3/24/2005

Anesthesia for Premies

Morris Dressler, MD

Introduction:

Six percent of births are premature.

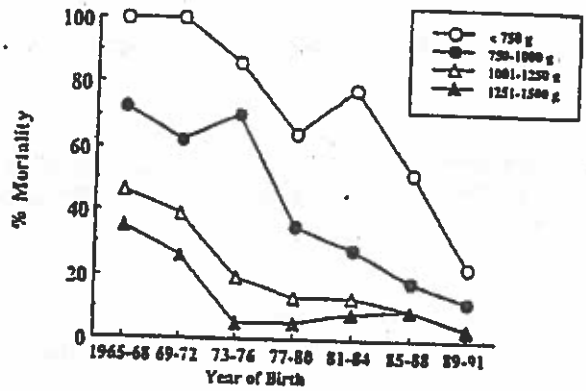
The last three months of gestation most body organs undergo much structural and functional development thus premature infants are ill prepared for adequate functioning outside the womb. They are less able to maintain temperature, suck , swallow or sustain ventilation. Many experience asphyxia at or just prior to birth, which predisposes them to CNS damage, intraventricular hemorrhage (IVH), respiratory distress syndrome (RDS) and necrotizing entercolitis.

Level of Prematurity:

Borderline 36-37 wk GA. 16% of births. 8% del. By CSx. develop RDS vs. 1% SVD

Moderately 31-36 wk GA. 6-7% of births. 1.5-2.5 Kg. W/ up to 5% mortality. (IVH, RDS, and sepsis)

Severely 24-30wk GA. 0.5-1.5 Kg. 1% of births. 70% of neonatal mortality and a major portion have significant CNS seq. Major causes of death ; asphyxia, acidosis, resp. failure (CHF, RDS, infxn. Esp. B-strep. and Listeria), NEC, and IVH.



Mortality by birth weight

Asphyxia:

Premies prone to asphyxia secondary to anemia and low O2 carrying cap. Small amounts of stress lead to anaerobic met. and met. acidosis , which in turn led to reduced card. Output and incr. in CBF.

Causes incl. Antepartum bleed . Intraut. Infxn., Breech delivery and RDS.

Rx.: intubation , hypervent., Blood volume expan. and if necessary slow infusion of NaHCO (no more rapidly than 1 mEq/kg/min) as it can lead to IVH due to rapid volume expansion and increasing CO levels. It may also reduce cerebral blood flow to dangerous levels.

Monitor bld. Gluc. Levels and try to maintain in the 45-90 mg/dl. range.

Temperature Regulation:

Hypothermia greatly increases metabolic rate and O2 consumption. Min requirements for preterm infants 4.3-5.4 ml/kg/min. on day one and 8-9 ml/kg/min. by 2 wk.

Heat loss by: **Conduction, convection, radiation and evaporation.** Room temp., Heating blanket, IR lights, Bair hugger, Saran wrap, Caps, Fluid warmers, etc.

Heat loss exacerbated by lack of fat, large surface area/small heat plant, open posture, thin skin (leading to 25+% of heat loss due to evaporation. Premies have little brown fat. Hypoglycemia and CNS damage led to loss of central therm. reg. Hypothermia leads to apnea, bradycardia, hyperglycemia and aspiration.

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Respiratory Manifestations:

Three times more common in CSx. Infants than vag. delivered infants.

Be careful of high vent pressures (< 20cm H2O).

Be careful of hyperoxygenation (PaO2 of 50-70, SpO2 of 87-92 is generally fine).

Is PEEP and Lasix being used to treat RDS? Is the pt. Alkalotic and compensated? Don't hyperventilate! Also Do Not have pt. self ventilate. Titrate FiO2 carefully.

Is there a PDA? Typically develops as RDS resolves (day 3-5) SEM (or continuos) heard at LSB. Bounding Pulses, Wide Pulse width and gallop noted frequently. Leads to CHF, increased respiratory effort, retractions, rales and decreased breath sounds and tachycardia. Low PaO2, high PCO2. Can lead to NEC and huge third space losses.

Sepsis:

Subtle signs often, esp. with sign. prematurity (hypo- or hyperthermic, lethargy, mottled, gray, apneic?). Often no positive blood cultures , WBC can be low, normal or high, may not mount a fever. Abx? Aminoglycosides - paralysis/potentiation. Lack of gut flora may lead to increased bleeding (Vit. K).

Necrotizing Entercolitis:

Recent start of feeds? Abdominal distention, vomiting, bloody stools, reducing substances in the stools and shock. Large volumes of Lactated ringers (may increase need for vent. support due to worsening RDS).

Hematologic Manifestations:

Hgb./Hct.? 15/45 lower chance of apnea. 8-10/24-30 incr. chance of apnea and CHF assoc. w/ PDA.

Nutrition and Growth:

Resp. distress decreases ability to absorb nutrients. D12.5/0.25 NS w/ AA.s 2-3 gm/kg and lipids 2-3 gm/kg should provide 80-100 kcal/kg/day. Na 3mEq/kg, K 2 mEq/kg, 200-500 mg/kg Calcium gluconate and Vitamins incl. Vit. E.

Metabolic Determinates:

Premies have low proteins and decreased ability to resorb bicarb. (renal tubular acidosis) and inability to secrete ammonia. If acidosis requires correction do so with NaHCO3 at 0.6 X base deficit X wt. in Kg.

Hypocalciumia (<7mg/dl) may be manifest as twitching, Sz.s, hypotension and can be corrected with calcium gluconate 100-200 mg/kg. (Be careful of hypervent.) EKG is generally normal?!

Hyponatremia (<120 mEq/kg) may ppt. Sz.s. Hypernatremia can cause CNS damage. Rx. Fluid restriction.

Glucose: most premies can tolerate 5-7mg/kg /min w/o developing hyperglycemia, glucouria, polyuria and dehydration, although some will with infusions as low as 2mg/kg/min. blood glucose's of <40mg/dl should be corrected with boluses of D10-20 at 2-5 mg/kg.

Bilirubin; levels of 10-15 mg/dl in an acidotic infant can cause kerniterus with disastrous CNS results. If time permits a two volume exchange transfusion can be done.

Oxygen; Retinopathy of prematurity (ROP) is seen in 3-43% of premies. In utero levels of PaO2 are30-40 mmHg (see rec.'s above).

Conclusions:

"Anesthesia for premature infants is often difficult because these infants have multisystem disease and respond poorly to anesthesia. It is important to garner as much information and help preoperatively as possible... A common mistake, especially among beginning anesthesiologists, is to ignore the (care plan of the neonatologists). (Gregory, 1994)

Try to discuss the case with the neonatologist and the RN taking care of the infant . The nurse will now the 'quirks' of the individual patient, things the physician may not be aware of. For example, the nurse

may have noted brief periods of apnea which may cause severe hypoxemia and cyanosis or that the patients perfusion decreases when his blood glucose decreases to 40 mg/dl or his calcium concentration falls below 7 mg/dl.

History:

Birth asphyxia? Lack of autoreg. of CBF → incr. B/P → ICB.
Depressed myocardial fxn?
Decreased blood flow to the gut?
Anemia?
Maternal Drug Hx?
Illicit?
Heroin-agitation, tremors, poor feeding, Szs.
Barbs., Benzos., methadone; same sx's 5-10 days later./
ASA, APAP; Pulm. HTN, PPHN
Congenital Abnormalities?
Cleft palate?
ROP?
Glaucoma? Atropine contraindicated.
Pulmonary Problems?
RDS? Vent. Sup.? PIP, PEEP, RR, FiO2, Insp. Time.
ABGs (Labile?)
CV?
CHD? Shunts, CHF? Gallop? Murmur?
Abdomen?
Liver size (very distensible and fragile). Distended? Tender?
Ascites? Free air?
Hydration?
Fontelle. Fluid overloaded but still intravascularly dry?
Hematology?
H/H. Platelets, clotting factor deficit due to Abx?
Electrolytes?
As above.
Oxygenation?
Retractions, other signs of distress, murmur/gallop, Vent. Settings,
ABG's (serial, trends, acid/ base).

Consider using Fentanyl 10 mcg/kg (up to 30 mcg/kg) and a relaxant.

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Review article

Anaesthesia for fetal surgery

LAURA B. MYERS MD*, DAVID COHEN MD**, JEFFREY GALINKIN MD**, ROBERT GAISER MD† AND C. DEAN KURTH MD**

**Department of Anesthesia, Children's Hospital, Harvard Medical School, Boston, MA, **Department of Anesthesiology and Critical Care, The Children's Hospital of Philadelphia, University of Pennsylvania School of Medicine, Philadelphia and †Department of Anesthesia and Critical Care, The Hospital of the University of Pennsylvania, University of Pennsylvania School of Medicine, Philadelphia, PA, USA*

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Introduction

The National Institute of Child Health and Development was asked recently to predict health care in the new millennium. The Institute predicted, by the year 2020, that the routine diagnosis and treatment of congenital malformations *in utero* before secondary morbidity would develop (1). Fetal surgery was specifically mentioned as standard therapy for most disabling malformations that are currently treated in young infants. With advances in prenatal ultrasonography techniques, many structural anomalies can now be identified in the first trimester, affording the opportunity for invasive fetal therapy and treatment before irreversible damage occurs (2). If this proves to be the case, anaesthesia for neonatal surgical emergencies will not be as common as it is today. This paper will review the indications, anaesthetic issues and postoperative pain management for fetal surgery as practiced in the year 2002 (2).

Historical perspective

The first successful fetal procedure was performed in 1963 by Sir William Liley, consisting of an intraperitoneal blood transfusion to a fetus affected with erythroblastosis fetalis (3). Years of animal investigations followed, most notably by Dr Michael Harrison and his team at the University of California, San Francisco (4–8). Surgical, anaesthetic and tocolytic techniques were first developed in non-human primates and then refined in fetal lambs and rhesus monkeys. This process ultimately led to the surgical techniques used for human fetal surgery today.

To date, three medical institutions perform the majority of fetal surgical procedures in the USA: The Children's Hospital of Philadelphia, Vanderbilt University Medical Center and University of California, San Francisco. These fetal teams have applied the knowledge acquired from years of animal research to human patients, performing human fetal surgery since the early 1990s. Fetal surgery has now become a treatment option for certain life-threatening diseases with promising results.

Distinction

Anaesthesia for fetal surgery involves two patients simultaneously, the mother and the fetus. Anaesthesia for fetal surgery differs from that for maternal surgery (e.g. Caesarean sections, cholecystectomy in the parturient) and fetal therapy (e.g. amniotic fluid reduction) (9). In fetal surgery, the fetus and mother are both active recipients of surgery whereas, in maternal surgery, the mother is an active recipient while the fetus is a bystander. In fetal therapy, the

Correspondence to: Laura B. Myers MD, Department of Anesthesia, Bader 3, Children's Hospital, 300 Longwood Ave, Boston, MA 02115, USA (e-mail: laura.myers@TCH.HARVARD.edu).

mother is a bystander while the fetus is an active recipient of therapy. The distinction will likely become more important as the mechanism of labour becomes better understood (10–12).

Fetal surgery consists of open or minimally invasive procedures. Open procedures require a hysterotomy on the mother and major airway, thoracic, cardiovascular and neurological procedures on the fetus. Minimally invasive fetal procedures include insertion of stents or shunts, occlusion or coagulation of fetoplacental structures, and transfusion of medications or blood products directly into the fetus. These procedures may be performed with sedation, regional anaesthesia or general anaesthesia, depending on maternal and fetal factors.

Indications for fetal surgery

The mother and fetus are considered appropriate for surgery only when the risk of death or severe disability to the fetus is greater than no intervention and the risk to the mother remains low (Table 1). Hydrops fetalis, a condition characterized by abnormal accumulation of fluid and oedema in the fetus, is the common final pathway in a number of pathological conditions. Several anatomical anomalies diagnosed *in utero* progress to hydrops with almost certain fetal demise. These anomalies are considered for fetal surgical intervention. Contraindications for fetal surgery include a lethal or disabling genetic disease in the fetus, other structural anomalies in the fetus, or a serious medical disease in the mother (e.g. preeclampsia, mirror syndrome) (6,9,13). After open fetal surgery, this pregnancy and all subsequent pregnancies require delivery by Caesarean section because the hysterotomy incision precludes a trial of labour. In contrast, fetal surgery using minimally invasive techniques permits vaginal delivery.

Thoracic diseases considered for fetal surgery include congenital cystic adenomatoid malformation (CCAM) and pulmonary sequestration in which the mass is increasing in size and hydrops is present (14). These masses and other intrathoracic masses can compress the heart and lungs, resulting in heart failure and severe pulmonary hypoplasia. The goals of these operations are to remove the mass to allow the lung to grow and to unobstruct systemic venous return to restore cardiovascular function (Figure 1). The longer the fetus remains *in utero* after surgery, the better the compensatory lung growth and chance of postnatal viability. Resection of the lesion through a thoracotomy usually takes place at 18–25 weeks of gestation (6,8,14).

Airway diseases for fetal surgery include large neck masses with anticipated airway obstruction and difficult intubation at birth, and congenital high airway obstruction syndrome (CHAOS). In these diseases, the airway is secured before birth with the EXIT procedure (*ex utero* intrapartum therapy) (6,8,9,14). The EXIT procedure entails delivering

Table 1
Fetal diseases eligible for fetal surgery

Disease	*Indication*
Thoracic	
Congenital cystic adenomatoid malformation	Hydrops
Congenital diaphragmatic hernia	Liver in chest; LHR < 1.0
Pulmonary sequestration	Hydrops
Cardiac	
Third-degree heart block	Ventricular response < 45 b·min^{-1}
Airway obstruction	
Congenital high airway obstruction	Hydrops
Giant neck mass	Polyhydramnios Anticipated difficult airway High-output state
Sacrococcygeal teratoma	
Twin syndromes	Acardiac-acephalic
TRAP sequence	Weight ratio < 0.7
TTTS	Growth discordance Oligo/polyhydramnios
Bladder outlet obstruction	Oligohydramnios Good prognostic profile

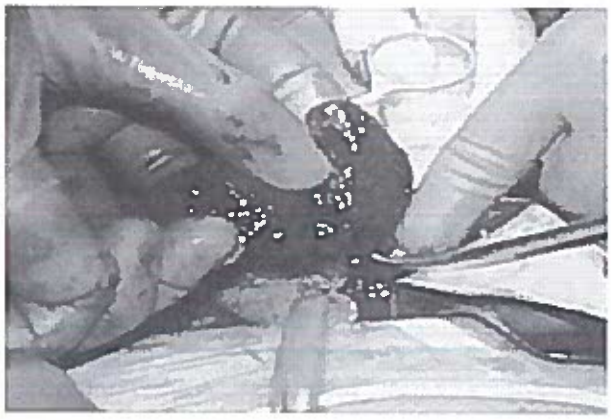

Figure 1
Resection of CCAM: operative exposure.

the fetal head through a controlled hysterotomy and managing the airway by direct laryngoscopy, bronchoscopy and intubation while fetal gas exchange is maintained via the placenta. If an orotracheal tube cannot be inserted, a tracheostomy is performed (Figure 2). In some circumstances, fetal gas exchange can be supported by *ex utero* placental circulation for over 60 min, affording ample time to secure the airway and partially resect the mass if needed. The mass is usually excised immediately after birth in an adjacent operating room by a separate surgical and anaesthesia team after airway evaluation, intubation and separation from the maternal circulation. The EXIT procedure is scheduled as close to term gestation as possible to avoid the problems associated with prematurity. However, the EXIT procedure may be earlier for CHAOS because of hydrops fetalis. In the latter circumstance, there is complete airway obstruction *in utero*, resulting in fluid accumulation in the developing lungs, pulmonary engorgement with compression of the heart and decreased venous return, leading to hydrops.

Twin syndromes considered for fetal surgery include twin reversed arterial perfusion sequence (TRAP) and twin–twin transfusion (6,9). In TRAP, one fetus has a lethal disease (e.g. acardiac or acephalic), which threatens the viability of the other fetus from high-output cardiac failure where hydrops ensues from the dual cardiac output required to support both twins. Fetal surgery involves ligation of the umbilical cord of the donor twin, which eliminates the source of the pump twin's high-output failure and the cord-ligated twin expires and mummifies *in utero*. This procedure is usually performed at 18–25 weeks of gestation. Birth of the live and mummified twins usually occurs near term by spontaneous vaginal delivery.

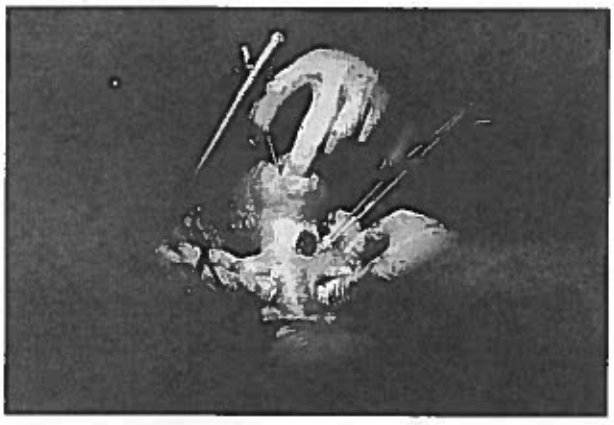

Figure 2
EXIT procedure.

In twin–twin transfusion syndrome (TTTS), monozygotic, monochorionic twins share communicating placental circulations. An imbalance of blood flow between them results in polyhydramnios in one twin (recipient) and oligohydramnios, and often growth retardation in the other (donor). The cause of this imbalance is thought to be arteriovenous anastomoses deep within the placenta that connect to superficial afferent and efferent vessels on the surface of the placenta. With laser ablation of these superficial vessels, survival and outcome of these twin fetuses may improve. Fetal surgery is indicated if the ratio of donor/recipient twin blood flow exceeds 0.7, because twins with this ratio develop cardiac failure, hydrops, neurological complications, preterm delivery or intrauterine demise (15).

Of all the fetal diseases, repair of meningomyelocele has recently received the most attention, in both lay press and professional publications (8,16–21). The objective for fetal meningomyelocele surgery is to prevent shunt-dependent hydrocephalus and further loss of spinal cord function. A growing body of evidence supports a dual causation of the loss of spinal cord function comprising an initial embryonic defect and a secondary injury of the neural tissue exposed to amniotic fluid throughout gestation. The contribution of the secondary injury relative to the initial embryonic defect remains unknown and is difficult to establish in human studies. However, an unexpected result of fetal closure of the meningomyelocele has been reversal of hindbrain herniation (Arnold Chiari defect) and a lower incidence of shunt dependent hydrocephalus. This benefit appears to result from the restoration of cerebrospinal fluid flow dynamics *in utero* after the spinal defect is closed. Fetal closure of the meningomyelocele through an open hysterotomy currently takes place at 22–25 weeks of gestation (Figure 3), although in the future closure may occur earlier in gestation to improve outcome (16,17,21).

Sacrococcygeal teratomas have also been removed *in utero* (6,9,22). These are highly vascular, benign tumours located near the sacrum. Large sized vascular defects can precipitate high-output cardiac failure and fetal hydrops, as well as obstruct

Figure 3
Myelomeningocele in 22-week-old fetus prior to repair.

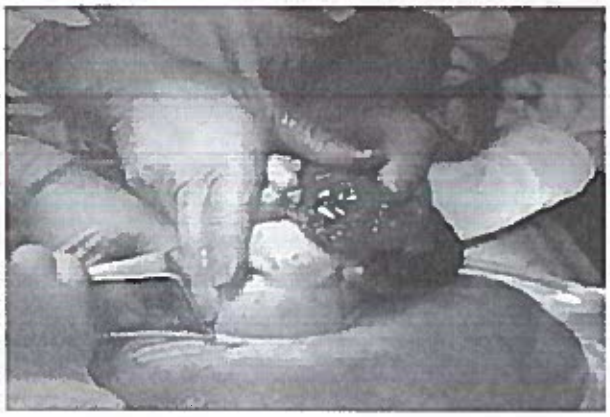

Figure 4
Sacrococcygeal teratoma in 24-week-old fetus prior to surgical repair.

urine output and cause oligohydramnios. Fetal surgery seeks to restore cardiovascular stability through complete or partial resection of the teratoma (Figure 4). The procedure usually occurs at 20–25 weeks of gestation.

Other fetal diseases under consideration for surgery include posterior urethral valves with bladder outlet obstruction, aqueductal stenosis of the fourth ventricle with resultant hydrocephalus and diaphragmatic hernia with liver in the chest (5,6,8,23,24). Over a decade ago, fetal surgery was performed for these diseases with dismal results. However, improved understanding of the pathophysiology, preoperative evaluation and surgical techniques has rekindled interest in fetal surgery for these disease processes.

Preoperative evaluation

Suspicion of fetal disease is usually raised by the detection of maternal polyhydramnios or oligohydramnios on a routine ultrasound examination during a prenatal visit. Medical evaluation of the fetus includes echocardiography to assess cardiovascular function, whole body ultrasound to delineate the defect and severity of hydrops and magnetic resonance imaging to detail the anatomy (25). A fetal karyotype analysis is performed for defects associated with genetic syndromes. The mother undergoes a complete history and physical examination, blood chemistry analysis and complete blood count, chest X-ray and electrocardiogram. The parents also undergo a psychosocial evaluation. After these evaluations, the fetal team convenes to discuss eligibility for surgery. The team consists of paediatric surgeons, perinatologists, anaesthesiologists, radiologists, geneticists, nurses, social workers and financial advisors. The team then meets with the parents to discuss the procedure and risks. Parents are given time to consider the risks and benefits of fetal surgery and to discuss the uncertainty of the fetal outcome for most procedures. Best surgical results require intervention early in gestation before irreversible damage has occurred so that sufficient *in utero* growth and healing can take place. After 30 weeks of gestation, it is usually too late for fetal surgery.

Anaesthetic considerations

These considerations include maternal, uteroplacental and fetal factors. The anaesthesiologist must balance these factors for optimal outcome during fetal surgery.

Virtually every organ system in the mother undergoes physiological changes during pregnancy (26–28). Those changes of particular importance to the anaesthesiologist are well known and include alterations in the gastrointestinal, pulmonary, cardiovascular and central nervous systems. The pregnant patient for fetal surgery is at increased risk of aspiration of gastric contents for several reasons. As the uterus enlarges, the gastroesophageal junction is shifted upward and posterior, resulting in incompetence. The pylorus is also displaced, slowing gastric emptying rates. With secretion of gastrin

from the placenta, the acid content within the stomach is elevated. These alterations can be exaggerated with obesity, multiple gestations and hydramnios. For these reasons, all pregnant patients must be considered at increased risk of aspiration and appropriate measures executed to minimize this risk.

Respiratory alterations during pregnancy are of particular significance to the anaesthesiologist (26–28). Minute ventilation is increased by 50% and oxygen consumption is increased to a lesser degree by the end of the first trimester. Because functional residual capacity decreases by 20%, these changes make the pregnant patient susceptible to hypoxia during anaesthetic induction. Mucosal capillary engorgement may also create difficulty with intubation of the trachea. It is also important to recognize that increased minute ventilation results in a normal resting $PaCO_2$ of 3.7–4.3 kPa (28–32 mmHg). Overzealous ventilation can further decrease the $PaCO_2$, resulting in a leftward shift of the oxyhaemoglobin curve, and may reduce the availability of oxygen to the fetus. With hyperventilation, a reduction of maternal cardiac output and uterine blood flow may also occur.

Supine hypotension syndrome can occur in pregnant patients from compression of the inferior vena cava by the gravid uterus (26–32). This compression can lead to a marked decrease in systemic venous return, as well as an increase in uterine venous pressure, and thus a decrease in uterine perfusion pressure, placing the fetus at risk for hypoxia. Compression of the aorta can further decrease uterine perfusion pressure by decreasing uterine blood flow. Therefore, it is imperative to provide left uterine displacement to minimize this risk.

Pregnancy is known to decrease minimal alveolar concentration (MAC) (13,26–32). This may be the result of increased levels of progesterone and beta endorphins. The epidural space is decreased by epidural venous engorgement. This may result in a greater chance of intravascular epidural placement, and less local anaesthetic to achieve the same level of epidural block compared with nonpregnant patients.

Total protein, serum albumin and plasma cholinesterase levels decrease during pregnancy. The resulting decrease in oncotic pressure from alterations in total protein make the pregnant patient vulnerable to fluid retention and pulmonary oedema and may prolong the effect of succinylcholine.

Uteroplacental factors considered for fetal surgery include the location of the placenta and cord structures in the uterus, maintenance of uterine and placental blood flow, maximal uterine relaxation for fetal surgical exposure and placental gas-exchange, prevention of premature labour in the postoperative period and placental passage of drugs during and after fetal surgery.

Volatile anaesthetics are powerful relaxants of uterine muscle (Figure 5). Near complete relaxation can be achieved with inhaled anaesthetic concentrations of 2 MAC. However, these high concentrations of volatile anaesthetics decrease uteroplacental perfusion and fetal cardiac output (30).

Uterine blood flow is the major determinant of placental blood flow and critical to the passage of drugs across the placenta (26–28,31,32). Any factors that decrease uterine blood flow during fetal surgery therefore may jeopardize fetal well being. These factors include increased uterine tone, maternal hypotension or hypertension and myometrial vasoconstriction from noradrenergic activity. As potent vasodilators, volatile anaesthetics decrease maternal arterial pressure and uteroplacental blood flow (9,33). Fetal arterial PaO_2 and pH decrease as isoflurane concentrations increase in the mother above 1.5 MAC (Figure 6). To maintain uteroplacental perfusion, maternal arterial pressure must be maintained during the anaesthetic. In addition, administration of sympathomimetics can cause this

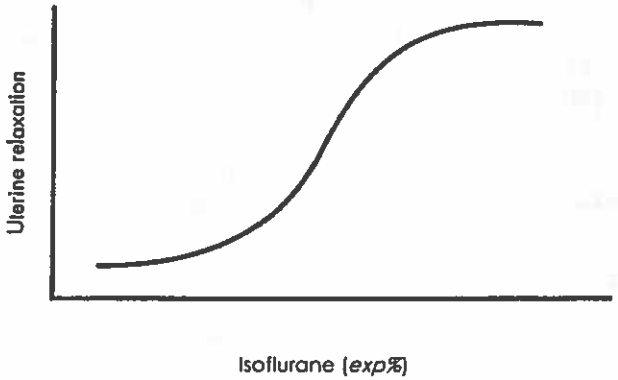

Figure 5
The effect of volatile anaesthetics on uterine tone. Reproduced with permission from Palahniuk and Schnider (31) and O'Hara and Kurth (9).

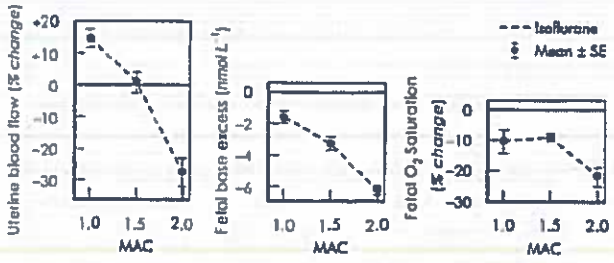

Figure 6
Effect of isoflurane on uterine blood flow, fetal base excess and fetal oxygen saturation in sheep. Reproduced with permission from Palahniuk and Schnider (31) and O'Hara and Kurth (9).

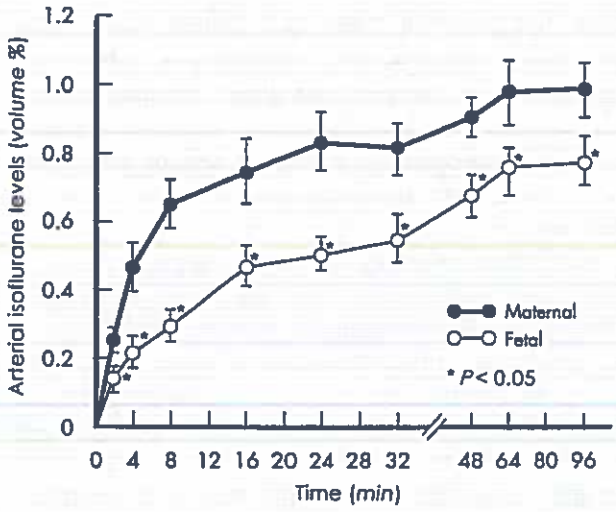

Figure 7
Anaesthetic uptake in mother and fetus in sheep. Reproduced with permission from Biehl *et al.* (34) and O'Hara and Kurth (9).

vasocontriction with a marked reduction in uterine blood flow. An exception is ephedrine, which possesses primarily beta-adrenergic effects and has minimal effects on uterine blood flow.

Known principles of placental transfer are used by the anaesthesiologist during fetal surgery. Substances (e.g. oxygen, carbon dioxide, fatty acids, sodium, glucose) cross the placental membrane by five mechanisms: diffusion, active transport, bulk flow, pinocytosis and via breaks of villi within the intervillous space (26–32). In addition, placental area, diffusion distance and permeability of the placental membrane play an important role in transfer of substances. Those substances that are lipid soluble, not ionized and of low molecular weight readily cross the placenta. All inhalational agents fit this criteria and placental transfer of inhaled agents occurs rapidly. Uptake of inhaled anaesthetic drugs occurs more slowly in the fetus that the mother (Figure 7) (34). Insoluble anaesthetics absorb faster than soluble anaesthetics. Because of the slower uptake by the fetus compared with the mother, it is very important to anticipate the timing of the fetal surgical procedure to achieve sufficient anaesthetic depth in the fetus. Fortunately, MAC in the fetus is less that that in the mother, and fetal MAC is well below that needed to obtain uterine relaxation (34,35). Thus, adequate maternal anaesthesia and uterine relaxation results in adequate fetal anaesthesia (34,36).

The combined immature organ system function (e.g. cardiovascular system) places fetal surgical patients at high anaesthetic risk. Fetal myocardial contractility is decreased compared with the neonate, child and adult (29,31,32,36). Blood volume is low in the fetal surgery patient (e.g. < 50 ml). Furthermore, decreased coagulation in the fetus predisposes to bleeding during surgery. Therefore, the fetus may require a blood transfusion in procedures usually associated with a minimal (10 ml) blood loss. Other concerns include thin, easily bruised skin, which offers little barrier to evaporative fluid and heat loss. The combination of decreased myocardial contractility, bleeding tendency and fluid loss predisposes the fetus to hypovolaemia, hypoperfusion and hypothermia. Decreased baroreceptor activity in the midgestation fetus limits compensatory venoconstriction in the presence of hypovolaemia (9). Hypoperfusion decreases fetal blood flow to the placenta, which in turn decreases fetal oxygenation. During surgery, all of these factors place the fetus at high risk for low cardiac output and fetal demize.

Nociceptive sensory pathways and EEG activity are present in the fetus by midgestation (9,28). Thus, the fetal surgery patient requires anaesthesia to prevent perception of pain and to induce unconsciousness (37,38). Because the uptake of volatile anaesthetics occurs more slowly in the fetus than in the mother, it is imperative to anticipate well in advance (> 20 min) the timing of the surgical incision on the fetus (Figure 7). Administration of 1.5–2 MAC to the mother more than ensures fetal anaesthesia as long as uteroplacental gas exchange is maintained. The fetus metabolizes opioids slowly,

given the half-life of fentanyl in very premature infants is > 12 h (27). Administration of intraoperative opioids directly to the fetus may last many hours and provide postoperative analgesia. Postoperative opioid infusions to the mother will reach the fetus and also provide analgesia (37,38).

Anaesthesia for open fetal surgery

Open fetal surgery requires general anaesthesia because both mother and fetus must be anaesthetized and the uterus must be atonic. Fetal surgery patients are usually admitted the morning of surgery. The anaesthetic previsit occurs at least 24 h before surgery, usually before the fetal surgery team meeting. At our institution, an anaesthesia nurse practitioner specially educated in fetal surgery screens the mother at the time of the surgical and obstetric work-up. The anaesthesiologist reviews this screening, notifies the surgical team of any issues and discusses the anaesthesia with the mother during the fetal surgery team meeting.

On the morning of surgery, the obstetrician examines the mother for premature labour and performs an ultrasound to assess fetal well-being. The availability of type-specific packed red blood cells for the mother and O-negative packed red blood cells divided into 50 ml aliquots for the fetus is confirmed. The operating room temperature is warmed to 26 °C. Resuscitation drugs for the fetus (atropine 0.02 $mg \cdot kg^{-1}$, epinephrine 1 $\mu g \cdot kg^{-1}$), vecuronium 0.2 $mg \cdot kg^{-1}$ and fentanyl 20 $\mu g \cdot kg^{-1}$ are prepared and given to the scrub nurse, thus making them immediately available during the procedure.

The mother is greeted in the holding area, NPO status is confirmed, and an intravenous line is started. If the mother has not received the tocolytic drug indomethacin (50 mg rectal suppository) prior to arrival, it is administered after induction of general anaesthesia. The mother then receives 30 ml of 0.3 M sodium bicitrate orally to reduce gastric acidity and 10 mg metaclopromide i.v. to enhance gastric emptying. After placement of standard monitors, a lumbar epidural catheter is inserted for postoperative pain management. Following a negative test dose with 1.5% lidocaine with 1 : 200 000 epinephrine, positioning the mother in left uterine displacement and preoxygenation, a rapid sequence induction is performed with thiopental (5 $mg \cdot kg^{-1}$), succinylcholine (2 $mg \cdot kg^{-1}$) and fentanyl (1–2 $\mu g \cdot kg^{-1}$). Anaesthesia is then maintained with 0.5 MAC of desflurane or isoflurane in oxygen while an ultrasound examination maps out surface anatomy with respect to the placenta and fetus. A second large bore peripheral intravenous catheter, radial arterial catheter, urinary catheter and nasogastric tube are inserted at this time. Fetal haemodynamics (heart rate, right ventricle contractility) are monitored intraoperatively by continuous fetal echocardiogram (30).

Special attention is given to the location of the placenta, as surgical access to the fetus via hysterotomy is more difficult with the placenta attached to the anterior wall of the uterus compared with the posterior position. This difficulty increases the risk of bleeding at hysterotomy and requires greater manipulation of the uterus, which predisposes to hypotension and fetal hypoxia.

Before maternal skin incision, the volatile anaesthetic is increased to 2 MAC and maternal skeletal muscle relaxation augmented with vecuronium. Maternal systolic arterial pressure is kept > 100 mmHg with intravenous ephedrine as needed, although it is often not needed once surgical stimulation commences. Total intravenous fluids (0.9% saline) are limited to 500 ml unless blood loss exceeds 100 ml in order to prevent postoperative pulmonary oedema (39). After exposure of the uterus, the surgeons assess uterine tone. The volatile anaesthetic is increased as necessary to decrease uterine tone. A special uterine stapling device is used to incise the myometrium to minimize bleeding and seal the amniotic membranes (35,40). The operative site of the fetus is delivered through the incision site (e.g. head, coccyx). Warm fluids are continuously infused into the uterine cavity via a red rubber tube connected to a Level 1 (Smith Industries Medical, Rockland, MA, USA) fluid warmer in order to replace amniotic fluid losses and prevent umbilical cord kinking (35,40). Limiting the size of the uterine incision helps to prevent evaporative fluid loss from the fetus, uterine haemorrhage and postoperative uterine contractions. However, a small uterine incision requires excellent uterine relaxation to deliver the operative fetal part. Volatile anaesthetics are powerful relaxants of the myometrium (13,27,28) (Figure 5). Complete uterine relaxation

can be achieved with 2 MAC, although these concentrations decrease material arterial pressure, uteroplacental perfusion and fetal oxygenation. To counteract these effects, β_2-adrenergic drugs (e.g. ephedrine) are administered liberally.

For open procedures, fentanyl (5–20 $\mu g \cdot kg^{-1}$) with or without atropine (20 $\mu g \cdot kg^{-1}$) and vecuronium (0.2 $mg \cdot kg^{-1}$) are injected i.m. into the fetus. Fentanyl is administered for intraoperative and postoperative fetal analgesia, atropine is administered to ablate the bradycardic response with fetal surgical manipulation and vecuronium ensures a still fetus during the surgical procedure. For the EXIT procedure and other potential blood loss procedures (e.g. sacrococcygeal teratoma, CCAM), the surgeon applies a pulse oximeter on the fetal forearm, and may sample blood from the umbilical artery to check fetal haemoglobin, pH and blood gases. Fetal desaturation ($SpO_2 < 50\%$) usually results from hypoperfusion with low cardiac output or umbilical cord kinkage. The anaesthesiologist infuses blood and medications as needed through a surgeon-held butterfly needle inserted into an exposed fetal vessel (e.g. superior vena cava, aorta) or the umbilical vein.

Magnesium sulphate ($MgSO_4$) 6 g bolus i.v. (over 20 min) followed by a 3 $g \cdot h^{-1}$ infusion is started during hysterotomy closure, which allows the volatile anaesthetic to be decreased and the mother to eventually emerge from anaesthesia with a quiescent uterus. The epidural catheter is dosed with local anaesthetic (15–20 ml of 0.25% bupivicaine) and morphine (3 mg) as the inhaled agent is decreased. The anaesthesiologist should monitor neuromuscular transmission because magnesium sulphate potentiates the muscle relaxation of the vecuronium. Smooth anaesthetic emergence and tracheal extubation are required to minimize tension on the uterine and abdominal suture line.

The serious postoperative issues include premature labour, pulmonary oedema, amniotic fluid leak and fetal demize (6,8,10,13,27,35,37,39,40). Virtually all patients experience premature uterine contractions in the immediate postoperative period, necessitating a continuous magnesium sulphate infusion. Postoperatively, fetal surgery patients are monitored initially in an obstetrical intensive care unit setting. Total hospital length of stay postoperatively averages 1 week and bed rest for the remainder of the pregnancy is required.

We believe that postoperative pain management is crucial to the success of fetal surgery. In our experience, excellent pain control helps keep the uterus from contracting (27,36,38). Patient controlled epidural analgesia (bupivacaine 0.75 $mg \cdot ml^{-1}$, fentanyl 10 $\mu g \cdot ml^{-1}$: bolus 4 ml, lock out 15 min, basal 6 ml, hourly maximum 15 ml) is used for 2–3 days postoperatively. Tocolytics include magnesium sulphate and indomethacin for 2–3 days, followed by subcutaneous terbutaline or oral nifedipine until delivery of the baby. Occasionally, intravenous nitroglycerin is used as a tocolytic. Uterine activity and fetal haemodynamics (echocardiography) are monitored frequently during the initial 3 days.

Anaesthesia for minimally invasive fetal surgery

Minimally invasive fetal surgery applies laparoscopic techniques ('fetoscopy') with ultrasound. The anaesthetic for these procedures depends mainly on surgical factors, and it is vital for the anaesthesiologist to attend the patient preparation meetings to understand the surgical approach and to select the best anaesthetic. Surgical factors to consider include the location of the placenta and umbilical cord, history of uterine activity, position of the fetus, relation of the fetal lesion to other structures and chance of converting to open fetal surgery (34–36, 40–42). These procedures have been performed under regional, general or sedation techniques. The advantage of minimally invasive fetal surgery over open fetal surgery is that complications and length of hospital stay for the former are considerably less. Some procedures are performed in an Obstetric Day Medicine Unit and others in the operating room.

The previsit and morning of surgery evaluations and premedication are the same as open fetal surgery. Subsequently, the anaesthetic for minimally invasive fetal surgery differs from open fetal surgery. An arterial catheter and nasogastric tube are not used and one peripheral i.v. is sufficient. General anaesthesia is usually a balanced technique (0.75–1 MAC desflurane or isoflurane supplemented with fentanyl) rather than a deep inhalation technique because profound uterine relaxation is not required. The skin, uterine and fetal incisions are small; pain and uterine activity are minimal postoperatively. Therefore, postoperative epidural anal-

gesia is not required. Tocolytic management includes intravenous magnesium sulphate transitioned to terbutaline s.q. or oral nifedipine after postoperative day one. Tocolytics may be discontinued later in the gestation and some maternal activity beyond bed rest may be permitted.

Conclusions

Anaesthesia for fetal surgery is becoming an exciting new area of practice for anaesthesiologists. By constantly refining anaesthetic techniques and readdressing important issues such as tocolysis, the anaesthesiologist can not only play a vital role in the care of fetal surgery patients today, but also help to establish improvements in care and research in these patients for years to come.

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