Fetal Surgery for Myelomeningocele and the Incidence of Shunt-Dependent Hydrocephalus

Myelomeningocele is the most common congenital anomaly of the central nervous system and a major cause of serious developmental disability. The birth prevalence reported in the United States from 1983 to 1990 was 4.4 to 4.6 cases per 10,000 live births.1 Myelomeningocele results from the failure of caudal neurulation during the fourth week of gestation. The lesion is characterized by protrusion of the meninges through a midline bony defect of the spine, forming a sac containing cerebrospinal fluid and dysplastic neural tissue. Most infants with myelomeningocele develop paraparesis and urinary incontinence. The Chiari II malformation, including herniation of the cerebellum and hindbrain, is almost universally present and is usually associated with hydrocephalus. The severity of hydrocephalus usually worsens after neurosurgical repair.

Context Intrauterine closure of exposed spinal cord tissue prevents secondary neurologic injury in animals with a surgically created spinal defect; however, whether in utero repair of myelomeningocele improves neurologic outcome in infants with spina bifida is not known.

Objective To determine whether intrauterine repair of myelomeningocele improves patient outcomes compared with standard care.


Setting Tertiary care medical center.

Participants A sample of 29 study patients with isolated fetal myelomeningocele referred for intrauterine repair that was performed between 24 and 30 gestational weeks and 23 controls matched to cases for diagnosis, level of lesion, practice parameters, and calendar time. All infants were followed up for a minimum of 6 months after delivery.

Main Outcome Measures Requirement for ventriculoperitoneal shunt placement, obstetrical complications, gestational age at delivery, and birth weight for study vs control subjects.

Results The requirement for ventriculoperitoneal shunt placement for decompression of hydrocephalus was significantly decreased among study infants (59% vs 91%; P = .01). The median age at shunt placement was also older among study infants (50 vs 5 days; P = .006). This may be explained by the reduced incidence of hindbrain herniation among study infants (38% vs 95%; P < .001). Following hysterotomy, study patients had an increased risk of oligohydramnios (48% vs 4%; P = .001) and admission to the hospital for preterm uterine contractions (50% vs 9%; P = .002). The estimated gestational age at delivery was earlier for study patients (33.2 vs 37.0 weeks; P < .001), and the birth weight of study neonates was less (2171 vs 3075 g; P < .001).

Conclusions Our study suggests that intrauterine repair of myelomeningocele decreases the incidence of hindbrain herniation and shunt-dependent hydrocephalus in infants with spina bifida, but increases the incidence of premature delivery.

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See also pp 1826 and 1873.
pair of the lesion in the newborn, requiring placement of a ventricular shunt apparatus. Despite the necessity of a shunt, many children with myelomeningocele will manifest developmental delay and learning disabilities. Structural abnormalities due to muscular imbalance, including talipes and dislocation of the hips, are common.

Until recently, the neurologic deficits associated with myelomeningocele were attributed entirely to the primary defect in closure of the neural tube. A growing body of experimental evidence, however, now supports the 2-hit hypothesis which, in addition to the initial embryologic error, also postulates a secondary injury to exposed neural tissue throughout gestation. If true, this theory would lead to the prediction that intrauterine repair of myelomeningocele may improve neurologic outcome by preventing at least part of the second-hit injury. Several animal studies now substantiate this prediction. As a direct consequence of those studies, intrauterine closure of myelomeningocele has been offered at Vanderbilt University Medical Center, Nashville, Tenn, since 1997. The purpose of the current study is to compare outcomes of the first 29 mother-infant pairs to undergo this innovative procedure to 23 contemporary controls.

METHODS
Control Population
The 2 primary investigators (J.P.B. and N.T.) have both been full-time members of the Vanderbilt University faculty since 1990 and have defined standard care of the pregnant woman with fetal myelomeningocele at the institution since that time. This care consists of weekly ultrasonographic examinations to observe the growth and development of the fetus, transabdominal amniocentesis beginning at 35 to 36 weeks of gestation to document fetal lung maturity, and cesarean delivery of the fetus when lung maturity is confirmed. The myelomeningocele is repaired within 48 hours of delivery using a standard layered closure. Serial physical examinations are performed, supplemented by ultrasonographic assessment of the neonatal brain, to determine the need for ventriculoperitoneal (VP) shunt placement. A VP shunt is placed if severe hydrocephalus is present at birth or when progressive ventricular enlargement is demonstrated on serial imaging studies. Criteria for shunt placement have not changed at the medical center during this time.

Control patients were initially identified from a computerized database of infants referred to the spina bifida clinic at our medical center since 1990. This list was cross-referenced with a second list generated by a search of the reports of all obstetrical ultrasound examinations performed during the same period. Finally, the resulting list was checked against hospital discharge International Classification of Diseases, Ninth Revision (ICD-9) diagnoses of all newborns to identify those with myelomeningocele. Inclusion criteria for controls were live-born infants with isolated myelomeningocele delivered by cesarean section during the study period. All of the controls could have fulfilled criteria for inclusion in the study group, although intrauterine repair was not available until 1997. For the purpose of this analysis, all control infants with anatomical lesions higher than the highest lesion identified in the study group were excluded.

Patients were considered study candidates if they requested or agreed to initial counseling with 1 of the primary investigators. None of the control patients completed this first step in the screening process, usually because of late referral or lack of interest. Only 1 patient completed the entire screening process for intrauterine repair and then declined participation. She was not placed into the control group because she lived out of state and received no further medical care at Vanderbilt University Medical Center.

Study Population
Since April 1997 patients referred with isolated fetal myelomeningocele in the midtrimester have been offered 2 options for management of the continuing pregnancy: standard care or intrauterine repair of the myelomeningocele. Prospective surgical candidates participate in 2 to 3 days of comprehensive multidisciplinary counseling in accordance with guidelines established by the International Fetal Medicine and Surgery Society. The only inclusion criteria for study participation are the absence of other major anomalies, a normal fetal karyotype, and the ability to fully comprehend the potential risks and benefits of the management options available.

All study patients gave informed consent as required by Vanderbilt University’s committee for the protection of human subjects. Patients were originally offered intrauterine repair between 22 (now 20) and 30 gestational weeks.

Procedure
Glucocorticoids are administered to the mother after 23 weeks’ gestation to enhance fetal lung maturity. Urinary conduction blockade is established in the mother with a mixture of local anesthetics, following which general endotracheal anesthesia is induced and subsequently maintained with a balanced technique, including muscle relaxants and halogenated inhalational agents. Fetal anesthesia is achieved by transplacental passage of medications administered to the mother. Extended-spectrum antibiotics, usually ampicillin sodium and sulbactam, are administered intravenously to the mother. Laparatomy is performed through a Pfannensteil skin incision and the uterus is exteriorized. Intrauterine contents are localized, and a normal fetal heart rate is confirmed by means of a sterile ultrasound transducer. Initial entry through a 1-cm incision in the uterine fundus is achieved with electrocautery or by placement of a specially designed hollow trocar with a Peel-Away sleeve (Tulipan-Bruner Trocar, Cook Inc, Bloomington, Ind) using a modified Seldinger technique. Most of the amniotic fluid is removed and stored in sterile syringes. An 8-cm
hysterotomy is created in the uterine fundus using an autostapling device (US Surgical Premium Poly CS-57, US Surgical Corp, Norwalk, Conn). The fetus is manually positioned with the myelomeningocele centered in the hysterotomy (FIGURE 1). The defect is repaired using the same standard neurosurgical closure used in controls after delivery. The neural placode is sharply dissected from surrounding arachnoidal tissue and allowed to drop into the spinal canal. The dura is then identified and freed from the skin and lumbodorsal fascia, reflected over the placode and closed. In the first 22 cases, a 1.5-mm Spetzler catheter (Heyer-Schulte NeuroCare, Pleasant Prairie, Wis) was trimmed. One end was placed next to the dural sac, while the other end was brought out through a stab incision in the fetal skin. The skin was mobilized and closed, and the drain secured (Figure 1). This drain has not been used after the 22nd case. The stored amniotic fluid with its known antibacterial properties is returned to the uterine cavity, along with 500 mg of nafcillin sodium. The uterus is closed in 2 layers, and each layer is sealed with commercially available fibrin glue (Tisseel Fibrin Sealant, Baxter Healthcare Corp, Glendale, Calif). A sheet of Interceed absorbable adhesion barrier (Johnson and Johnson Medical Inc, Arlington, Tex) is attached over the incision to prevent adhesion formation. After closing the laparotomy, the patient is awakened and transferred to labor and delivery for observation. Preterm labor prophylaxis is instituted with intravenous magnesium sulfate (MgSO4) (6 g bolus over 30 min followed by 2 g/h continuous infusion) and oral or rectal indomethacin (25 mg every 4 hours). These are replaced within 24 hours by a subcutaneous terbutaline pump (Matria Healthcare Inc, Atlanta, Ga).

After discharge on the third or fourth postoperative day, patients return to their home community where their local physicians provide continuing perinatal and neonatal care. Consultation with any of the investigators is freely available. In general, weekly outpatient visits are planned for evaluation of both mother and fetus. Cesarean delivery is anticipated, with the timing to be determined by the usual obstetrical factors. Evaluation of the newborn is similar to that described for control patients. Specific indicators for placement of a VP shunt are not imposed; the general criteria for shunt placement apply throughout the United States and Canada, although regional and individual preferences may be expected. All study infants older than 6

Figure 1. Exteriorized Uterus During Surgery and Neonate Immediately After Delivery

A, During surgery, hysterotomy is created and most of the amniotic fluid removed to a sterile warmer. The fetus is manually positioned with the myelomeningocele centered in the hysterotomy. B, After delivery of the neonate of the Spetzler catheter, secured with a single silk suture, is seen exiting through a stab incision in the fetal skin. Intrauterine repair of myelomeningocele was performed 44 days previously. Measurement in centimeters is supplied for scale.
radiographs. Hindbrain herniation was assessed postnatally using both ultrasonography and magnetic resonance imaging (MRI). Images were obtained at each patient’s local facility using standard technique, and the films were collected for central review. All postnatal images were blinded and reviewed by 2 of the authors (M.H.-S. and L.H.L.). The degree of hindbrain herniation was graded as follows: normal (cerebellum and brainstem entirely within the posterior fossa, fourth ventricle in normal position); mild (fourth ventricle displaced inferiorly less than halfway to foramen magnum, less than half of vermis below foramen magnum); moderate (fourth ventricle displaced inferiorly more than halfway to foramen magnum, more than half of vermis below foramen magnum); and severe (fourth ventricle displaced to level of foramen magnum, most or all of vermis below foramen magnum). Concordance was reached between the 2 pediatric radiologists for each grading.

Outcome Measures

The primary end points were the requirement for VP shunt placement, the presence of obstetrical complications (including hemorrhage, infection, preterm labor, membrane disruption, intrauterine growth restriction, and oligohydramnios), gestational age at delivery, and birth weight. Secondary end points included the age at shunt placement and the degree of hindbrain herniation.

All preoperative ultrasonographic examinations were performed by 1 investigator (J.P.B.) using a Toshiba 270 with a 5.0-MHz transducer as the primary imaging tool (Toshiba, Tustin, Calif). The estimated delivery date was established by a reliable last menstrual period and a confirmatory ultrasonographic examination. Oligohydramnios was defined as an amniotic fluid index of less than 5 cm or a subjective decrease in amniotic fluid volume documented on at least 1 ultrasonographic examination after repair. Small-for-gestational-age was defined as birth weight less than the tenth percentile for gestational age.

The anatomical position of the myelomeningocele was determined by comparison of antenatal ultrasonographic imaging, physical examination of the fetus or newborn, and postnatal

RESULTS

Since April 1997, more than 60 cases of myelomeningocele have been repaired in utero at Vanderbilt University Medical Center. The first 29 infants delivered have been followed up for at least 6 months since delivery and constitute the study group. None of these patients died. The median follow-up of this group is 311 days (range, 182-799 days). All procedures in the study group were performed between 24 and 30 gestational weeks. Four study patients remained under the care of the primary investigators for the remainder of their pregnancy, while 25 study patients returned to their home communities and were treated by their local physicians in consultation with the authors, as needed. Only those data verified by examination of the medical records by the authors are included in this analysis.

Between January 1990 and the birth of the 29th study infant in February 1999, 32 mother-infant control pairs received standard care from the primary investigators. The highest anatomical level of any lesion among the study infants was T12, so all control infants with upper limits of the myelomeningocele higher than T12 were excluded; 9 controls were excluded, resulting in a final control group of 23 patients. The maternal age of the study group was significantly older than the controls (31.2 [range, 13-39] vs 24.9 [22-39] years; \( P = .0002 \)), but no relationship within the study group between maternal age and shunt placement was detected. Study patients were also more likely than controls to have been pregnant at least once (48% [11/23] vs 10% [3/29], respectively; \( P = .004 \)) and to have given
pared with those who did not (48% vs 4%, respectively; *P* = .001), although in some cases the decrease in amniotic fluid volume was transient. Overall, 13 of 26 study patients were admitted to the hospital with preterm uterine contractions at a higher rate than the controls (50% vs 9%, respectively; *P* = .002); approximately one third of the study patients gave birth prior to discontinuation of tocolytics compared with the controls (38% vs 4%, respectively; *P* < .001), usually due to persistent uterine contractions or preterm rupture of membranes, or both. A similar trend was detected in the incidence of preterm premature rupture of membranes, although the difference did not reach statistical significance (28% of study patients vs 4% of control patients; *P* = .05). The estimated gestational age at delivery was significantly earlier for study patients (33.2 vs 37.0 weeks; *P* < .001; mean difference, 3.8 weeks; 95% confidence interval [CI], 2.6-5.0).

Five study neonates were delivered before 30 weeks' gestation (27.3, 28.3, 29.0, 29.1, and 29.2 weeks); 1 of these deliveries is described in detail below. The birth weight of study neonates was also significantly less than control neonates (2171 vs 3075 g, respectively; *P* < .001; mean difference 904 g; 95% CI, 543-1263). The difference in birth weights was entirely attributable to gestational age at delivery, since no statistically significant difference was found in the incidence of newborns who were small for gestational age. All data are presented as number (percentage) unless otherwise indicated.

By design, no statistically significant differences in the median anatomical level of the myelomeningocele could be discerned between infants repaired before or after delivery (*P* = .74). Despite this, the requirement for VP shunt placement for decompression of hydrocephalus was significantly decreased among study infants (59% vs 91%; *P* = .01). The median age at shunt placement was also older among study infants, compared with controls (50 vs 5 days; *P* = .006). Because 3 infants in the study group received shunts at ages older than 6 months (193, 242, and 285 days), we calculated the rate at which the failure curve would plateau (a cure rate) to estimate the likely long-term prevalence of shunting in both groups. This gave us estimated rates of 62% vs 91% (*P* = .01), indicating a significant decrease in long-term prevalence of shunt placement in the study infants. Only 2 of the 29 newborns repaired in utero demonstrated evidence of significant cerebellar herniation through the foramen magnum (both moderate), while 10 of 22 newborns who were repaired after delivery had significant hindbrain herniation (7 moderate, 3 severe) (7% vs 45%; *P* = .002). Finally, study infants were less likely to have talipes (28% vs 70%; *P* = .005) (Table 2).

In 1 patient with polyhydramnios, the uterus felt unusually firm on examination. Removal of the large amount of amniotic fluid initiated uterine contractions, which in turn led to precipitous extrusion of the fetus through the hysterotomy at the time of surgery. This subsequently led to placental abruption, which necessitated definitive delivery. The newborn was easily resuscitated and underwent uncomplicated myelomeningocele repair on the fifth day of life. He was discharged in good health after an uneventful hospital stay. There was no evidence of either chronic lung disease or intraventricular hemorrhage. The mother suffered no ill effects. Another study patient developed signs and symptoms of a small bowel obstruction approximately 5 weeks after open fetal surgery. She eventually required surgical exploration at 31 weeks' gestation. At surgery a small hysterotomy dehiscence with adherent bowel was found. The fetus was delivered without incident and is doing well. Subsequent culture of the resected hysterotomy edge revealed mucormycosis. The mother recovered uneventfully. A third study patient was admitted to the hospital at 33 weeks' gestation with abdominal pain, and ultrasonographic examination revealed a fetal leg protruding through the hysterotomy. The fetus was safely delivered through the dehiscence, and both newborn and mother were discharged in good health. Only 1 study infant required prolonged mechanical ventilation longer than 72 hours, in this case despite delivery at 35.6 weeks. He was later diagnosed with an idiopathic congenital pulmonary disease, cellular interstitial pneumonitis, which is apparently unrelated to either the neural tube defect or the intrauterine repair.

### Table 1. Obstetrical Complications and Perinatal Outcomes*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Study Patients (n = 29)</th>
<th>Control Patients (n = 23)</th>
<th><em>P</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligohydramnios</td>
<td>13/27 (48)</td>
<td>1 (4)</td>
<td>.001</td>
</tr>
<tr>
<td>Preterm uterine contractions</td>
<td>13/26 (50)</td>
<td>2 (9)</td>
<td>.002</td>
</tr>
<tr>
<td>PPROM</td>
<td>7/25 (28)</td>
<td>1 (4)</td>
<td>.06</td>
</tr>
<tr>
<td>Mean EGA at delivery, wk (range)</td>
<td>33.2 (27.4-36.6)</td>
<td>37.0 (32.5-39.4)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Mean birth weight, g (range)</td>
<td>2171 (938-2877)</td>
<td>3075 (1625-4573)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>SGA</td>
<td>0 (0)</td>
<td>4 (17)</td>
<td>.05</td>
</tr>
</tbody>
</table>

*PPROM indicates preterm premature rupture of membranes; EGA, estimated gestational age; and SGA, small for gestational age. All data are presented as number/total (percentage) unless otherwise indicated.

### Table 2. Selected Measures of Neurologic Outcome in Infants*

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Study Patients (n = 29)</th>
<th>Control Patients (n = 23)</th>
<th><em>P</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP shunt placement</td>
<td>17 (59)</td>
<td>21 (91)</td>
<td>.01</td>
</tr>
<tr>
<td>Upper level of lesion, median (range)</td>
<td>L4 (S1-T12)</td>
<td>L3 (S1-T12)</td>
<td>.74</td>
</tr>
<tr>
<td>Median age at VP shunt placement, d (range)</td>
<td>50 (0-285)</td>
<td>5 (3-40)</td>
<td>.006</td>
</tr>
<tr>
<td>Hindbrain herniation</td>
<td>11 (38)</td>
<td>21/22 (95)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Hindbrain herniation, moderate/severe</td>
<td>2 (7)</td>
<td>10/22 (45)</td>
<td>.002</td>
</tr>
<tr>
<td>Talipes</td>
<td>8 (28)</td>
<td>16 (70)</td>
<td>.005</td>
</tr>
</tbody>
</table>

*VP indicates ventriculoperitoneal. All data are presented as number (percentage) unless otherwise indicated.
The developmental outcome of 26 of the 29 study infants was evaluated at 2 to 18 months of age by administration of the Bayley Scale of infant development. Using a chronological age corrected for prematurity, scores of the mental development index were 80 to 118 with a mean of 100.

**COMMENT**

The results of this study strongly suggest that fetuses that undergo intrauterine repair of myelomeningocele are less likely to develop significant hydrocephalus or exhibit hindbrain herniation than those receiving standard care. This was an unanticipated benefit of intrauterine repair of myelomeningocele repair, which was initially devised to prevent at least part of the secondary exposure injury to the dysplastic spinal cord. In the current report, the need for VP shunt placement in children whose myelomeningocele was closed in utero was reduced 36% compared with controls. The incidence of shunt-dependent hydrocephalus in controls and the newborn’s age when surgery was performed are in close agreement with reports from other institutions. Inadvertent bias against shunt placement in the study infants was reduced by the fact that almost 90% of the 29 study patients were delivered in their local communities and decisions regarding the need for shunt placement, as well as the timing of the procedure, were made by physicians at the local institution.

In all, 16 different neurosurgeons from 13 different states placed the 17 shunts in this series; 2 of the 4 study newborns who were delivered at Vanderbilt University Medical Center received shunts, a rate similar to that of the overall group. It is to be expected that the specific criteria used to determine the need to place a VP shunt may vary among pediatric neurosurgeons. Generally, severe and/or progressive hydrocephalus is shunted, but the timing is largely subjective. There are still neurosurgeons in the United States who place shunts in all newborns with spina bifida at the time of myelomeningocele repair, while others wait until head circumference measurements cross various percentile thresholds. Despite these differences, the neurosurgeons who followed up with the infants in this study represented a cross-section of pediatric neurosurgeons nationwide. No attempt was made by the authors to influence the decision to place a VP shunt. Therefore, the criteria used to determine the need for a VP shunt in the patients in the study are no different from those used in published series of conventionally treated patients. In addition to a reduction in the need for placement of a VP shunt, the average age at the time of shunting was significantly older in the study patients, suggesting that even in those patients the severity of cerebrospinal fluid (CSF) malabsorption was less than in controls.

The mechanism by which the severity of hydrocephalus is reduced by early closure of myelomeningocele is felt to be intimately related to CSF circulatory dynamics. Current theory teaches that hydrocephalus associated with neural tube defects develops, in part, from obstruction of normal CSF circulation at the skull base by herniation of the cerebellum through the foramen magnum. In a prenatal ultrasonographic study of 51 fetuses with myelomeningocele, the severity of hydrocephalus increased with worsening of observed hindbrain herniation. We have previously reported in a subset of the current study group that hindbrain herniation can be reduced by intrauterine repair of the myelomeningocele, an observation reinforced by the present study. Thus, repair of a myelomeningocele in the immature fetus apparently initiates a different chain of events than the same procedure does in the mature neonate. We hypothesize that intrauterine myelomeningocele repair may promote the restoration of a more normal CSF circulation by relieving herniation of the hindbrain and cerebellum, a process of which the mature newborn is incapable. This sequence, which we term hindbrain restoration, may well be enabled by the flexibility of the fetal cranium and the plasticity of the poorly myelinated fetal brain. Since the process of hindbrain restoration is apparently initiated by preterm closure of the myelomeningocele defect, placement of an epidural drain to allow continued egress of CSF may impede the beneficial effects of intrauterine repair, and use of the Spetzler catheter was discontinued after case 22.

The functional neurologic level of study infants is obviously a matter of intense interest. Although the incidence of talipes is significantly reduced in the study group, motor function has not exceeded expectations based on the anatomical levels of the lesions. Since most of the study infants are not yet old enough to walk or toilet train, early assessments of lower extremity and bladder function must be interpreted with caution. At present, the 2-hit hypothesis still remains unproven in human trials.

While intrauterine repair of myelomeningocele resulted in a reduced incidence of shunt-dependent hydrocephalus and hindbrain herniation, a price was paid in obstetric complications and prematurity. Hysterotomy was associated with significantly more oligohydramnios, preterm uterine contractions, and preterm delivery. Despite these complications, no infant was delivered because of oligohydramnios, and no significant neonatal morbidity resulted from prematurity. Still, an important question that must be answered before fetal surgery can be recommended for treatment of spina bifida or any other malformation is whether any neurologic harm is visited on the fetus as a result of the therapy. Open fetal surgery followed by weeks of tocolysis, culminating in preterm labor and delivery of a premature infant are all risk factors for a poor neurologic outcome. Bealer et al reported that 7 (21%) of 33 infants demonstrated significant neurologic abnormalities after intrauterine repair of congenital diaphragmatic hernia. Determining neurologic sequelae in our patients is much more problematic since the incidence of significant neu-
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REFERENCES