JNS PEDIATRICS

CLINICAL ARTICLE

J Neurosurg Pediatr 35:229–236, 2025

Tubular single-port endoscope-assisted surgery for fetal myelomeningocele repair

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OBJECTIVE The authors aimed to describe a low-cost and easily reproducible alteration of the Bruner and Tulipan procedure to preserve uterine muscular fibers. They conducted a retrospective cohort study of 10 pregnant women whose fetuses developed lumbosacral myelomeningocele (MM). The MM was repaired through a fetal neurosurgical procedure using a tubular single-port endoscope-assisted technique.

METHODS This study was conducted at the Santa Joana Hospital and São Paulo Hospital between January 2020 and June 2023. The procedure consisted of tubular retraction of circular fibers from the uterine body without excision of the uterine wall. Tubular devices with progressively larger diameters were used for retraction without cutting the uterine muscular fibers, and a 25-mm-diameter tubular retractor was used to allow endoscope-assisted closure of the MM using microsurgical techniques.

RESULTS The average birth age was 36 weeks 3 days. Defect repair was possible in all cases. The mean surgical time was 130 minutes. Two of the patients developed hydrocephalus. One patient underwent a ventriculoperitoneal shunt, and the other underwent endoscopic third ventriculostomy with choroid plexus coagulation.

CONCLUSIONS This procedure avoids excision of the uterine wall, promotes a workspace for microsurgical techniques assisted by endoscopy, and is possibly the first step for future single-port correction using robotic techniques.

https://thejns.org/doi/abs/10.3171/2024.9.PEDS24239

KEYWORDS myelomeningocele; fetal surgery; tubular surgery; fetal neurosurgery; single port; congenital

Myelomeningocele (MM) is the most common open spinal dysraphism, affecting approximately 1/1000 live births. In 1998, Bruner and Tulipan performed the first surgery to repair MM during the fetal period at Vanderbilt University.[1] This procedure has completely changed the treatment philosophy for this disease. Furthermore, a multicenter prospective randomized clinical trial, the Management of Myelomeningocele Study (MOMS), was carried out in 2011. The study revealed that when surgery is performed at a gestational age < 26 weeks, it provides great benefits to the fetus.[2] Subsequently, centers recommending this treatment during this fetal period have multiplied. However, several changes have been proposed to improve the original technique, mainly focusing on preserving the uterus and reducing maternal morbidity. Hence, endoscopic procedures have become widespread and are performed by obstetricians, fetologists, and pediatric surgeons[3] with different results and objectives.

Therefore, in this study, we aimed to describe an alteration of the Bruner and Tulipan procedure[1] to preserve uterine muscular fibers.

Methods

Surgical Procedure

Pregnant women were anesthetized using general and spinal anesthesia. Magnesium sulfate was administered at an initial dose of 4 g at induction time and maintained after that at 1 g/day for 12 hours to exert a tocolytic action. Furthermore, the fetuses were anesthetized with transplacental general anesthesia, and bladder catheterization was performed. The patient was placed on a gynecological operat-

ABBREVIATIONS ETV = endoscopic third ventriculostomy; MM = myelomeningocele; MOMS = Management of Myelomeningocele Study; VP = ventriculoperitoneal.

SUBMITTED May 10, 2024. **ACCEPTED** September 23, 2024.
INCLUDE WHEN CITING Published online December 20, 2024; DOI: 10.3171/2024.9.PEDS24239.

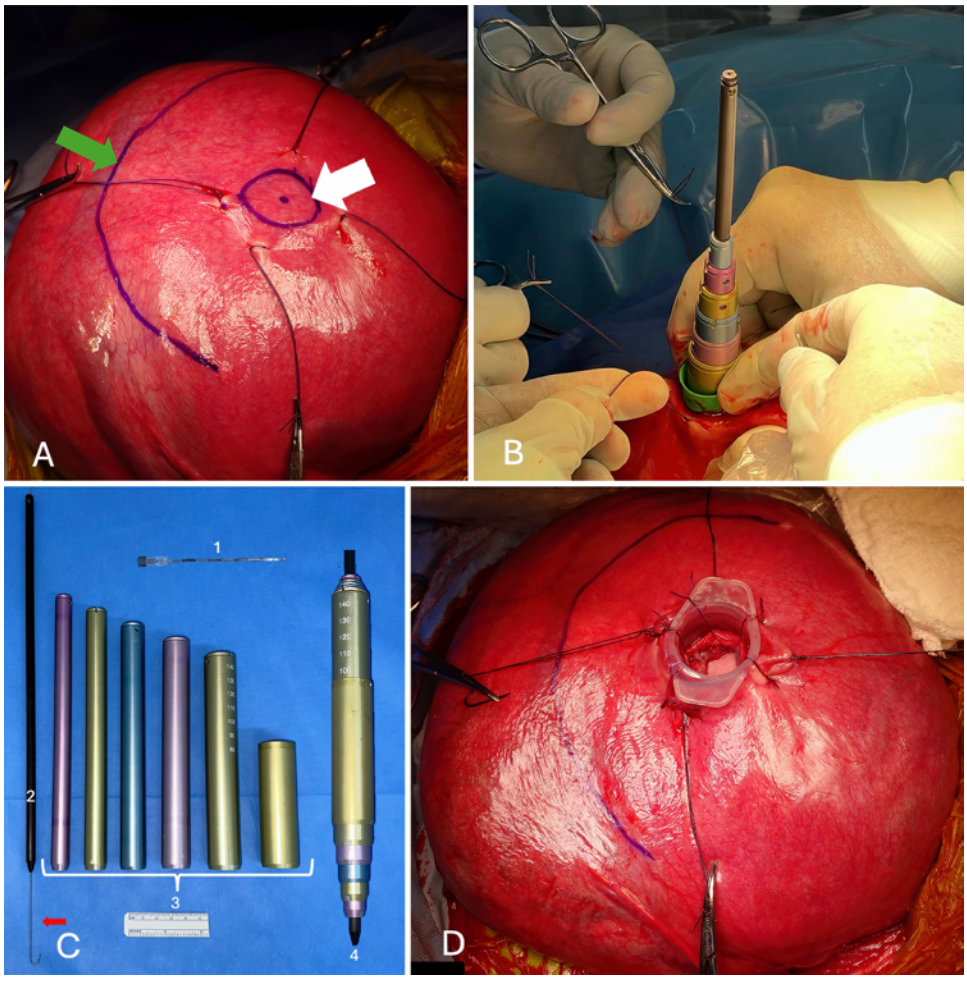

FIG. 1. Surgical photographs illustrating the steps of the procedure. **A:** The entry point is demarked by the *dot inside the circle* (*white arrow*) and a drawn *line* to demark the placenta (*green arrow*). **B:** The progressive use of dilators in the uterus. **C:** Photograph of the instruments used to progressively dilate the myometrium: 16-gauge, 3.5-inch epidural anesthesia needle (Procare) (*1*); first dilator with the guidewire (*red arrow*) (*2*); the dilators (*3*); and final setup of the dilators (*4*). **D:** The ring retractor is held in place.

ing table, and her legs were gently spread apart. The uterus was exteriorized through a Joel-Cohen abdominal incision.

The placenta was mapped using ultrasound guidance, and the procedure was performed on the opposite wall. The entry point was chosen on the basis of placental implantation, presence of amniotic fluid space, identification of fetal parts, and ultrasound measurement of uterine wall thickness. A sterile surgical pen was used to mark the entry point into the uterus, and a 25-mm-diameter retractor was used (Fig. 1A). Plication was performed on the uterine wall using digital maneuvers. In addition, 4 external and equidistant sutures of this circumference were made using 0 polyglactin 910 sutures to anchor the myometrium and amniotic membrane. Furthermore, a 16-gauge, 3.5-inch epidural anesthesia needle (Procare) was used to puncture the uterus (Fig. 1B and C), reaching the amniotic cavity and pointing at the larger fluid space, which was at the center of the previously described circumference. The Seldinger technique was used to insert the guidewire through the needle. A cone-shaped sharp-tipped trocar with cylindrical extensions, which looked like a pencil at one end, was inserted through the guidewire to separate the uterine fibers without incisions when the needle was removed. The tip of the trocar was 1 mm long, progressively reaching a diameter of 5 mm for the trocar body to enter the uterine cavity (Fig. 1B and C).

Aluminum tubes (Macon), with external diameters larger than the previous ones, were inserted externally in the trocar. This favored the progressive separation of the circular uterine muscle fibers. In addition, the tips of the aluminum tubes were thin, enabling the uterine fibers to be pulled apart without causing damage. Eight tubes were inserted after the previously described steps until the desired diameter of 25 mm was achieved (Figs. 1B and 2A). The last tube—a plastic cylinder that was 25 mm thick like the uterine wall—was measured using ultrasound and inserted and fixed to the uterine wall with 0 polyglactin 910 sutures (Figs. 1D and 2B). All these steps of the procedures were guided by ultrasound to monitor the uterine wall, the amniotic membranes, and fetal viability.

A cold-light, 4-mm, 0° neuroendoscope was introduced into the amniotic cavity through this tube (Figs. 2B

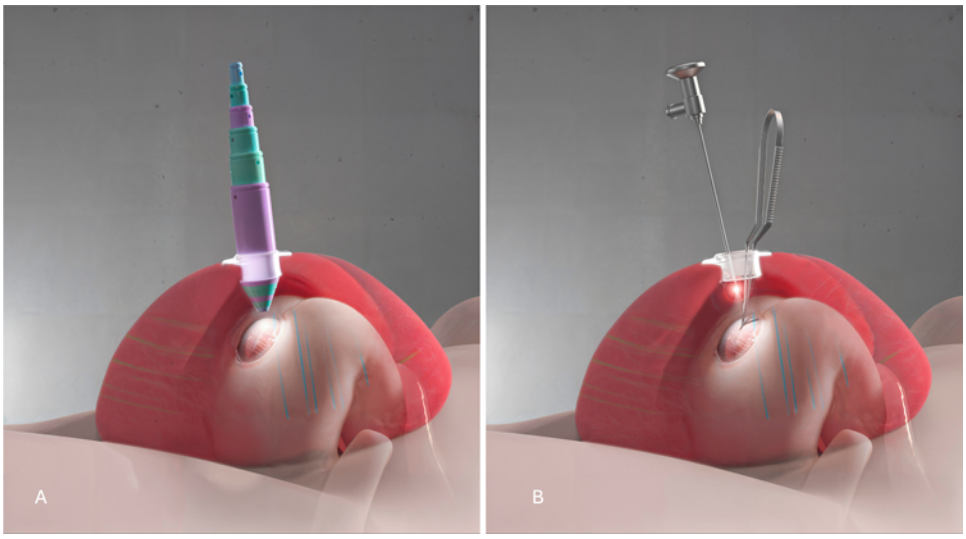

FIG. 2. Illustrations showing the procedure. **A:** Final aspect after the dilatation process and the plastic ring retractor held in place. **B:** The plastic ring retractor is held in place with the endoscope and microsurgical instruments. © Marcos Devanir Silva da Costa, published with permission.

and 3A). It was possible to visualize the MM and properly hold and stabilize the position of the fetus using fetal movement maneuvers. Furthermore, the spinal cord was gently released using a neuroendoscope and microsurgical techniques (Fig. 2B). The edges of the placode, which appear as an "open book," were released and approximated, allowing its return to a cone shape. The apical ligament, often identified in the upper part of the placode between

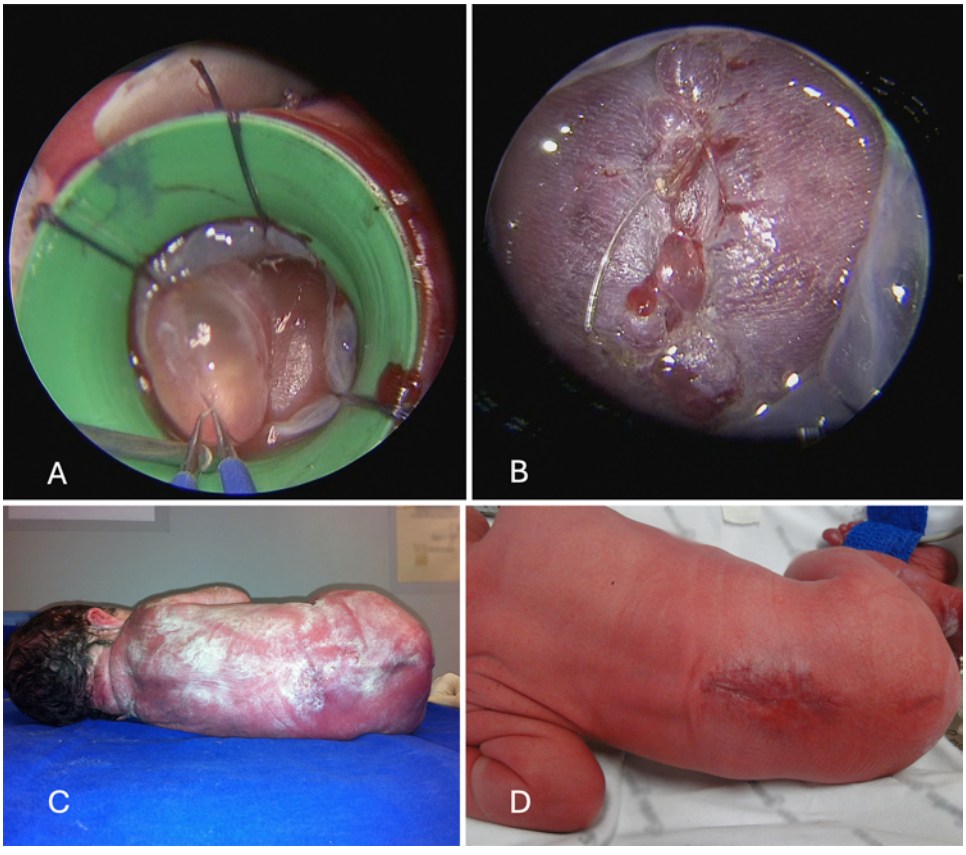

FIG. 3. Surgical photographs depicting MM at different times. **A:** Initial endoscopic view of MM, exposed through the plastic ring retractor. **B:** Final endoscopic view after MM closure. **C:** Scar at birth. **D:** Scar 30 days after birth.

the spinal cord and dura mater, was sectioned to release the spinal cord. The dura mater attached to the lateral fascia of the quadratus lumborum was incised and tightly closed to reconstruct the spinal canal with a 5-0 poliglecaprone 25 suture. The skin was sutured using absorbable threads, and if the defect was large, myocutaneous flaps were used to close the spinal dysraphism completely (Fig. 3B). The tubular retractor was removed after closing the MM, and the edges of the uterine wall were closed with 4-0 poliglecaprone 25 sutures, including the amniotic membranes and part of the myometrium. This occurred in a second-layer closure performed with anchored continuous 0 polyglactin 910 sutures. A Foley 16-Fr bladder catheter was placed to fill the amniotic cavity with 0.9% saline solution at body temperature, and 2 g cefazolin was added before the uterine walls were fully closed. A third closure was performed using 0 polyglactin 910 sutures to separate the sutures on the external uterine layer. The uterus was returned to the abdominal cavity, and the abdominal wall was reconstructed.

Tocolysis was maintained using magnesium sulfate at 1 g/hr for 12 hours. Subsequently, 20 mg nifedipine was administered every 8 hours until the day of delivery.

The uterus was assessed using ultrasound after closing the abdominal cavity. The assessment included the placenta, the site of the uterine suture, the closure of the MM, the degree of herniation of the hindbrain, and the fetal heartbeat. The patients began to walk on the 1st day after the operation. However, they were assessed daily by an obstetrician, and an ultrasound was performed on the 3rd day after the operation. They were discharged from the hospital on the 3rd or 4th day and were assessed weekly using ultrasound scans until delivery.

Study Inclusion and Exclusion Criteria

Fetal Inclusion Criteria

Fetuses with a gestational age of < 26 weeks with open spinal dysraphism diagnosed using ultrasound and/or MRI and had lesions located between L1 and S2 were included. In addition, the presence of herniation of the hindbrain through the foramen magnum (Chiari malformation type II) was noted.

All patients had normal genetic findings and no other abnormalities. They were followed up by the same neurosurgical team during the postoperative period for a minimum of 6 months.

Fetal Exclusion Criteria

We excluded fetuses with open spinal dysraphism at gestational age > 26 weeks, thoracic or cervical spinal dysraphism, and genetic diseases, as well as twins and those subjected to the procedure who did not receive follow-up during the postoperative period. Furthermore, fetuses with closed spinal dysraphism and absence of radiological signs of Chiari malformation, defects below S2, presence of kyphoscoliosis, and diastematomyelia were excluded.

Maternal Inclusion Criteria

Healthy singleton pregnant mothers with a cervix > 25 mm and body mass index < 40 kg/m^2 were included.

Maternal Exclusion Criteria

Mothers with clinical and/or obstetric comorbidities, psychiatric disorders, < 18 years of age, twin pregnancies, and a cervix < 25 mm were excluded.

Inclusion and Evaluation

Patients who fulfilled all the maternal and fetal inclusion criteria and had none of the exclusion criteria were eligible for the procedure and could agree to participate or not. Patients with fetuses that met the fetal inclusion criteria for the procedure were assessed by a multidisciplinary team comprising obstetricians, general practitioners, pediatric neurosurgeons, and anesthesiologists.

Ten pairs of patients (mother and fetus) with a gestational age < 26 weeks met the maternal and fetal inclusion criteria. They underwent the procedure at Santa Joana Hospital and São Paulo Hospital, which is affiliated with Universidade Federal de São Paulo, in São Paulo, Brazil, between January 2020 and June 2023.

All patients were assessed by measuring the head circumference and motor skills and using transfontanellar ultrasound. This was performed initially every month for the first 3 months and every 3 months until the fontanels had closed. All patients underwent MRI scans of the skull and total spine to evaluate for Chiari malformation type II and the presence of syringomyelia, as well as the position and appearance of the spinal cord at 6 months of age. In addition to postnatal neurosurgical follow-up, all patients were assessed by orthopedists and urologists.

The criteria for hydrocephalus treatment based on Tulipan et al.[4] were as follows: 1) progressive increase in cranial circumference to > 95th percentile; 2) bulging of the fontanel; 3) splitting of the cranial sutures; 4) progressive enlargement of the lateral ventricles; 5) a round appearance of the third ventricle; 6) voluminous syringomyelia; and 7) symptoms of Chiari malformation (apnea, bradycardia, swallowing difficulties, and laryngeal stridor).

If hydrocephalus treatment was indicated, the patient underwent an MRI study. Furthermore, if the floor of the third ventricle was concave, with a patent cerebral aqueduct and no cerebellar herniation, a ventriculoperitoneal (VP) shunt was indicated (communicating hydrocephalus). However, if the shape of the floor of the third ventricle was convex, with an obstructed aqueduct and cerebellar herniation, endoscopic third ventriculostomy (ETV) with coagulation of the choroid plexus was performed (obstructive hydrocephalus).

Results

Maternal Aspects

This was a retrospective study involving 10 patients. However, 3 of the patients who did not have clinical conditions did not undergo the procedure. Six pregnant women had been preventively taking folic acid for > 3 months before becoming pregnant. The gestational age ranged from 23 weeks 2 days to 26 weeks (average 24 weeks 6 days) at the time of surgery. Five cases showed anterior placenta, and the thickness of the uterine wall at the entrance point site measured at the time of surgery was average (range) 18 (12–23) mm. Notably, two sizes of tubular retractors

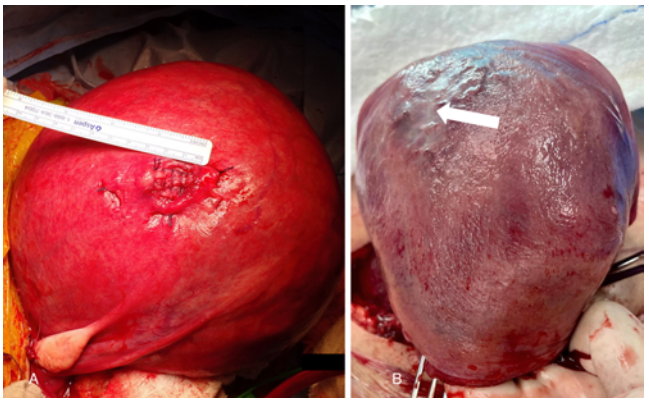

FIG. 4. A: Surgical photograph shows the uterine wound until the time of the fetal surgery. **B:** Surgical photograph shows the uterus after cesarean section at 37 weeks of gestation and a small scar on the body of the uterus (*white arrow*).

were used: 15 and 20 mm in height, with a diameter of 25 mm. The procedure time was average (range) 130 (120–140) minutes. None of the patients required a blood transfusion. Furthermore, no mother presented with uterine dehiscence (Fig. 4), pulmonary edema, or placental abruption or died. However, 1 patient presented with oligohydramnios due to chorioamniotic membrane separation. The comparison between the different techniques is shown in Table 1.

Fetal Aspects

Five fetuses had MM and the remaining had myeloschisis. The defect was repaired without artificial membranes or parallel release incisions in all cases. In all fetuses, anatomically reversing the Chiari type II malformation was possible, and none of the patients showed Chiari symptoms after birth. All patients were born via cesarean section and the gestational age at birth was average (range) 36 weeks 3 days (33–38 weeks). In addition, no neonate required respiratory assistance. The average postnatal hospital stay was 5 days. One patient, who was 33 weeks premature, had premature rupture of the membranes and developed oligohydramnios. Cesarean section was indicated after corticosteroids were administered, and the newborn did not require intubation after birth. All fetuses had reversion of hindbrain herniation, as presented in Fig. 5.

Neonatal Aspects

The follow-up period ranged from 6 to 39 months after birth. No patient required further intervention on the spine due to scar dehiscence, anchored spinal cord, or inclusion cysts. Motor function improved based on the anatomical sensory level in 5 patients. One patient required a VP shunt after birth and presented with a 14-mm lateral ventricle during fetal surgery. However, another presented with hydrocephalus and transependymal edema at 6 months of age. The newborn underwent ETV with coagulation of the choroid plexus and did not require a VP shunt (Fig. 6). The follow-up time was too short to complete the urological assessment. One patient required bladder catheterization, and no deaths occurred during this study. The results are summarized in Table 2.

Discussion

The uterus is a smooth-muscle organ consisting of longitudinal and circular muscle fibers. Fujimoto et al. used the diffusion tensor imaging technique to show the presence of many circular and longitudinal fibers in the uterine body and fundus, respectively.[5–7] The present technique was proposed to elongate uterine fibers without cutting based on the elastic capacity of uterine myocytes. Retraction was performed on the uterine body; in all cases, this mainly comprised circular fibers. Maintenance of the uterine fibers should help the uterine wall and ad integrum return to normal and allow carrying of the pregnancy to term, thereby facilitating the occurrence of future pregnancies and vaginal delivery. In our series, all deliveries

TABLE 1. General characteristics of the mothers and fetuses

Case No.	Folate Use	Level of Injury	Position of Placenta	Type of Dysraphism	Thickness of Uterine Wall at Surgery (mm)	Gestational Age at Surgery	Chiari II Reversal	Gestational Age at Birth	Uterine Scar	Post-Birth Follow-Up (mos)	Hydrocephalus Treatment	Motor Level
1	No	L1–S4	Anterior	Myeloschisis	17	23 wks 2 days	Yes	37 wks	Normal	39	VPS	+2
2	Yes	L3–S1	Posterior	MM	23	24 wks 1 day	Yes	36 wks 2 days	Normal	28	No	−1
3	Yes	L5–S2	Posterior	Myeloschisis	18	24 wks	Yes	38 wks	Normal	22	No	+2
4	No	L4–S1	Anterior	Myeloschisis	20	25 wks 6 days	Yes	36 wks 2 days	Normal	24	No	0
5	Yes	L3–S2	Posterior	Myeloschisis	19	25 wks 6 days	Yes	36 wks 5 days	Normal	15	No	+2
6	Yes	L2–S3	Anterior	MM	18	24 wks 5 days	Yes	37 wks 2 days	Normal	12	No	0
7	Yes	L5–S2	Posterior	MM	20	23 wks 3 days	Yes	33 wks	Normal	8	ETV + CPC	0
8	Yes	L4–S2	Anterior	Myeloschisis	16	24 wks	Yes	36 wks 3 days	Normal	9	No	0
9	No	L3–S2	Posterior	MM	15	25 wks 6 days	Yes	37 wks 2 days	Normal	6	No	+2
10	No	L5–S1	Anterior	MM	12	26 wks	Yes	38 wks	Normal	7	No	+1

CPC = choroid plexus coagulation.

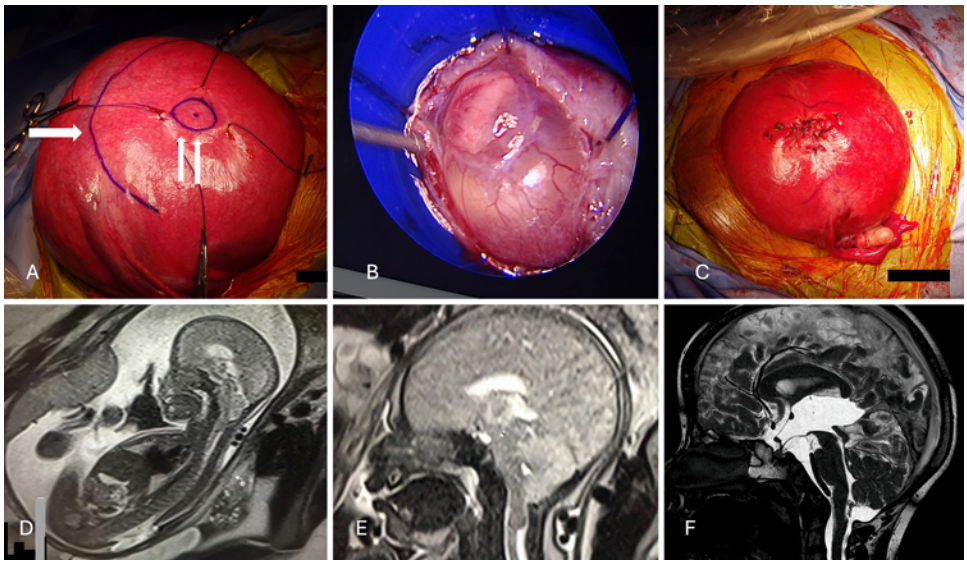

FIG. 5. Panel of images from case 6. **A:** A 24-week uterus gravidarum with delineation of the placenta (*arrow*) and the point of entry into the uterus (*double arrow*). **B:** Exposure of the MM. **C:** Aspect of the uterus after closure. **D:** Fetal MR image at 23 weeks 3 days showing herniation of the brainstem and cerebellum into the spinal canal (Chiari malformation type II). **E:** Fetal MR image obtained 30 days after MM repair surgery, with reversal of cerebellar herniation. **F:** MR image obtained 3 months after surgery with complete reversal of Chiari malformation type II, opening of the cerebral aqueduct and fourth ventricle, development of the cisterna magna, remodeling of the posterior fossa after reversal of cerebellar herniation, and mild communicating hydrocephalus with elevation of the floor of the third ventricle.

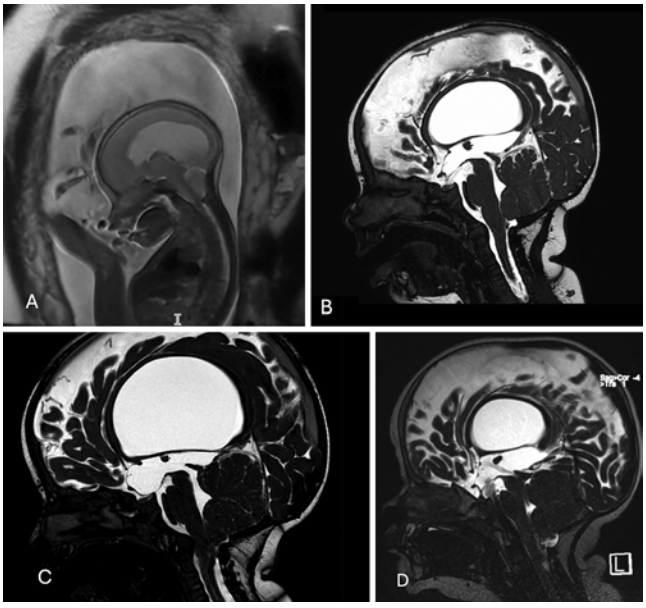

FIG. 6. A panel of images from case 7. **A:** Fetal MR image at 24 weeks gestation showing hydrocephalus and herniation of the brainstem and cerebellum. **B:** MR image obtained at 2 months after birth. Reversal of Chiari malformation type II, with opening of the cerebral aqueduct and fourth ventricle and elevation of the floor of the third ventricle characterizing communicating hydrocephalus, is shown. **C:** MR image at 6 months of age. Return of Chiari malformation type II, with lowering of the floor of the third ventricle and herniation of the cerebellar tonsils characterizing obstructive hydrocephalus, is shown. **D:** Control after ETV with the presence of flow in the floor of the third ventricle and reversal of cerebellar herniation.

were carried out by cesarean section, not because of fear of uterine rupture but to preserve the fetal surgery. Furthermore, of the 10 patients included in our series, only 1 was born before term (33 weeks) due to rupture of the amniotic membrane.

MOMS showed that the need for a shunt decreases by as much as 50% when surgery is performed early in the fetal period.[2] Notably, only 2 of 10 patients required hydrocephalus treatment with this technique. In this study, Chiari malformation type II was reversed in all patients. Different series showed complete reversal in 60%–80% of cases.[8–10]

Many centers have begun treating these patients on the basis of the MOMS results. Several changes to the initial surgical procedure have been proposed, mainly endoscopic techniques and including transabdominal or transuterine laparoscopy with two or three portals.[8–18] Transabdominal or hybrid endoscopic surgery requires a long learning curve. The costs of these procedures are elevated because of the use of disposable trocars and heated and humidified carbon dioxide gas.[19]

This technique was, on average, faster than the results of the International Fetoscopic Neural Tube Defect Repair Consortium, and its time was very similar to those of open techniques.[17] The rates of placental abruption were higher with endoscopic techniques (25 of 280 cases); however, this was not seen in our cases. Premature rupture of the amniotic membrane, a determining factor in prematurity, was seen in all series; in contrast, the lowest rates were found in our series, and in that of Belfort et al.[12] Concerning uterine rupture at the suture site, these were not found in the endoscopic cases; however, they were more common in the open techniques. Moron et al.[9] found a 3.8%

TABLE 2. Comparison of maternal outcomes between prenatal correction cohorts treated by different groups and techniques

	Adzick et al., 2011[2]	Degenhardt et al., 2014[18]	Belfort et al., 2017[12]	Lapa Pedreira et al., 2018[20]	Moron et al., 2018[9]	Sanz Cortes et al., 2021[17]	Present Study
No. of cases in each cohort	78	51	10	45	236	300	10
Chorioamniotic membrane separation	20 (26)	1 (1.9)	2 (20)	NA	49 (20.8)	72/190 (37.9)	0
Oligohydramnios	16 (21)	7 (13.7)	1 (10)	NA	55 (203.3)	53/267 (19.9)	1 (10)
Placental abruption	5 (6)	0	1 (10)	NA	2 (0.8)	25/280 (89)	0
Chorioamnionitis	2 (3)	1 (1.9)	0 (0)	NA	7 (3)	NA	0
Spontaneous membrane rupture	36 (46)	43 (84.3)	1 (10)	36 (80)	63 (26.7)	153/280 (54.6)	1 (10)
Spontaneous labor	30 (38)	NA	NA	NA	57 (24.2)	NA	0
Op time, mins	105.2	NA	246	193	119	204	130
Status of hysterotomy site at delivery							
Intact, well-healed	46/76 (64)	51 (100)	4/4 (100)	NA		162/162 (100)	10/10
Very thin	19/76 (25)						
Area of dehiscence	7/76 (9)						
Complete dehiscence	1/76 (1)				9 (3.8)		
Gestational age at birth, wks	34.1	33	38.5	32.8	33.6	34.6	36.3

NA = not applicable.
Values are shown as number, number (%), or mean unless indicated otherwise.

rate of complete dehiscence in the uterine suture area. In our series, the uterine fiber divulsion site was intact during delivery. The results were also superior when comparing prematurity. In the cooperative study,[17] the average gestational age at birth was 34.3 weeks, while in our series the gestational age was 36.3 weeks. The worst results were reported by Lapa Pedreira et al.[20] with the purely endoscopic technique. These results were also different concerning the need for shunts: the cooperative study used shunts or ETV in 43.8% of cases. However, in our series, 2/10 patients required treatment for hydrocephalus: one through a shunt and the other underwent successful ETV.[17]

Conceptually, MM is characterized by a tethered spinal cord considering its low medullary cone position. Therefore, spinal cord release is the key to improving motor and sphincter functions in these patients during fetal surgery. Surgeons should not be satisfied with performing a superficial procedure by simply repairing the defect using different types of patches. Neurosurgeons need to release the spinal cord and re-establish its normal anatomy, leaving the placode in a tubular shape, unlike an open book. Furthermore, spinal cord release prevents the future development of tethered cord syndrome.[21,22]

Tubular single-port endoscopy-assisted procedures are inexpensive and can be performed in any neurosurgery center because they rely on traditional microsurgery materials. Many pediatric neurosurgeons have mastered this surgery, as it is routinely performed to remove deep or intraventricular brain tumors and skull base tumors such as pituitary tumors, craniopharyngiomas, and clivus chordomas.[23–25]

We recognize the study's limitations resulting from its retrospective nature, the relatively small number of cases included, and short postnatal follow-up. However, despite these limitations, this present technique is simple and reproducible. It allows for presenting a 25-mm working field through a tubular retractor, which maintains the fetus with sufficient stability and provides a first step toward correction assisted with robotic techniques in a single portal.

Conclusions

Advancements in fetal medicine have improved the quality of life of patients with MM who undergo surgery in the fetal period. The tubular single-port endoscope-assisted approach allows the treatment of fetal spinal dysraphism and is possibly the first step toward future single-port correction using robotic techniques. However, additional cases and longer follow-up periods are essential to confirm the efficacy of this technique.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Cavalheiro, Barbosa, Sarmento, Capraro Suriano, Kusano, Moron. Acquisition of data: da Costa, Cavalheiro, Barbosa, Dastoli, Sarmento, Capraro Suriano, Kusano. Analysis and interpretation of data: Cavalheiro, Barbosa, Capraro Suriano. Drafting the article: da Costa, Cavalheiro, Barbosa, Dastoli, Moron. Critically revising the article: Dastoli. Reviewed submitted version of manuscript: da Costa, Dastoli. Approved the final version of the manuscript on behalf of all authors: da Costa. Administrative/technical/material support: Sarmento, Capraro Suriano, Kusano, Moron. Study supervision: Dastoli, Pares, Kusano, Moron.

Supplemental Information

Previous Presentations

The abstract was submitted and presented at the 50th Annual Meeting of the International Society for Pediatric Neurosurgery, Toronto, ON, Canada, October 13–17, 2024.

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