Anesthesiology
72:65–70, 1990

Maternal Anesthesia and the Stressed Fetus: Effects of Isoflurane on the Asphyxiated Fetal Lamb

B. Wycke Baker, M.D., S. C. Hughes, M.D.,† S. M. Shnider, M.D.,‡ D. R. Field, M.D.,§ M. A. Rosen, M.D.¶*

The effects of maternal isoflurane-oxygen anesthesia (isoflurane, 1% inspired) were measured in eight pregnant ewes and their asphyxiated singleton fetuses. Stable fetal asphyxia, indicated by a stable fetal arterial *p*H of 7.1–7.2 units, was produced by maternal uterine artery occlusion. Maternal and fetal heart rates and blood pressures; maternal uterine artery flow; maternal arterial, fetal arterial, and sagittal sinus *p*H; and blood gas tensions were determined during an awake control period, during fetal asphyxia alone, and during fetal asphyxia plus isoflurane–oxygen. Measurements of representative fetal whole organ blood flows, cardiac output, and cerebral oxygen consumption were also made during each of the three experimental periods. During asphyxia alone regional and total brain, heart, and adrenal flows increased above control while flow to the spleen and carcass decreased. Similar responses were seen during asphyxia plus isoflurane–oxygen. Fetal arterial and sagittal sinus *p*H, base excess, p_{O_2}, and oxygen saturation decreased, and hydrogen ion concentrations and p_{CO_2} increased during asphyxia alone and asphyxia plus isoflurane–oxygen. Cerebral oxygen consumption decreased significantly from control during asphyxia plus isoflurane–oxygen, whereas no significant changes occurred in cerebral oxygen delivery. These results support the conclusions that in the asphyxiated fetus: 1) acidosis is increased; 2) cardiac output is redistributed to vital organs; and 3) the balance of cerebral oxygen supply-to-demand is maintained during maternal isoflurane–oxygen anesthesia. (Key words: Anesthesia: obstetric. Anesthetics, volatile: isoflurane. Blood flow: regional. Complications: fetal asphyxia.)

COMPROMISED UTEROPLACENTAL blood flow and fetal distress require aggressive obstetric management, typically involving rapid anesthetic intervention, to preserve the life of the fetus. In the absence of maternal hypotension, brief exposure of the healthy fetus to anesthetics produces minimal deleterious effects.[1–3] However, the response of the asphyxiated fetus to volatile anesthetics is largely unknown. The present study is one of a series of investigations from which the long-term objective is to determine the optimum anesthetic management in the presence of fetal distress.

Using pregnant sheep in which an adjustable uterine artery occluder was used to induce a controlled state of fetal asphyxia, we investigated the effects of isoflurane–oxygen anesthesia on maternal and fetal hemodynamics. In addition, fetal cardiac output, regional and cerebral blood flows, and fetal cerebral oxygen consumption were determined.

Methods

Surgical Preparation

Following approval of the Institutional Committee on Animal Research, eight pregnant ewes with singleton fetuses at 124–127 days gestation (term 145 days) were prepared for study. Each animal was anesthetized with an iv infusion of ketamine and with a tetracaine subarachnoid block. Using sterile surgical technique, sterile polyvinyl catheters were inserted into one maternal femoral artery and one femoral vein and the incision closed. Following a midline laparotomy, an adjustable loop occluder was secured around the common uterine arterial trunk and an electromagnetic flow transducer (Gould-Statham, Oxnard, California) placed around the uterine artery division supplying the uterine horn containing the fetus.

A hysterotomy was then carefully performed, and under local lidocaine anesthesia catheters inserted into both fetal axillary arteries, a femoral artery, a femoral vein, and the sagittal sinus. The axillary arterial catheters were advanced into the brachiocephalic trunk and the femoral venous catheter into the inferior vena cava. Three ECG electrodes were sutured directly to the fetal chest. Following replacement of the approximate volume of amniotic fluid lost during these procedures with sterile normal saline, the uterus was closed tightly around an intraamniotic catheter. The maternal and fetal cannulae, the flow transducer, the fetal ECG cables, and the uterine artery occluder were tunneled subcutaneously to the maternal flank and enclosed in a protective pocket. After closure of the abdominal incision and recovery from the anesthetic, each animal was allowed to stabilize for a min-

* Assistant Professor in Anesthesiology, Obstetrics and Gynecology, Baylor College of Medicine, Houston, Texas; Research Fellow in Obstetric Anesthesia, University of California, San Francisco.

† Associate Professor of Clinical Anesthesia, University of California, San Francisco.

‡ Professor and Vice Chairman of Research in Anesthesia, University of California, San Francisco.

§ Chief, Maternal Fetal Medicine, Naval Hospital, Oakland, California.

¶ Associate Professor of Clinical Anesthesia and Obstetrics, Gynecology and Reproductive Sciences, University of California, San Francisco.

Received from the Departments of Anesthesia and Obstetrics, Gynecology and Reproductive Sciences, University of California, San Francisco, California, the Department of Anesthesia, San Francisco General Hospital, San Francisco, California, and the Division of Maternal-Fetal Medicine, Naval Hospital, Oakland, California. Accepted for publication August 1, 1989. Supported in part by NIH Grant No. 104-32-1684. Presented at the Annual Meeting of the American Society of Anesthesiologists, October 1986, Las Vegas, Nevada.

Address reprint requests to Dr. Hughes: Department of Anesthesia, 3S50, San Francisco General Hospital, 1001 Potrero Avenue, San Francisco, California 94110.

imum of 48 h. During this period the cannulae were irrigated twice daily with sterile heparinized saline and the animals allowed free access to water and a standard ovine diet.

Experimental Protocol

Each ewe was positioned comfortably on the left side and loosely restrained. A nonconstricting blindfold was applied over the eyes so that the animal would remain calm and an ECG electrode was applied to each extremity. During the subsequent 30-min control period, with the animal breathing room air, maternal and fetal blood pressures, heart rates, and ECGs were continuously recorded on a direct writing oscillograph. The fetal heart rate was also recorded on a Hewlett-Packard Model 8030A cardiotocograph. Both the maternal and fetal heart rates were counted directly from the ECG records. Uterine blood flows were measured using a Gould-Statham, SP 2202 flowmeter. Maternal femoral and fetal axillary artery and sagittal sinus blood samples were analyzed for P_{O_2}, P_{CO_2}, and *p*H (Corning, 158pH/blood gas analyzer) at the beginning and at the end of the control period. These values were corrected for temperature. The oxyhemoglobin saturation and hemoglobin concentration of arterial blood from each fetus were measured (Radiometer, OSM22 hemoximeter) and the oxygen content was calculated. The definitive study was not performed unless the fetal arterial *p*H was 7.35 or above, and the fetal P_{O_2} above 15 mmHg during the control period.

The distribution of fetal cardiac output, regional and cerebral blood flows, and cerebral oxygen consumption determinations were made using the radionuclide-labeled microsphere technique.[4] These determinations consisted of the injection of 15 μm microspheres (^{125}I, ^{141}Ce, ^{51}Cr, ^{85}Sr, ^{95}Nb, or ^{46}Sc) into the fetal femoral vein, while simultaneously withdrawing blood from the fetal axillary and femoral arteries during a 90-s interval. Following each determination the fetus was transfused with a quantity of blood equal to that withdrawn. The radioactivity of the fetal arterial samples was determined and used to calculate cardiac output, regional, and cerebral blood flows. These measurements were made during the control period for comparison with similar measurements after 15 min of fetal asphyxia and after 15 min of fetal asphyxia plus isoflurane–oxygen anesthesia. A different radionuclide was used for each injection.

Following the control determinations, fetal asphyxia was produced by gradually occluding the maternal common uterine artery and reducing uterine artery blood flow to approximately 50% of the control value.[5] During this intervention there were occasional decelerations of the fetal heart rate. When this occurred the arterial occlusion was discontinued and the fetus was allowed to recover. At 15-min intervals following successful occlusion, fetal axillary arterial samples were drawn for measurements of *p*H and the occluder adjusted until a stable level of acidosis was established. Stable acidosis was defined as an arterial *p*H of 7.1–7.2 in two consecutive samples drawn 15 min apart. At this time: 1) maternal femoral and fetal axillary arterial and sagittal sinus blood samples were obtained for P_{O_2}, P_{CO_2}, and *p*H determinations, and 2) the second microsphere injected for determinations of fetal cardiac output, regional, and cerebral blood flows.

The effects of isoflurane–oxygen anesthesia in the presence of continuing fetal asphyxia were then determined. Each ewe was anesthetized with an inspired concentration of 4% isoflurane in oxygen by mask. Tracheal intubation was carried out following iv succinylcholine, 1 mg/kg and the inspired isoflurane concentration was reduced to 1%. The time from induction to intubation was recorded. Ventilation was controlled and adjusted as necessary to maintain arterial P_{CO_2} at control levels. The end-tidal concentrations of isoflurane (Beckman, LB2 infrared medical gas analyzer) were 1.05 ± 0.07% at 5 min, 1.09 ± 0.05% at 10 min, and 1.13 ± 0.02% at 15 min during the continuing fetal asphyxia. At this time: 1) maternal femoral and fetal axillary arterial and sagittal sinus blood samples were obtained for P_{O_2}, P_{CO_2}, and *p*H determinations, and 2) the third microsphere injected for determination of fetal cardiac output, regional, and cerebral blood flows.

At the conclusion of these three periods of observation, each ewe was killed by an iv injection of pentobarbital and succinylcholine. Each fetus was removed surgically and as rapidly as possible post mortem, weighed and dissected. The fetal heart, brain, thymus, adrenals, liver, spleen, kidneys, both large and small bowel, carcass (musculoskeletal system and skin), and placenta were removed intact. To verify that admixture from extracerebral venous drainage had not occurred, the position of each sagittal sinus catheter was confirmed to be above the confluence of sinuses at necropsy. Each brain was further subdivided into the cerebral hemispheres, cerebellum, and brain stem. These tissues were individually coded, weighed, treated with formalin, carbonized, and ground. Each of the ground, particulate, whole organ samples was placed in a separate scintillation counter vial. The amount of each radionuclide in the blood samples obtained during the control, stable acidosis, and stable acidosis plus isoflurane–oxygen anesthesia periods, as well as in each of the fetal tissue specimens was measured in a well-type gamma scintillation counter with a 1,000-channel pulse height analyzer (Ino./Tech, Ft. Atkinson, WI).

The blood flow to each organ, during each of the three experimental periods, was calculated from the ratio of

radioactivity in the reference blood sample, *i.e.*, femoral or axillary arterial or sagittal sinus, and that in each corresponding tissue specimen using the following equation:

$$\text{Blood flow (ml} \cdot 100\ \text{g}^{-1} \cdot \text{min}^{1}) = F_a \cdot i \cdot t$$

where

F_a = sample withdrawal rate;
i = nuclide count of reference blood; and
t = nuclide count of reference tissue.

Fetal cerebral oxygen consumption was calculated using the Fick equation:

$$CMR_{O_2} = CBF \cdot C(a - v)O_2$$

where

CMR_{O_2} = cerebral metabolic rate for O_2;
CBF = cerebral blood flow;
$C(a - v)O_2$ = axillary arterial − sagittal sinus O_2 content difference.

The changes in maternal and fetal blood pressure, heart rate, oxygen saturation, p_{O_2}, p_{CO_2}, *p*H, base excess, hydrogen ion concentration, hemoglobin, maternal uterine blood flow, as well as fetal cardiac output, fetal organ blood flows, and fetal cerebral oxygen consumptions were tested for statistical significance using analysis of variance (ANOVA) for repeated measures. Power analysis was performed if ANOVA indicated no statistically significant differences despite major changes between the periods of observation and if there was wide variability in experimental results. This was used to determine the likelihood that true differences between mean values were detectable by ANOVA. In situations in which power was less than 0.8, *i.e.*, a 20% or greater risk of type II error (β) existed, optimal sample size to reveal significant differences was calculated by iteration.[6] Power results are expressed as $1 - \beta$ and iterated sample size by n. The Student-Newman-Keuls multiple-range test was used where appropriate following these comparisons.[7] Differences were considered significant when $P < 0.05$, and variability was expressed as the SEM.

Results

Physiologically significant changes between the periods of observation are highlighted in this section. The mean time to establish initial fetal acidosis between *p*H 7.1 and 7.2 was 44 ± 7.3 min. Maternal induction-to-intubation time required 4.6 ± 0.2 min.

During asphyxia alone mean maternal blood pressure did not change, but addition of isoflurane to asphyxia caused a significant decrease in maternal blood pressure. Mean uterine blood flow was decreased 57% from control during asphyxia alone ($P < 0.05$). During asphyxia plus isoflurane–oxygen, mean uterine blood flow decreased an additional 33%; this was not significant. Power analysis indicated that the likelihood of committing a type II error with a sample of this size was less than 5% ($1 - \beta \geq 0.95$). Mean fetal heart rate decreased significantly from control during asphyxia but returned to near-control values during asphyxia plus isoflurane–oxygen. The 25% increase in fetal heart rate during isoflurane–oxygen was significantly higher than asphyxia alone (table 1).

During asphyxia alone maternal oxyhemoglobin saturation increased approximately 3% ($P < 0.05$). During asphyxia plus isoflurane–oxygen, the maternal arterial *p*H and hemoglobin decreased while the p_{O_2} and oxyhemoglobin saturation increased ($P < 0.05$). During asphyxia alone the mean fetal arterial *p*H and oxyhemoglobin saturation decreased significantly. The p_{O_2} remained relatively constant, and the p_{CO_2} and hemoglobin increased significantly. During asphyxia plus isoflurane–oxygen, the fetal arterial *p*H decreased significantly with respect to both control and asphyxia alone and the p_{CO_2} increased significantly from both control and asphyxia alone (table 2).

During asphyxia alone the mean fetal sagittal sinus *p*H and oxyhemoglobin saturation decreased significantly, whereas the p_{O_2} and p_{CO_2} were not significantly different from control. During asphyxia plus isoflurane–oxygen, the *p*H decreased further and was significantly less than that during both control and asphyxia alone. The p_{O_2} remained unchanged and thep_{CO_2} was significantly higher than that during both control and asphyxia alone. The oxyhemoglobin saturation was significantly lower than during control but unchanged compared with that during asphyxia alone. Fetal arterial base excess during asphyxia alone decreased significantly from control. During asphyxia plus isoflurane–oxygen it decreased further. This

TABLE 1. Mean (±SE) Maternal and Fetal Heart Rates and Blood Pressures and Uterine Blood Flows during Control, Fetal Asphyxia, and Fetal Asphyxia + Isoflurane–Oxygen

Source	Control	Asphyxia	Asphyxia + Isoflurane
Maternal			
Heart rate (beats/min) (5)	112 ± 7	104 ± 6	114 ± 19
BP (mmHg) (5)	106 ± 10	112 ± 9	86 ± 13*†
UBF (ml/min) (7)	762 ± 133	326 ± 60*	217 ± 39*
Fetal			
Heart rate (beats/min) (8)	190 ± 8	147 ± 12*	183 ± 11†
BP (mmHg) (8)	45 ± 2	49 ± 3	47 ± 4

Values in parentheses are the number of observations.
* $P < 0.05$, *versus* control.
† $P < 0.05$, *versus* asphyxia.

TABLE 2. Mean (±SE) Maternal FI_{O_2}, Maternal and Fetal Arterial and Sagittal Sinus Venous, Blood Gas, Acid–Base, and Hemoglobin Values during Control, Fetal Asphyxia, and Fetal Asphyxia + Isoflurane–Oxygen

Source	Control	Asphyxia	Asphyxia + isoflurance
Maternal arterial			
Femoral (6)			
FI_{O_2}	0.21	0.21	0.98
O_2 saturation	88.6 ± 2.2	91.7 ± 1.6*	97.8 ± 1.9*†
P_{O_2} (mmHg)	69.8 ± 5.1	77.0 ± 4.2	296.6 ± 59.8*†
P_{CO_2} (mmHg)	33.8 ± 2.1	34.4 ± 2.1	36.8 ± 3.3
*p*H	7.53 ± 0.01	7.54 ± 0.01	7.49 ± 0.02*†
Base excess	6.7 ± 1.6	7.5 ± 1.7	6.2 ± 1.4
H^+ (nM/l)	29.3 ± 0.4	29.2 ± 0.6	32.9 ± 1.9
Hemoglobin (g/dl)	8.4 ± 0.4	8.5 ± 0.6	7.8 ± 1.8*
Fetal arterial			
Axillary (8)			
O_2 saturation (%)	47.8 ± 4.6	20.5 ± 2.1*	19.0 ± 4.1*
P_{O_2} (mmHg)	19.7 ± 1.3	15.8 ± 1.0	18.7 ± 2.3
P_{CO_2} (mmHg)	43.0 ± 1.9	55.9 ± 3.0*	79.9 ± 6.3*†
*p*H	7.39 ± 0.02	7.16 ± 0.01*	6.99 ± 0.03*†
Base excess	1.8 ± 1.6	−9.3 ± 0.5*	−14.6 ± 1.0*†
H^+ (nM/l)	40.7 ± 2.0	68.8 ± 2.3*	104.0 ± 7.2*†
Hemoglobin (g/dl)	9.8 ± 0.6	10.3 ± 0.7*	10.4 ± 0.6*
Fetal venous			
Sagittal sinus (6)			
O_2 saturation (%)	34.2 ± 4.7	14.2 ± 1.8*	16.0 ± 4.9*
P_{O_2} (mmHg)	16.7 ± 1.2	12.6 ± 1.2	14.4 ± 3.3
P_{CO_2} (mmHg)	47.5 ± 1.7	55.7 ± 2.2	78.8 ± 8.1*†
*p*H	7.35 ± 0.03	7.16 ± 0.01*	6.99 ± 0.05*†
Base excess	0.9 ± 2.4	−9.2 ± 0.7*	−14.9 ± 1.4*
H^+ (nM/l)	45.6 ± 3.3	68.7 ± 1.2	105.4 ± 11.3*†

Values in parentheses are the number of observations.
* $P < 0.05$, *versus* control.
† $P < 0.05$, *versus* asphyxia.

change was significantly different from both control and asphyxia alone (table 2).

The calculated fetal cardiac output and organ blood flows are summarized in table 3. During asphyxia alone heart, brain, and adrenal blood flows were significantly higher, whereas spleen and carcass flows were lower than control. During asphyxia plus isoflurane–oxygen heart, brain, and adrenal flows remained elevated above control. The heart and adrenal flows (but not the brain flow) were significantly higher than control. Calculated fetal cardiac output decreased during asphyxia alone and further during asphyxia plus isoflurane–oxygen. These differences were not significant ($1 - \beta = 0.5$; $n \geq 12$).

TABLE 3. Mean (±SE) Fetal Whole Organ Blood Flows and Cardiac Output Values during Control, Fetal Asphyxia, and Fetal Asphyxia + Isoflurane–Oxygen

Blood Flow (ml · 100 g^{-1} · min^{-1})	Control	Asphyxia	Asphyxia + Isoflurane
Heart (8)	310 ± 40	711 ± 106*	691 ± 74*
Brain (8)	196 ± 24	346 ± 46*	267 ± 43
Thymus (7)	83 ± 13	55 ± 10	40 ± 10*
Adrenal (8)	334 ± 45	988 ± 222*	773 ± 90*
Gut (8)	77 ± 18	68 ± 18	53 ± 11
Liver (8)	12 ± 8	15 ± 6	16 ± 5
Spleen (7)	466 ± 101	200 ± 58*	162 ± 71*
Kidney (8)	215 ± 28	141 ± 35	90 ± 25*
Placenta (6)	344 ± 54	330 ± 58	202 ± 20
Carcass (8)	35 ± 4	20 ± 3*	19 ± 5*
Cardiac output (ml/min) (7)	750 ± 104	703 ± 85	485 ± 70

Values in parentheses are the number of observations.
* $P < 0.05$, *versus* control.

Regional cerebral blood flow data are summarized in table 4. The brain stem and total brain flows increased significantly above control during asphyxia alone but returned toward control during asphyxia plus isoflurane–oxygen.

Fetal axillary arterial and sagittal sinus oxygen contents and $C(a\text{-}v)O_2$ decreased significantly from control during both asphyxia alone and asphyxia plus isoflurane–oxygen. Cerebral oxygen consumption decreased during asphyxia alone and during asphyxia plus isoflurane–oxygen. The change during asphyxia plus isoflurane–oxygen was significantly different from control but not different from asphyxia alone ($1 - \beta = 0.91$). Cerebral oxygen delivery decreased from control during asphyxia alone and as-

TABLE 4. Mean (±SE) Fetal Regional and Total Brain Blood Flows (ml · 100 g^{-1} · min^{-1}) during Control, Fetal Asphyxia, and Fetal Asphyxia + Isoflurane–Oxygen

Source	Control	Asphyxia	Asphyxia + Isoflurane
Hemisphere (8)	176 ± 20	310 ± 43	241 ± 43
Cerebellum (8)	247 ± 34	412 ± 70	311 ± 22
Brain stem (8)	320 ± 42	676 ± 113*	495 ± 56
Total brain (8)	196 ± 24	346 ± 46*	267 ± 43

Values in parentheses are the number of observations.
* $P < 0.05$, *versus* control.

phyxia plus isoflurane–oxygen. These differences were not significant ($1 - \beta = 0.25$; $n \geq 22$) (table 5).

Discussion

Previous methods used to induce experimental fetal asphyxia include maternal hypoxemia, fetal hypovolemia, and umbilical cord compression.[8–10] However, these experimental models do not directly address uteroplacental perfusion, which is the primary determinant of normal gas exchange across the placenta. Accordingly, we used incremental uterine artery occlusion to reduce uteroplacental perfusion and impair gas exchange between mother and fetus. As a result, our model may be more applicable to clinical situations involving acutely diminished uteroplacental blood flow, *e.g.*, uterine artery vasoconstriction and hypertonic disorders of labor.

General anesthesia is often reserved for situations in which emergency delivery is indicated. This typically involves a rapid-sequence iv induction with thiopental or ketamine, for example, and maintenance with an inhaled agent. All animals in this study were anesthetized by inhalation of isoflurane–oxygen. Although we tried to simulate the clinical situation as much as possible, this is a departure from what would occur in clinical practice. However, in our experimental design, the addition of thiopental, ketamine, or other anesthetics would have confounded any attempt to isolate the effects of isoflurane–oxygen.

Another possible limitation in the design of the present studies is that there were no time-matched control experiments. However, subsequent to this study and using the same preparation, we extended the uterine artery occlusion with stable fetal acidosis for an additional 30 min and observed no significant deterioration in fetal arterial *p*H.[11]

We found that the administration of isoflurane–oxygen during fetal asphyxia exacerbated combined metabolic and respiratory acidosis. These observations are consistent with those of Biehl *et al.*, who found progressive fetal acidosis during maternal exposure to 2% isoflurane in a similar sheep model.[12] In their studies, which did not employ fetal asphyxia, acidosis became statistically significant at 48 min of isoflurane exposure. In contrast, during maternal halothane anesthesia (1.5% inspired), acid–base status and regional blood flows were well maintained in the normal sheep fetus,[3] whereas 1% halothane administered to the pregnant ewe was associated with progressive acidosis in the fetus compromised by uterine artery occlusion.[11]

The near-term sheep fetus has functioning adrenergic and cholinergic receptors, baroreceptors, and chemoreceptors that regulate cardiovascular responses to various stimuli.[13–15] During hypoxemia these reflexes are activated to increase systemic vascular resistance preferentially and redistribute cardiac output toward vital organs, such as the brain, placenta, heart, and adrenals, and away from tissue, such as the trunk. In the present study administration of isoflurane–oxygen did not alter this pattern: 1) compensatory increases in myocardial and adrenal blood flow, and 2) decreases in renal and carcass blood flow were preserved.

Other hemodynamic findings in our study were more complex. During asphyxia plus isoflurane–oxygen, in the presence of a constant level of uterine artery occlusion, uterine blood flow decreased in proportion to the reduction in maternal mean arterial blood pressure. During asphyxia alone fetal heart rate decreased, whereas fetal mean arterial blood pressure and cardiac output were unchanged. These sequelae to fetal asphyxia have been reported by others and are attributed to a combination of vagal and α- and β-adrenergic activity.[15–17] In the present study fetal heart rate increased toward control values during asphyxia plus isoflurane–oxygen compared with asphyxia alone. Fetal mean arterial blood pressure remained unchanged and cardiac output decreased. These results suggest that fetal systemic vascular resistance increased and that fetal stroke volume decreased during isoflurane–oxygen, although we did not measure these

TABLE 5. Mean (±SE) Fetal Axillary Arterial and Sagittal Sinus Oxygen Contents, Arteriovenous Oxygen Differences, Cerebral Oxygen Consumption, and Oxygen Delivery Values during Control, Fetal Asphyxia, and Fetal Asphyxia + Isoflurane–Oxygen

Variable	Control	Asphyxia	Asphyxia + Isoflurane
O_2 content (ml/dl)			
Axillary artery (8)	6.21 ± 0.63	2.81 ± 0.28*	2.65 ± 0.51*
Sagittal sinus (6)	4.38 ± 0.71	1.88 ± 0.25*	2.19 ± 0.63*
$C(a-v)O_2$ (ml/dl) (6)	2.13 ± 0.14	0.94 ± 0.09*	0.83 ± 0.16*
CMR_{O_2} (ml O_2 · 100 g^{-1} · min^{-1}) (6)	3.54 ± 0.65	2.54 ± 0.35	1.73 ± 0.22*
O_2 delivery (ml O_2 · 100 g^{-1} · min^{-1}) (6)	10.00 ± 2.93	6.66 ± 1.34	6.43 ± 1.99

Values in parentheses are the number of observations.
* $P < 0.05$, *versus* control.

variables. Hypoxemia combined with acidemia depresses fetal myocardial performance,[16] as does isoflurane alone.[12] These two factors could account for a decrease in fetal stroke volume.

In the present studies fetal brain stem and total brain blood flows increased in response to asphyxia, although fetal mean arterial blood pressure did not change significantly (tables 1 and 4). Thus, even at low oxygen saturations, some reflex redistribution of blood flow was evident. This increase in brain blood flows may have been enhanced by the effect of hypercarbia on cerebral blood flow.[18] During isoflurane–oxygen anesthesia, brain stem and total brain blood flows decreased toward control values. Thus, isoflurane appears to blunt the compensatory increase in brain stem and total brain blood flows that accompany fetal asphyxia. However, cerebral oxygen delivery remained relatively constant, whereas cerebral oxygen consumption decreased (tables 4 and 5). Thus, the balance between fetal cerebral oxygen supply and demand was maintained.

At the inception of this study, one of a series investigating optimum maternal anesthetic management in the presence of fetal distress, we hypothetized that isoflurane–oxygen might offer significant protection to the fetal brain compromised by asphyxia.[19] Indeed, and as shown in table 5, fetal brain oxygen consumption was reduced approximately 32% during asphyxia plus isoflurane–oxygen compared with asphyxia alone. However, power analysis indicated (with over 90% certainty) that the observed reduction in fetal brain oxygen consumption during isoflurane–oxygen was not statistically significant. Because it is known that fetal brain oxygen consumption is reduced by asphyxia,[20] it is possible that the present observations may have been due to the effect of asphyxia alone, independent of isoflurane–oxygen, or to some combination of the two. This conclusion awaits experimental confirmation.

In summary, brief maternal isoflurane–oxygen anesthesia exacerbated preexisting acidosis in the asphyxiated fetal lamb. The redistribution of cardiac output to vital organs that normally occurs during fetal asphyxia was preserved during isoflurane–oxygen administration. Although the increase in blood flow to the brain stem and total brain was blunted, the balance between cerebral oxygen supply and demand remained favorable.

References

1. Levinson G, Shnider SM, Gildea JE, DeLorimier AA: Maternal and foetal cardiovascular and acid–base changes during ketamine anaesthesia in pregnant ewes. Br J Anaesth 45:1111–1115, 1973
2. Palahniuk RJ, Shnider SM: Maternal and fetal cardiovascular and acid–base changes during halothane and isoflurane anesthesia in the pregnant ewe. ANESTHESIOLOGY 41:462–472, 1974
3. Biehl DR, Tweed WA, Cote J, Wade JG, Sitar D: Effect of halothane on cardiac output and regional flow in the fetal lamb in utero. Anesth Analg 62:489–492, 1983
4. Rudolph AM, Heymann MA: The circulation of the fetus in utero: Methods for studying distribution of blood flow, cardiac output and organ blood flow. Circ Res 21:163–184, 1967
5. Yaffe H, Katz M, Parer JT: Technique for stepwise reduction of uterine blood flow in the chronically prepared pregnant sheep. Gynecol Obstet Invest 13:257–260, 1982
6. Pearson ES, Hartley HO: Charts of the power function for analysis of variance tests, derived from the non-central *F*-distribution. Biometrika 38:112–130, 1951
7. Zar J: Multiple comparisons, Biostatistical Analysis. Englewood Cliffs, Prentice-Hall, 1974, pp 151–155
8. Tweed WA, Cote J, Pash M, Lou H: Arterial oxygenation determines autoregulation of cerebral blood flow in the fetal lamb. Pediatr Res 17:246–249, 1983
9. Tweed WA, Cote J, Wade JG, Gregory G, Mills A: Preservation of fetal brain blood flow relative to other organs during hypovolemic hypotension. Pediatr Res 16:137–140, 1982
10. Johnson GN, Palahniuk RJ, Tweed WA, Jones MV, Wade JG: Regional cerebral blood flow changes during severe fetal asphyxia produced by slow partial umbilical cord compression. Am J Obstet Gynecol 135:48–52, 1979
11. Cheek DBC, Hughes SC, Dailey PA, Field DR, Pytka S, Rosen MA, Parer JT, Shnider SM: Effect of halothane on regional cerebral metabolic oxygen consumption in the fetal lamb in utero. ANESTHESIOLOGY 67:361–366, 1987
12. Biehl DR, Yarnell R, Wade JG, Sitar D: The uptake of isoflurane by the foetal lamb in utero: Effect on regional blood flow. Can Anaesth Soc J 30:581–586, 1983
13. Barrett CT, Heymann MA, Rudolph AM: Alpha and beta adrenergic receptor activity in fetal sheep. Am J Obstet Gynecol 112: 1114–1121, 1972
14. Sheldon RE, Peeters LLH, Jones MD Jr, Makowski EL, Meschia G: Redistribution of cardiac output and oxygen delivery in the hypoxemic fetal lamb. Am J Obstet Gynecol 135:1071–1078, 1979
15. Reuss ML, Parer JT, Harris JL, Krueger TR: Hemodynamic effects of alpha-adrenergic blockade during hypoxia in fetal sheep. Am J Obstet Gynecol 142:410–415, 1982
16. Cohn HE, Sacks EJ, Heymann MA, Rudolph AM: Cardiovascular responses to hypoxemia and acidemia in fetal lambs. Am J Obstet Gynecol 120:817–824, 1974
17. Court DJ, Parer JT, Block BSB, Llanos AJ: Effects of beta-adrenergic blockade on blood flow distribution during hypoxaemia in fetal sheep. J Dev Physiol 6:349–358, 1984
18. Rosenberg AA, Jones MD Jr, Traystman RJ, Simmons MA, Molteni RA: Response of cerebral blood flow to changes in P_{CO_2} in fetal, newborn, and adult sheep. Am J Physiol 242:H862–H866, 1982
19. Newberg LA, Michenfelder JD: Cerebral protection by isoflurane during hypoxemia or ischemia. ANESTHESIOLOGY 59:29–35, 1983
20. Jones MD, Sheldon RE, Peeters LL, Meschia G, Battaglia FC, Makowski EL: Fetal cerebral oxygen consumption at difficult levels of oxygenation. J Appl Physiol 43:1080–1084, 1977