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Development of an Artificial Uterus for Neurosurgical Training in Intrauterine Repair of Myelomeningocele

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DEVELOPMENT OF AN ARTIFICIAL UTERUS FOR NEUROSURGICAL TRAINING IN INTRAUTERINE REPAIR OF MYELOMENINGOCELE

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ABSTRACT:

Purpose: Fetoscopic repair of myelomeningocele (MMC) may reduce maternal risks compared with open fetal surgery, but the rarity of cases limits training opportunities for neurosurgeons and lengthens the learning curve. This study aimed to evaluate the feasibility of combining two simulators already established on the market, an artificial uterus for laparoscopy with insufflation (SIM-L) and a fetal MMC model, for training in intrauterine MMC repair.**Methods**: A fetal model with a lumbosacral MMC and arachnoid sac was placed inside the SIM-L uterine cavity. The cavity was insufflated with a Veress needle, a 12 mm port was introduced for the optic, and two further ports were placed under direct visualization. Surgeons trained in both open and fetoscopic repair performed the three-layer closure (pia-to-pia, dura mater, subcutaneous tissue), followed by skin closure, at Orlando Health Hospital, Florida, USA.**Results**: All surgical steps could be simulated, from maternal positioning and fetal adjustment to port introduction, insufflation, three-layer closure, and port removal. The repair was completed successfully, with an approximate mean time of 50 minutes from insufflation to port removal. The surgeons described the tactile and visual experience as very close to real surgery.**Conclusion**: Combining an artificial uterus with a fetal MMC model is feasible and reproduces the main steps of intrauterine repair, providing a repeatable training environment for residents and neurosurgeons. Formal validation with objective performance measures is still needed.

Introduction

Myelomeningocele (MMC) is the most common presentation of spinal dysraphism, with a prevalence of 0.5 cases per 1,000 live births globally and 1 in 1,500 in the United States.[4, 12] It usually occurs in association with Chiari II syndrome (posterior fossa herniation), hydrocephalus, developmental delay, and motor

deficits in the lower limbs, varying according to the level of the lesion.[12]

Primary surgical treatment is the treatment of choice, with variations regarding the prenatal or postnatal approach, as well as the open approach or fetoscopy as prenatal possibilities [17, 28]. Since the MOMS trial (2011) [1], the prenatal approach has become established because it reduces the "two-hit effect": it closes the defect early and reduces its exposure to the intrauterine environment, improving motor outcomes and reducing the need for ventriculoperitoneal shunting at 30 months.[1, 36]

Given the scarcity of practice settings [10, 16, 37] and the need for methods that incorporate simulation models to support medical practice [7, 11, 13, 14, 23, 27, 30, 35], this project emerges with the goal of improving residents' skills in this surgical technique and developing fundamental abilities for routine neurosurgical practice.[3]

This was an important advance in neonatal outcomes from a developmental standpoint. However, the open uterine approach (maternal laparotomy and hysterotomy) proved to be associated with worse pregnancy outcomes, with higher rates of preterm birth, placental abruption, uterine rupture during labor, premature rupture of membranes, and a higher rate of postnatal hospital admission for respiratory infections in neonates. [1, 21]

In this scenario, in an effort to improve maternal outcomes while maintaining the gains of fetal surgery for child development, the minimally invasive surgical technique was pursued [6]. The technique consists of gaining access to the uterine cavity through ports (2–5), insufflation with carbon dioxide, and repair of the defect using techniques that still vary (skin closure or three-layer closure) [6, 28]. However, the rarity of cases limits access for neurosurgeons in training, which makes the learning curve of the technique more difficult [22] and increases operative time, which is associated with unfavorable outcomes for the mother-fetus dyad. [7]

To increase exposure time to the technique, accelerate the learning curve, and improve maternal-fetal outcomes, this study aimed to evaluate the feasibility of combining two simulators already established on the market. The SIM-L (simulator for

laparoscopy with insufflation®) was used as the uterine cavity, and the simulator developed by Ferreira's team (2023) for training in open MMC closure was used in this study as the intrauterine fetus. [15]

Materials and methods

To carry out simulation training of corrective myelomeningocele surgery, the authors of this study used anatomical models developed by a Brazilian company. The manikin consists of an artificial uterus, developed for laparoscopic surgery training, which replicates the anatomy and tactile feedback of human abdominal structures, allowing training very close to the real procedure. It includes an insufflation pump with pressure control, an artificial lower abdomen, and an artificial upper abdomen, allowing puncture and port placement for introduction of Veress needles through the umbilical scar to create the pneumoperitoneum. In addition, the model has an acrylic base that provides the structure needed to secure the uterus to a rigid table, facilitating training.

The use of the artificial uterus allowed surgeons to train from pelvic access through laparoscopic abdominal dissection and suturing techniques, anticipating the difficulties and possible complications in a manner similar to real surgery. In addition to the artificial uterus, a second manikin, produced by the same Brazilian company, was used as an additional model of a fetus with myelomeningocele and an arachnoid sac in the lumbosacral region. The study with the anatomical models for intrauterine myelomeningocele repair was conducted at Orlando Health Hospital in Florida, USA.

Fetal microsurgery training followed the standard sequence of surgical steps for myelomeningocele repair [17]. After port introduction, pneumoperitoneum formation (Figure 1), and introduction of the forceps into the uterus, the meningeal defect was located, and dissection of the arachnoid and exposure of the placode were begun (Figure 2). Next, the placode was isolated medially, and closure of the spinal cord was started under microscopy in three layers.

The first layer was a pia-to-pia suture with 6-0 Prolene, converting the

placode into a tube. For the second layer, we dissected the superior, lateral, and inferior edges with microsurgical instruments (scissors and dissectors) to perform lateral-to-medial approximation of the dura mater to cover the entire placode. Finally, the third layer was sutured with 4-0 Vicryl (Figure 3) for the subcutaneous tissue. The skin was closed with 5-0 Nylon (Figure 4).



Figure 1 – Port insertion in the artificial uterus simulator



Figure 2 – Dissection of the arachnoid and exposure of the placode with real forceps

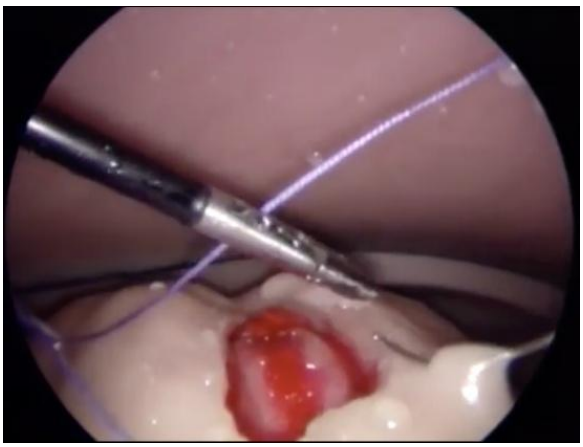


Figure 3 – Suturing of the fetal tissue layers with suture thread

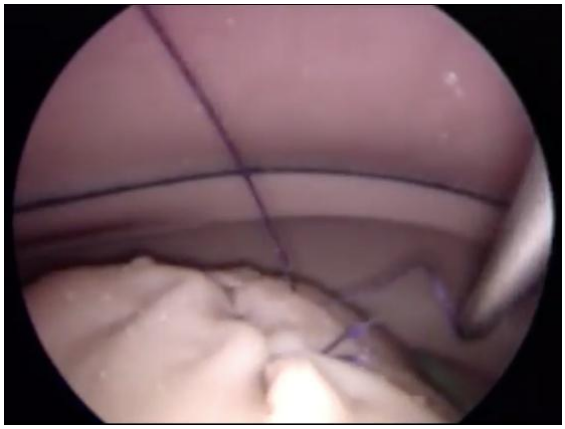


Figure 4 – Intrauterine suture of the fetal skin

Results

An artificial uterus model was demonstrated for performing intrauterine surgery to resolve myelomeningocele. This technique was chosen to evaluate the practical applicability of the model for teaching the procedure.

The simulator was assembled with the fetus inside the SIM-L cavity. A Veress needle was used to insufflate the cavity, a 12 mm port was introduced for the optic, and two more ports were then placed under direct visualization. The defect was repaired using the three-layer technique, which is well established for intrauterine closure [6, 28], with an approximate mean time of 50 minutes from insufflation of the cavity to removal of the ports, indicating that the technique was performed successfully.

The surgeons who performed the repairs are trained and qualified to carry out these corrections by both open and fetoscopic approaches, and they described the tactile and visual experience as very close to reality. The surgical steps can be simulated realistically, from maternal positioning, adjustment of fetal position, port introduction, and insufflation, through the detailed main stage and three-layer closure, to port closure.

The use of models such as the artificial uterus for intrauterine repair of myelomeningocele represents an advance in the development of surgical training models, moving beyond practice based solely on rudimentary models, such as those using animals [14, 23, 38]. In this way, the model expands the possibilities for training and facilitates the development of this technique.

Discussion

Myelomeningocele repair surgery can be performed in utero or after birth. However, performing the procedure during pregnancy reduces the incidence of malformations, attributed to the neuroprotection

resulting from shorter exposure to mechanical trauma and to amniotic fluid, which is considered toxic to spinal cord structures [1, 19, 34]. In addition, by allowing early correction, fetal surgery, compared with postnatal surgery, favors greater neural development of the genitourinary system, reducing urological complications such as bladder dysfunction [9], as well as cases of hydrocephalus [1, 36] and, consequently, the need for further surgical interventions, thereby preserving the child's neuromotor function.[19, 20, 29]

It is well known that the main complications associated with intrauterine surgery for myelomeningocele involve the risk of uterine rupture and prematurity, since the ideal window for the procedure is between the 20th and 25th weeks of gestation [1, 21, 28, 29, 34]. For this reason, together with the scarcity of neurosurgical skills for intrauterine repair, corrective surgery came to be restricted to the postnatal period. [22, 33] However, this increases the incidence of tethered cord syndrome, owing to possible intraspinal adhesions to structures adjacent to the surgical site, which limit movement and cause excessive stretching of the spinal cord, leading to progressive neurodevelopmental dysfunction.

The development of surgical techniques and of fetoscopy training reduces the risks of maternal complications and increases the safety of fetal surgery for myelomeningocele repair, making this approach an important strategy that is not only therapeutic but also neuroprotective, and crucial for these patients' future autonomy [22, 28]. Thus, the production of simulators for intrauterine surgery represents an advance in the training of neurosurgical skills, aiming to reduce surgical risks and promote postnatal quality of life for patients with myelomeningocele. [24]

Furthermore, owing to its anatomical and tactile similarity to the human organ, the uterine prototype allows training in other types of fetal and gynecological surgeries, making it a promising tool for developing surgical skills in other areas of medicine.[18, 31]

Conclusions

Therefore, the uterine simulator provides training for real situations

within the variables present in fetal as well as uterine surgery, for residents and neurosurgeons. It is an important innovation for the treatment of neurological conditions such as myelomeningocele, owing to the possibility of numerous repetitions to refine the different surgical techniques in a model with human-like size and texture [22, 23].

Because few similar prototypes are available on the market and in academic centers, this simulator is expected to add value to medical research aimed at developing teaching strategies and surgical practice in training environments for neurosurgeons, fetal surgeons, and gynecological surgeons.

Finally, uterine and fetal simulators offer advantages over other traditional surgical training methods [5, 8, 25, 26], as they foster early manual skills in a controlled environment with models very similar to real structures [2, 32]. They are also practical, being easy to store and maintain, representing excellent cost-effectiveness given the need to produce skilled and experienced physicians for the surgical treatment of myelomeningocele and other fetal and uterine conditions.

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Author contribution:

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Christian Diniz Ferreira, Samer K. Elbabaa, and Marcos Eugênio Sellaro Lyra. The first draft of the manuscript was written by Christian Diniz Ferreira and Steyllon Pedro Andrade Leopoldino and Reviewed by Giordano Bruno Correia Lima, Marcos Aulete Ribeiro Lyra and Michael C. Dewan.

Availability of data and material: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

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Consent to participate: Not applicable.

Consent for publication: Not applicable.

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