
P_{O_2}	69 ± 7.7	328 ± 118*	25.6 ± 10.6*†
P_{CO_2}	43 ± 2.7	38 ± 7.8	36 ± 6.7

Values are mean ± SD (n = 5).
* $P < 0.05$, Awake *versus* MAC 1.0 or MAC 1.0 + hypoxia.
† $P < 0.05$, MAC 1.0 *versus* MAC 1.0 + hypoxia.

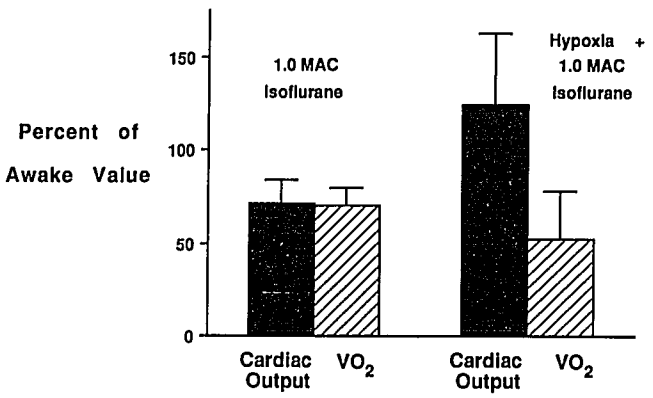

FIG. 1. Cardiac output (CO) and total body oxygen consumption ($\dot{V}_{O_2}$) were at a similar percentage of awake values during 1.0 MAC isoflurane. When hypoxemia was added, CO increased above the level during isoflurane alone, but $\dot{V}_{O_2}$ decreased below the control value. The values represented are 71.0 ± 12.9 (CO) and 70.3 ± 9.24 ($\dot{V}_{O_2}$) for 1.0 MAC isoflurane and 124.6 ± 38.4 (CO) and 52.1 ± 25.8 ($\dot{V}_{O_2}$) for 1.0 MAC isoflurane + hypoxia. These per cent of control values were calculated by calculating the per cent of control of each parameter for each animal and then calculating the mean ± SD.

per cent of cardiac output received by the kidney and the myocardium decreased (table 4).

The addition of hypoxemia increased blood flow to the adrenals, kidney, myocardium, and brain above that during isoflurane alone (table 3). Blood flow to the adrenals and brain was significantly higher and flow to the kidney significantly lower than flow during control. The redistribution of cardiac output during hypoxemia was significant, with the myocardium, adrenals, and brain receiving a significantly greater per cent of cardiac output that during isoflurane alone. The per cent of cardiac output received by the myocardium and the brain exceeded the awake values. The kidney, continued to receive significantly reduced per cent of output compared with the awake value.

Discussion

The adaptation to acute hypoxemia is complex, requiring neural and hormonal input[13–15] and local tissue autoregulation.[16–20] An intact sympathoadrenal response is vital.

In both the adult[21] and young sheep,[2,5–8] the stress response to hypoxemia increases cardiac output and heart rate and redistributes blood flow to the myocardium, brain, and adrenals. Because of the higher heart rate[22] and cardiac output[2] in the young animal at rest, quantitative differences can be seen when the response of adults is compared with that seen in the young. During isoflurane anesthesia the response of the young lamb to hypoxemia mimics that seen during the awake state, including a transient increase in cardiac output.[2] When the demand for oxygen increases, the newborn lamb has the capacity to increase cardiac performance. This conflicts with the perception of 1.0 MAC isoflurane as a "myocardial depressant." Because our purpose was to determine whether cardiovascular performance could increase in response to stress during 1.0 MAC isoflurane, we did not study our lambs under steady state conditions and we did not evaluate the risk for metabolic acidosis or cardiovascular collapse during exposure to prolonged hypoxemia.

However, there may be some blunting of the hypoxemia-induced tachycardia. During hypoxemia plus isoflurane, mean value for heart rate was 86% of the mean awake value and 117% of the mean value during isoflurane alone. In contrast, heart rate in the awake hypoxemic lamb increases to 108–140% of the baseline value.[2,4–8] Isoflurane, therefore, may blunt the peak heart rate response to hypoxemia, assuming the baseline to be the awake value. If we consider isoflurane anesthesia as the baseline, the response of heart rate to hypoxemia is in the range reported in awake lambs of similar age.

As in the awake animal, hypoxemia during isoflurane anesthesia caused a redistribution of cardiac output toward the adrenals, myocardium, and brain. There was no redistribution to the adrenals during isoflurane alone, suggesting the absence of "stress." Hypoxemia, however, redistributes cardiac output to the adrenals in both awake and anesthetized animals, indicating that the young lamb can invoke this normal, awake state compensatory mechanism while anesthetized.

Although cardiac output increased during hypoxemia and isoflurane anesthesia, total body oxygen consumption decreased below awake levels but did not differ from that during isoflurane alone. Because oxygen demand (oxygen

TABLE 2. Myocardial Blood Flow, Myocardial Oxygen Consumption, Inner-to-Outer Ratio (Flow to Left Ventricular Free Wall)

	Awake	MAC 1.0	MAC 1.0 + Hypoxia
Myocardial blood flow ($ml \cdot 100\ g^{-1} \cdot min^{-1}$)	275 ± 162	103 ± 36*	990 ± 802†
Myocardial oxygen transport ($ml \cdot kg^{-1} \cdot min^{-1}$)	2,624 ± 1,408	1,068 ± 355	2,681 ± 1,854
Myocardial oxygen consumption ($ml \cdot 100\ g^{-1} \cdot min^{-1}$)	19.0 ± 10.6	7.2 ± 2.5*	19.8 ± 12.4†
Inner-to-outer ratio	1.35 ± 0.21	1.17 ± 0.34	1.28 ± 0.26
Myocardial % oxygen extraction	71.6 ± 2.3	67.9 ± 10.8	75.4 ± 7.3

Values are mean ± SD (n = 5).
* $P < 0.05$, Awake *versus* MAC 1.0 or MAC 1.0 + hypoxia.
† $P < 0.05$, MAC 1.0 *versus* MAC 1.0 + hypoxia.

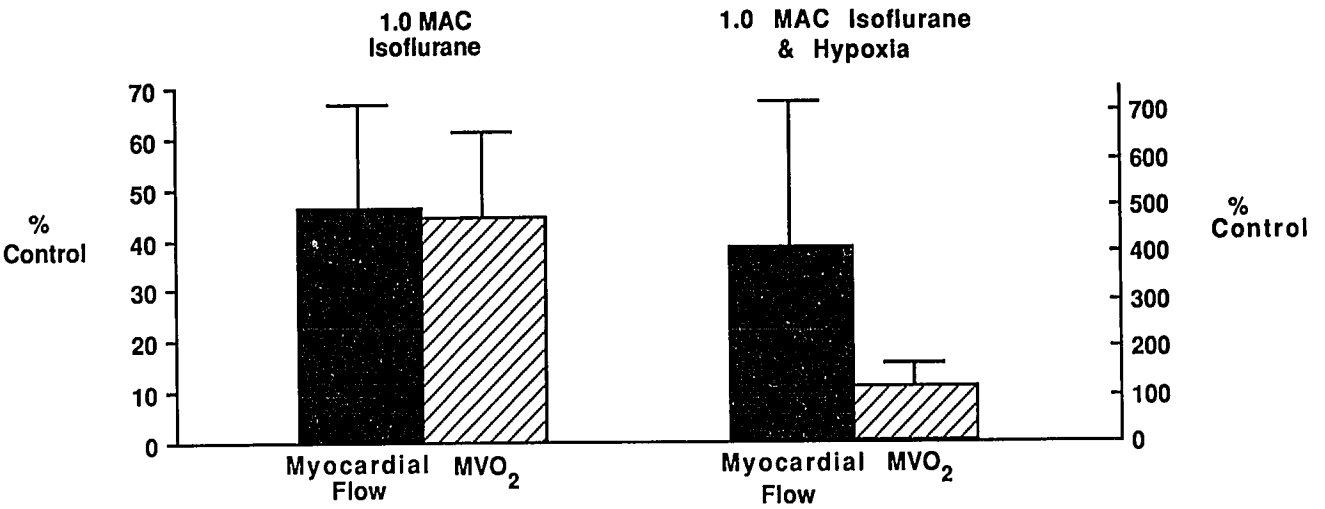

FIG. 2. Myocardial blood flow and myocardial oxygen consumption ($M\dot{V}_{O_2}$) (as a per cent of awake value) decreased in parallel during 1.0 MAC isoflurane. When hypoxemia was added, myocardial blood flow increased above that during isoflurane alone and $M\dot{V}_{O_2}$ increased to the awake level. The values represented are 46.3 ± 20.3 (myocardial blood flow) and 44.6 ± 16.8 ($M\dot{V}_{O_2}$) for 1.0 MAC isoflurane and 410 ± 309 (myocardial blood flow) and 114 ± 46.3 ($M\dot{V}_{O_2}$) for 1.0 MAC isoflurane + hypoxia. These per cent of control values were calculated by calculating the per cent of control of each parameter for each animal and then calculating the mean ± SD. Note that the scale for "1.0 MAC Isoflurane" is different than the scale for the "Hypoxia + 1.0 MAC Isoflurane."

consumption) and supply (oxygen delivery) were matched during isoflurane anesthesia, the further decrease in oxygen delivery induced by hypoxemia elicited compensatory cardiovascular activity. Similar to the awake lamb,[2] anesthetized lambs decrease oxygen consumption during moderate hypoxemia without developing acidosis. In contrast, the adult dog[22] does not decrease oxygen consumption until acidosis is present and cardiovascular collapse is imminent. Myocardial blood flow increased dramatically above normoxic isoflurane anesthesia values, and myocardial oxygen consumption also increased. Because we did not follow our lambs for more than approximately 20 min after initiating hypoxemia, we cannot comment on the ultimate ability of these young animals to tolerate a stress superimposed on a low-flow state, such as general anesthesia. Also, we have not examined the pattern and time course of cardiovascular recovery after discontinuing hypoxemia.

Cameron *et al.*[23] studied the cardiovascular effects of 0.5 and 1.0 MAC halothane in normoxic and hypoxic lambs. Their lambs were paralyzed and their lungs were mechanically ventilated during the awake state and had a cardiac output of 373 $ml \cdot min^{-1} \cdot kg^{-1}$ and a heart rate of 241 beats/min. During 1.0 MAC halothane, cardiac output and plasma catecholamine levels decreased below awake values. The addition of hypoxemia did not increase cardiac output in either their awake or anesthetized (0.5 and 1.0 MAC) lambs. Their findings differ from ours, probably because of differences in study design. First, their awake, paralyzed, mechanically ventilated lambs had a higher cardiac output and heart rate than our awake, spontaneously breathing lambs. Because normal cardiac output for a lamb during the first 10 days of life is 250–300 $ml \cdot min^{-1} \cdot kg^{-1}$,[4] their paralyzed, awake state probably already included an element of stress (cardiac output 373 $ml \cdot min^{-1} \cdot kg^{-1}$). Second, and more important,

TABLE 3. Regional Blood Flow ($ml \cdot 100\ g^{-1} \cdot min^{-1}$)

	Awake	MAC 1.0	MAC 1.0 + Hypoxia
Adrenal	216 ± 73	96 ± 42*	358 ± 80*†
Carcass	19 ± 10	14 ± 6	19 ± 4
Splanchnic	84 ± 17	58 ± 14*	63 ± 24
Kidney	296 ± 28	121 ± 18*	167 ± 31*†
Myocardium	168 ± 84	76 ± 21	606 ± 430†
Brain	102 ± 26	85 ± 38	255 ± 191*†

Values are mean ± SD (n = 5).
* $P < 0.05$, Awake *versus* MAC 1.0 or MAC 1.0 + hypoxia.
† $P < 0.05$, MAC 1.0 *versus* MAC 1.0 + hypoxia.

TABLE 4. Regional Flow: % Cardiac Output

	Awake	MAC 1.0	MAC 1.0 + Hypoxia
Adrenal	0.17 ± 0.10	0.10 ± 0.07	0.20 ± 0.05†
Carcass	48.8 ± 10.8	53.3 ± 9.05	44.5 ± 9.09
Splanchnic	26.9 ± 6.57	25.9 ± 7.59	19.3 ± 8.79
Kidney	9.48 ± 3.10	5.14 ± 1.03*	4.16 ± 0.54*
Myocardium	5.95 ± 1.14	4.23 ± 0.78*	18.7 ± 12.6*†
Brain	4.02 ± 1.37	4.62 ± 0.81	7.76 ± 3.35*†

Values are mean ± SD (n = 5).
* $P < 0.05$, Awake *versus* MAC 1.0 or MAC 1.0 + hypoxia.
† $P < 0.05$, MAC 1.0 *versus* MAC 1.0 + hypoxia.

Cameron *et al.* reported that each condition was maintained for 30 min before cardiac output was measured.[23] Because cardiac output increases within 5–15 min after hypoxemia begins and returns to baseline values by 30–40 min, they may have missed the peak cardiac output response in their lambs.[2] Cardiac output in our lambs was measured continuously by the flow probe around the pulmonary artery and started to decrease by 20–30 min after hypoxemia was introduced. Similar to our study, Cameron *et al.*[23] noted that total body oxygen consumption decreased during isoflurane alone and decreased further during hypoxemia.

In summary, the cardiovascular system of the newborn lamb is capable of increasing oxygen delivery in response to the stress of hypoxemia during isoflurane anesthesia. Thus, at reasonable anesthetic depth (1.0 MAC), and in the absence of myocardial or peripheral cardiovascular disease, the newborn lamb can coordinate neural, endocrine, and local tissue responses to increase cardiovascular performance in response to hypoxemia.

This ability to match oxygen delivery and oxygen supply is vital in the clinical setting, especially when any component of oxygen delivery is impaired. For example, children with cyanotic congenital heart disease may actually have higher arterial oxygen saturation during isoflurane anesthesia if total body oxygen consumption decreases more than cardiac output decreases. During sudden onset of hypoxemia during surgery and anesthesia infants may maintain oxygen delivery acutely by increasing cardiac output to compensate for the decreased oxygen saturation. However, it is hazardous to extrapolate information gained from studies in lambs to the human, even though the cardiovascular physiology of the newborn human is similar to that of the lamb. It will be important to perform studies during inhalation anesthesia, comparing the cardiovascular performance of young humans with congenital lesions associated with low oxygen saturation to that of normal infants.

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