The Use of Models from Anatomical Simulators for Training Professional Skills in Intrauterine Myelomeningocele Correction by the Fetoscopic Technique: A Scope Review

Luciana Maria de Oliveira Nascimento (Corresponding author)
Federal University of Ceará, Brazil
Coronel Nunes de Melo Street, S/N, Rodolfo Teófilo, Fortaleza, Ceará, Brazil
Tel: 55-85-9616-8285 E-mail: lucianamoliveira19@gmail.com

Lanese Medeiros de Figueiredo
Federal University of Ceará, Brazil
E-mail: lanese_figueiredo@yahoo.com.br

Lilian Oliveira Medeiros
Christus University, Brazil
E-mail: lilianmedeiros250@gmail.com

Luana de Oliveira Medeiros
Christus University, Brazil
E-mail: luanamedeiros1801@gmail.com

Francisco Herlânio Costa Carvalho
Federal University of Ceará, Brazil
E-mail: herlaniocosta@uol.com.br

Emmanuel Prata de Souza
Federal University of Ceará, Brazil
E-mail: emmanuelprata@gmail.com

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Abstract

Fetal neurosurgery for MMC can be performed openly or fetoscopically. Anatomical simulators have been developed for the training of the fetoscopic technique of intrauterine myelomeningocele correction. This scoping review aimed to map the evidence available in the scientific literature about anatomical simulators models used for training the fetoscopic technique in intrauterine correction of myelomeningocele. The Study is a Scope Review, conducted according to the methodological recommendations of the Joanna Briggs Institute (JBI) Manual and six databases were consulted. The publications selected in this review include most of the publications in the Cochrane Library databases (889; 55.0%), followed by Web of Science (509; 31.5%) of the publications found and published between 2009 and 2024, with the majority in mid-2020. We found 10 studies of models of existing anatomical simulators used in professional training. It is considered, therefore, that the main advance of this series of studies consists not only in the defense of a single model or an isolated approach, but in the implicit proposal of a progressive training environment, ethical and progressive for MMC fetoscopic surgery. Many future challenges and developments will involve continuous improvements in the realism, safety and reuse of these models, along with evidence of their effectiveness in surgical training.

Keywords: meningomyelocele, models anatomic, neurosurgery, high fidelity simulation training, fetoscopy.

1. Introduction

Myelomeningocele (MMC), also known as cystic or open spina bifida, is a congenital abnormality in the closure of the embryonic neural tube, occurring between the third and fifth weeks of gestation. It results in a visible herniation containing cerebrospinal fluid (CSF), meninges, nerves, and spinal cord. The lack of fusion of the vertebral laminae, along with malformation of the spinal cord, meninges, and nerve roots, results in this alteration during embryogenesis and the possible exposure of the spinal cord and meninges in the dorsal region of the newborn, presenting as a cystic protrusion of exposed nervous tissue (Bowman, 2020).

Children affected by MMC require immediate surgical care to treat CSF leakage, prevent infections, and restore the anatomical defect as much as possible. Additional surgeries are often indicated to treat some associated conditions. These infants need multidisciplinary support and lifelong follow-up to manage urological, orthopedic, and neurological problems (Carraba et al., 2019).

Until recently, treatment of the malformation was only possible after birth, with surgical correction of the defect in the patient's spine. Until 2011, only this treatment was validated and used. With the advent of fetal surgery for the correction of intrauterine MMC, it was found that significant clinical and functional benefits were obtained for the fetus, improving the neuropsychomotor prognosis at birth (Adzick et al., 2011).

Fetal neurosurgery for MMC can be performed via open surgery or fetoscopically, with open surgery currently being a widely reported procedure, and its results were confirmed in the MOMS (Management of MMC) study. Myelomeningocele Study), a large randomized controlled clinical trial, conducted in the USA, in three maternal-fetal centers (Alencar, 2022).

Patients who underwent prenatal surgery showed better outcomes, such as a twofold increase in the likelihood of ambulation, and prematurity, as 13% of those born after fetal surgery were born before 30 weeks, compared to patients who underwent postnatal repair (Silveira et al., 2018).

However, fetoscopy then emerged as a less invasive and potentially safer alternative to open hysterotomy for this procedure, with less maternal morbidity (Patel *et al.,* 2021). Fetoscopic repair of open spina bifida can minimize maternal risks and preterm birth, with similar neonatal neuroprotective effects (Belfort et al., 2020).

The fetoscopic technique for intrauterine myelomeningocele repair is a minimally invasive procedure that aims to correct the neural tube closure defect in the fetus, characteristic of myelomeningocele, without the need for a large hysterotomy as in open surgery (Lapa et al., 2021).

Fetoscopic repair of MMC in humans reported in the literature were performed at the German Center for Fetal Surgery. The technique used involved the placement of three percutaneous intrauterine trocars, guided by maternal transabdominal ultrasound, with coverage of the spinal cord using a collagen/Teflon adhesive (Paz et al., 2022).

Another technique developed in Brazil (São Paulo) addressed the modified fetoscopic technique, using three trocars, but involved placing a biocellulose adhesive over the spinal cord (Paz et al., 2022).

At the Texas *Children's Fetal Center, the* fetoscopic technique approach was developed, where the uterus is accessed through a maternal laparotomy using two uterine ports. The membranes are secured against the uterine wall with absorbable sutures, and the uterine ports are closed. Dissection of the neural placode is performed, and the dura mater and skin are closed as a single layer over the spinal cord (Paz et al., 2022).

Intrauterine fetal repair of myelomeningocele is a technically challenging procedure, and therefore considered one of the most significant advances in contemporary fetal surgery. Several changes have been proposed aiming at uterine preservation and reduction of maternal morbidity (Cavalheiro et al., 2024). However, it is a technically complex but promising procedure that requires skill and specific training to master minimally invasive techniques, which need to be improved (Horzelska et al., 2020).

Repair of myelomeningocele (MMC) requires high technical complexity, and because most pediatric neurosurgeons have not received specific training for this purpose, it is necessary to define specific protocols and invest in resources to improve surgical dexterity and skill in order to ensure better clinical outcomes and maternal-fetal safety (Wataganara et al., 2021).

In this context, simulators emerge as essential tools for the development and improvement of the required skills, allowing surgeons to practice in a controlled, safe, and ethical environment, thereby reducing the learning curve and mitigating risks to maternal and fetal health. They are also useful for teaching new techniques to specialists and for developing non-technical skills, such as teamwork and communication (Spoor et al., 2023; Coelho et al., 2022).

The scientific literature describes different types of simulators—physical, hybrid, virtual, and 3D-printed—each with its own characteristics, advantages, and limitations. Simulation models can be effective in shortening learning curves; however, for myelomeningocele (MMC), current models are either expensive, animal-based, or of low fidelity (Spoor et al., 2023).

Several anatomical simulators have been developed for training in the fetoscopic technique for intrauterine myelomeningocele repair. Models using non-living animal tissues, such as chicken breast combined with spherical structures simulating the uterus, provide better tactile feedback and allow the practice of suturing and dissection, although they are considered low fidelity and low cost (Belfort et al., 2018).

High-fidelity synthetic simulators, produced with silicone and 3D printing, accurately reproduce the uterus, the fetus, and the spinal defect, enabling full practice of the surgical steps (Spoor et al., 2023; Miller et al., 2023). Likewise, high-fidelity surgical models using live animals increase the realism of training (Joyeux et al., 2021).

Finally, augmented virtual reality simulators offer repetitive and interactive training in a digital environment. Although they still present limitations regarding tactile feedback, they allow professionals to experience surgical simulations comparable to challenging real-life procedures (Coelho et al., 2022).

Fetoscopic technique training, and what gaps remain. Developing an anatomical simulator that faithfully reproduces the surgical scenario of closing an open neural tube defect, with a mannequin that reproduces the trunk, and that allows the adjustment of sequential layers of simulated tissue regarding the morphometric parameters of the anatomical structures, is a unique and characteristic challenge (Mattei et al., 2013).

Even surgeons experienced in postnatal myelomeningocele (MMC) repair are unable to adapt the steps of open repair to the endoscopic technique, making the use of an anatomical model necessary for training and improvement. The learning curve, even for teams experienced in open fetal surgery, requires specific training for the technique migration. The creation of anatomical training models emerges as an alternative for both experienced teams and those wishing to begin and accelerate learning the endoscopic approach (da Costa, 2023).

Fetoscopic MMC correction program, a place for the team to practice, a reasonably realistic simulator to practice on, and adequate time and resources to allow this to happen are crucial for the team's growth. However, the skill set to perform this type of fetoscopic surgery is still not widely disseminated in standard surgical teaching programs, although having experience in laparoscopic surgery presumably shortens the learning curve (Belfort et al., 2018).

However, there is a global gap regarding the anatomical models available for use in training, the degree of realism, costs, teaching-learning methods for surgical skills and pedagogical validity, standardization of the technique used for intrauterine myelomeningocele repair via fetoscopic approach, and the impact on professional training for this purpose.

A scoping review on the subject is therefore relevant in gathering existing scientific evidence, making it possible to identify existing anatomical simulator models for the practice of fetal surgery, with the aim of enabling the implementation of training programs for multidisciplinary teams, reducing the learning curve and increasing maternal-fetal safety; identifying gaps that guide future research and stimulate technological innovation in the area of health education and fetal surgery.

This study aims to map the evidence available in the scientific literature regarding anatomical simulator models, made from biological and non-biological materials, used for training in fetoscopic techniques for intrauterine correction of myelomeningocele in human fetuses.

2. Method

This is a scoping review, conducted in accordance with the methodological recommendations of the *Joanna Briggs Institute* (JBI) Manual (Aromataris et al., 2024). The scoping review is exploratory and descriptive in nature, and its choice is justified by being an appropriate method for mapping the available evidence in the scientific literature on the proposed topic, identifying key concepts, deepening the concepts, and identifying gaps on the topic, providing a broad overview of the subject (Peters et al., 2020). The scoping review protocol was registered on the Open Science Framework (OSF) platform (https://doi.org/10.17605/OSF.IO/HF582).

The following steps were adopted in the conduct of the study: elaboration of the guiding question, systematic search in the literature and selection of references for analysis, evaluation of the selected studies, extraction and preparation of data.

The research question was constructed according to the PCC (Population, Concept, Context) strategy (Peters et al., 2022): "P" (Population): professionals in fetal surgery training for fetoscopic correction of intrauterine myelomeningocele ; "C" (Concept): anatomical simulator models used for training in the fetoscopic technique for intrauterine myelomeningocele correction ; and “C” (Context): training of professionals to develop skills in the correction of intrauterine myelomeningocele using the fetoscopic technique.

The following research question was formulated:

- What anatomical simulator models exist, described in scientific publications, and are used in professional training for developing skills in the correction of intrauterine myelomeningocele using the fetoscopic technique?

Eligible articles included original articles, reviews, technical reports, editorials, and grey literature that described, evaluated, and/or used anatomical simulator models made of biological and non-biological materials, employed for training in fetoscopic techniques for intrauterine correction of myelomeningocele in human fetuses.

Duplicate publications and those that described, evaluated, and/or used anatomical simulator models made of biological and/or non-biological material, intended for training in surgical techniques other than intrauterine myelomeningocele repair, as well as studies conducted exclusively on non-human animal models, were excluded.

For the execution and structuring of all stages of this review, the PRISMA- ScR (Preferred*) Checklist was adopted. Reporting Items for Systematic Reviews)* and *Meta- Analyses Extension for Scoping Review)* (Page et al., 2021) and a search of the scientific literature was conducted by consulting electronic databases, following the recommendations of the *Joanna Briggs Institute* (JBI) for scoping reviews (Aromataris et al., 2024).

Initially, a preliminary search was conducted in the Cochrane Library (https://www.cochranelibrary.com/search) and the *Open Science Framework* (OSF) Institution (https://osf.io/search) to verify the existence of records of previously published protocols and scoping reviews; however, no records were found.

The keywords, similar terms and descriptors contained in the multilingual structured vocabulary DeCS/MeSH (Descritores em Ciências da Saúde - Medical Subject Headings) were chosen, and in combination with the boolean operators AND, OR and AND NOT, the search strategies were elaborated. A librarian was consulted to ensure rigor in this process and in the definition of combinations.

The search strategies were applied to the advanced search interface of the CAPES Periodicals Portal, accessible to servers of the Federal University of Ceará (UFC) via *login* to the Federated Academic Community (CAFe).

The search was carried out in six databases, from the Portal Periódicos CAPES, namely: COCHRANE Library, Scopus (Elsevier), Web of Science, grey literature, Brazilian Digital Library of Theses and Dissertations (BDTD), (https://bdtd.ibict.br/vufind/); Portal CAPES in Catalogue of Theses and Dissertations - Brazil (https://catalogodetes.capes.gov.br/catalogo-theses/#!/). The search was conducted on 14 October 2025.

The files generated after applying the search strategies to the databases, containing the identified articles, were imported into the *Rayyan® (AI- Powered) reference manager. Systematic Review Management Platform)* (https://www.zotero.org/support/).

In *Rayyan®,* duplicates were removed, and references were analyzed and selected independently and blindly by two reviewers, considering the content present in the titles and abstracts, and the full content of the selected articles.

The evaluation of the studies occurred in two stages: initially, the titles and abstracts were read, followed by the selection of articles to be examined in full. In the next stage, the complete titles were read to determine their inclusion in the review results.

In cases of disagreement regarding the inclusion or exclusion of articles in both stages, the final decision was made with the assistance of a third reviewer, at which time 1 article was excluded from the 14 indicated for full reading, because it described the myelomeningocele correction technique as having been performed in an extrauterine model.

Table 1 presents the search strategies used in the respective databases of the CAPES Periodicals Portal.

Table 1. Databases and search strategies used. Fortaleza, Ceará, Brazil, 2025

Source	Search strategies
Cochrane Library	High Fidelity Simulation Training in Title Abstract Keyword OR Simulation Training in Title Abstract Keyword AND "meningomyelocele" in Title Abstract Keyword OR Spina Bifida Cystica in Title Abstract Keyword OR "spinal dysraphism" in Title Abstract Keyword - (Word variations have been searched)
Scopus	(ALL (Simulation Training) AND ALL (Models Anatomic) AND ALL (meningomyelocele) OR ALL (Spina Bifida Cystica) OR ALL (Nervous System Malformations) OR ALL (Neural tube defects) OR ALL (Spinal Dysraphism) OR ALL (meningomyeloceles))
Web of Science	Simulation Training (Title) and Fetoscopy (Title) and Models, Anatomic (Title) and Neurosurgery (Title) or meningomyelocele (Title)
BVS	(Models, Anatomic) AND (meningomyelocele), filters: Titles, abstracts and subject.
BDTD	
CTDB	"anatomical model"

Note. Caption: Brazilian Digital Library of Theses and Dissertations (BDTD), (https://bdtd.ibict.br/vufind/) ; Virtual Health Library Nursing (BVSE), in the theses and dissertations collection (https://bvsenfermeria.bvsalud.org/pt) ; CAPES Portal in Catalog of Theses and Dissertations Brazil (CTDB) (https://catalogodeteses.capes.gov.br/catalogo-teses/#!/).

Tables were created from information extracted from the selected articles to compile the results of this scoping review, as presented in the results section.

After reading all the titles and abstracts of the studies found in the searches in the grey literature databases, guided by the search strategies described in Table 2, no item was found that answered the research question.

Table 2. Grey literature databases and search strategies used. Fortaleza, Ceará, Brazil, 2025

Brazilian Digital Library of Theses and Dissertations (BDTD)	Number of documents found
(All fields: Anatomical Models and All fields: Anatomical Model)	1.767
(All fields: Myelomeningocele)	99
(All fields: Meningomyelocele)	28
(All fields: Cystic Spina Bifida)	2
(All fields: Anatomical Models and All fields: Anatomical Model and All fields: Myelomeningocele)	1
(All fields: Anatomical Model and All fields: Myelomeningocele)	1
(All fields: Myelomeningocele and All fields: Surgery)	43
(All fields: Myelomeningocele AND All fields: surgical correction)	19
(All fields: surgery) fetoscopic	4
(All fields: Neurosurgery and All fields: Fetoscopy)	1
(All fields: Neurosurgery and All fields: newborn)	5
(Title: Anatomical Model and All fields: Anatomical Models and All fields: Surgery) (Fetoscopic) - does not correspond to any record.	0
(Title: Anatomical Model and All fields: Anatomical Models and All fields: Neurosurgery) - does not match any record.	0
(All fields: Anatomical Models AND All fields: Meningomyelocele AND All fields: Meningomyelocele AND All fields: Neurosurgery AND All fields: High-Fidelity Simulation Training AND All fields: Simulation Training AND All fields: Spinal Dysraphism AND All fields: Neural	0

Tube Defects AND All fields: Fetoscopy AND All fields: Cystic Spina Bifida) - does not match any record.	
(All fields: Meningomyelocele AND All fields: Myelomeningocele AND All fields: Cystic Spina Bifida AND All fields: Spinal Dysraphism AND All fields: Neural Tube Defects) - does not match any record.	0
(All fields: Spinal Dysraphism)	17
(All fields: Spinal Dysraphism and All fields: Neurosurgery)	6
(All fields: Cystic Spina Bifida)	2
(All fields: Neural tube defects and All fields: newborn)	17
(All fields: Spinal Dysraphism and All fields: Anatomical Model)	0
(All fields: Cystic Spina Bifida and All fields: Anatomical Model)	0

Figure 1 presents the flowchart adapted from PRISMA (Page et al., 2021), with the respective quantities of studies found, included, excluded, after reading the titles and abstracts, after reading the full article, and the number of those that comprised the results.

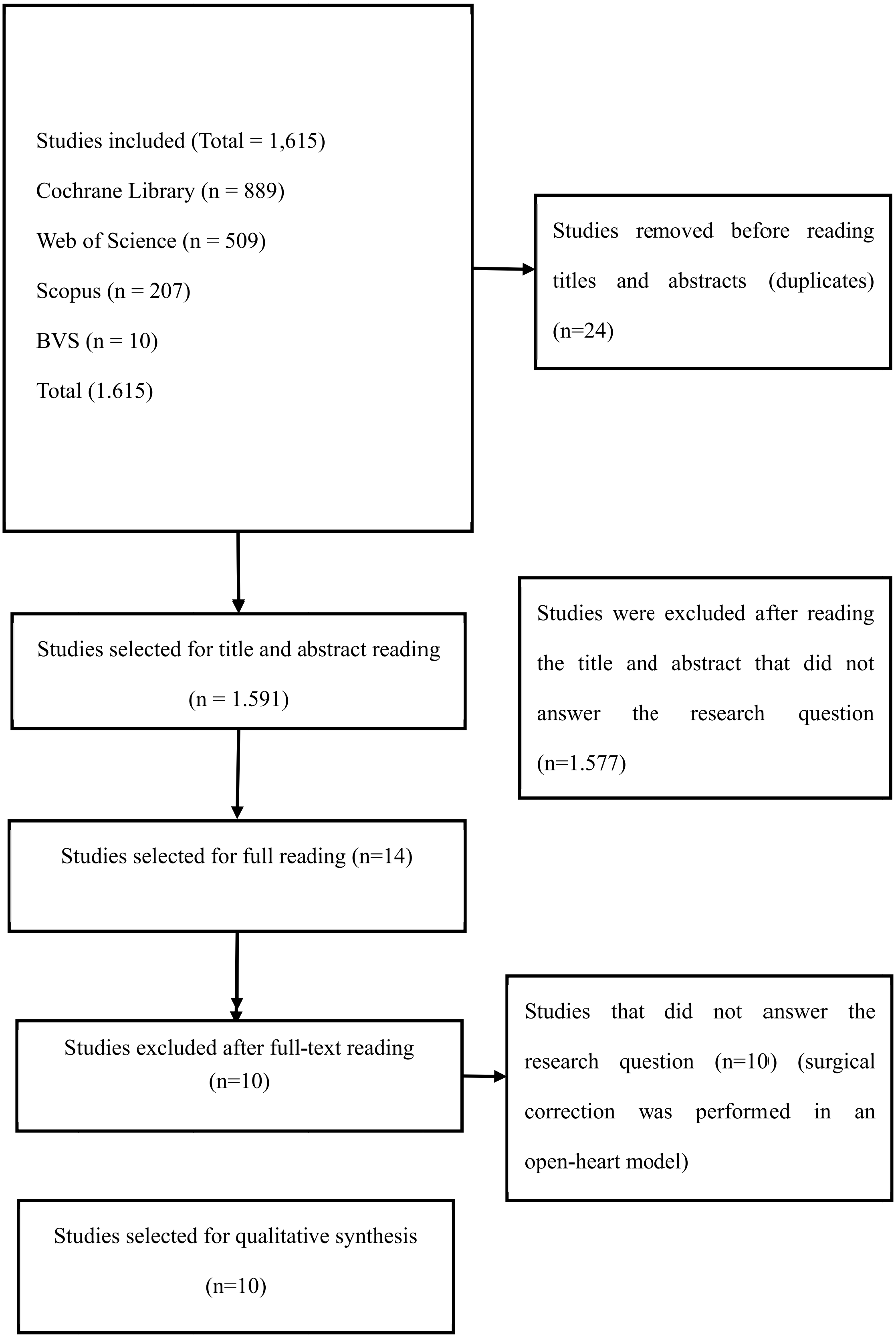

Figure 1. Flowchart developed, with an explanation of the results of the study selection, Fortaleza, Ceará, Brazil, 2025.

3. Results

Ten studies were found on existing anatomical simulator models used in professional training for developing skills in the correction of intrauterine myelomeningocele using fetoscopic techniques. The following data were extracted from these studies: study type, objectives, method, anatomical model used, main results, and conclusions.

The data in Table 3 were collected in four categories. The first category is "type of study conducted," the second category was the "objectives" of each study, the third category was the "method" used to collect the study data, and the fourth category identified the "anatomical model used" to develop the working method.

Table 4 summarizes the "main results of the studies" and the "conclusions" drawn from these works, taking into account the evaluation of the 4 categories used in Table 3.

In Tables 3 and 4, the studies were identified by the letter "E" followed by the corresponding number (1 to 10).

Table 3. Distribution of studies, according to type, objective and method of study and anatomical model described. Fortaleza, Ceará, Brazil, 2025

Study	Type of study	Objectives	Method	Anatomical model used
E1	In vivo experimental study with an animal model.	To develop and test a simplified technique for prenatal correction of MMC-like defects.	Creation of the defect in sheep fetuses, intrauterine correction, and macroscopic and histological analysis.	Sheep fetuses (ovine model), validated as a suitable model to simulate human MMC.
E2	In vivo experimental study in an animal model.	To evaluate the long-term results of fetal MMC correction using a cellulose patch.	Surgical creation of a spinal defect, correction with a cellulose patch via hysterotomy, functional and histological evaluation after birth.	Sheep fetuses (sheep model).
E3	Prospective, randomized, crossover clinical trial	To evaluate the usefulness of customized three-dimensional anatomical models in surgical planning and	Proficiency-based training using physical and virtual simulators, with cross-evaluation of performance.	No biological models were used. Only biological models were used. Artificial models: FLS (box with synthetic

		outcomes for the correction of complex spinal deformities in children with MMC.		materials) and LapSim (virtual reality simulator).
E4	Descriptive experimental study / technical report	Develop a low-cost simulator for training and refining the two-port fetoscopic technique in MMC.	Construction and repeated use of a low-fidelity fetoscopic simulator for technical training.	Hybrid model (plastic doll + animal tissue + artificial uterus).
E5	Case report with technical description and validation of a surgical simulation model.	Develop a customized fetal model for preoperative testing of fetoscopic correction of MMC.	3D ultrasound, anatomical segmentation, multi-material 3D printing, and fetoscopic surgical testing.	Customized artificial anatomical model, 3D printed from fetal ultrasound (patient-matched model), simulating the tissue layers of the MMC.
E6	Study descriptive experimental	Develop and evaluate a simulator for training in fetoscopic correction of MMC.	Construction of a simulator and evaluation by surgeons via questionnaires.	Artificial model of a human uterus and fetus with simulated MMC.
E7	Descriptive experimental study	Develop and describe a realistic and reproducible simulation model intended for Surgical skills training, aimed at	Construction of a anatomical simulator using synthetic and/or biological materials, followed by practical application by surgeons or trainees.	An artificial or hybrid anatomical model, designed to reproduce the anatomical structures relevant to the surgical procedure being

		improving the learning curve in a safe environment.		studied.
E8	Descriptive experimental study	fetoscopic correction of MMC.	Construction and use of a fetoscopic simulator with evaluation of realism and applicability.	Artificial model of a human uterus and fetus with simulated MMC.
E9	Study descriptive experimental	To present and evaluate a synthetic simulator for microsurgical training in MMC.	Development and use of a synthetic model with execution of the microsurgical technique.	Synthetic human lumbosacral MMC model.
E10	Descriptive experimental study (original research)	To develop a high-fidelity synthetic model for training in fetoscopic repair of MMC.	Construction of a multilayer model and evaluation through fetoscopic simulations with objective metrics.	Synthetic model of a fetal MMC with simulated uterine cavity and 3D printed components.

Source: research data.

Table 4. Distribution of studies, according to main results and conclusions. Fortaleza, Ceará, Brazil, 2025

Study	Key results	Conclusions
E1	Correction success rate of 90.9%, improved skin closure and spinal cord protection compared to the control group.	This simplified technique is effective, reproducible, and promising for fetal MMC surgery.
E2	The simplified technique preserved the medullary architecture and avoided adhesions; the classic technique caused structural damage.	The simplified technique proved superior and may represent a safer alternative for prenatal correction of MMC.
E3	Both groups improved; FLS showed greater skill transfer and better	Low-fidelity simulators are effective, cost-effective, and

	suturing performance.	superior in transferring skills.
E4	The low-fidelity simulator allowed for repetitive training, instrument testing, and team organization.	Simple and low-cost models are effective for initial training and technical refinement.
E5	Correspondence between the surgical rehearsal on the customized 3D model and the actual procedure, with similar operating times, number and arrangement of sutures, and adequate closure of the defect.	Customized 3D-printed fetal models are effective tools for preoperative planning and optimization of fetoscopic correction of MMC (multiple mucous membrane disease).
E6	The model enabled the safe practice of fetoscopic procedures, with positive evaluations regarding its realism and educational applicability.	Artificial simulators are effective tools for progressive training in fetoscopic correction of MMC.
E7	Repeated execution of technical steps, good perception of realism, and educational viability of the model.	The simulator is a useful tool for surgical training, contributing to a shorter learning curve and offering an ethical alternative to animal models.
E8	The simulator allowed for the complete execution of the fetoscopic technique, with good reproducibility and a positive perception of realism by the surgeons.	Artificial models are useful for initial training and standardization of the fetoscopic MMC technique.
E9	The synthetic model allowed for faithful reproduction of the anatomical layers and execution of the microsurgical technique under microscopy.	Synthetic simulators are viable alternatives for neurosurgical training in MMC.
E10	Improved technical performance, reduced operating time, and positive objective evaluation after repeated use of the simulator.	High-fidelity synthetic models contribute to objective evaluation and a shorter learning curve in MMC fetoscopy.

Source: research data.

Cochrane Library database (889; 55.0%), followed by the *Web of Science* (509; 31.5%) of the publications found and published between 2009 and 2024, with the majority in mid-2020.

The level of evidence for the studies was distributed for research evaluation based on the American categorization of the *Agency for Healthcare Research. and Quality* (AHRQ): level 1, meta-analysis of multiple controlled studies; level 2, individual study with experimental design; level 3, study with quasi-experimental design such as non-randomized single-group pre- and post-test studies , time series or case-control studies; level 4, study with non-experimental design such as descriptive correlational and qualitative research or case studies; level 5, case reports or systematically obtained data of verifiable quality or program evaluation data; level 6, opinion of reputable authorities based on clinical competence or opinion of expert committees, including interpretations of information not based on research (Galvão, 2006).

Each article was classified according to the *Agency for Healthcare Research 's level of evidence. and Quality* (AHRQ), where the classic hierarchy of levels 1 to 4 (Galvão, 2006) was rigorously applied. The implicit methodological design of each description was considered. Studies 3 and 10 were classified within level 3, studies with a quasi-experimental design. Level 4 included studies 1, 2, 4, 5, 7, and 9, which includes descriptive experimental studies using animals or simulators, with case reports obtained systematically. Level 6 included studies 6 and 8, where the evidence comes from expert opinion, based on clinical competence.

The studies predominantly used experimental and descriptive methods, based on animal models and surgical simulators, applied to the training and evaluation of fetoscopic techniques. In vivo experiments involved the intrauterine creation and correction of spinal defects in sheep fetuses, with postnatal macroscopic, histological, and functional evaluation. Other studies highlighted the development and validation of anatomical simulators using synthetic, biological, or multimaterials, including low-fidelity models, multilayer models, and prototypes derived from 3D ultrasound with anatomical segmentation and 3D printing. These simulators were employed in technical trials and training sessions, with performance evaluation using objective metrics, comparative analysis between physical and virtual platforms, or questionnaires administered to surgeons and trainees, focused on analyzing realism, applicability, and educational validity.

The studies used biological, artificial, and hybrid anatomical models to simulate myelomeningocele (MMC) and the fetal surgical environment. Biological models were based on sheep fetuses (ovine model), widely used to simulate human MMC. Artificial models included physical laparoscopic training simulators, virtual reality platforms, synthetic MMC models, and 3D-printed prototypes, some derived from fetal ultrasound and structured in multiple tissue layers. Hybrid models combined synthetic components and animal tissues, often associated with an artificial uterus, to reproduce the fetoscopic surgery environment.

The main results of the studies identified a high success rate in correcting MMC, with better skin closure, spinal cord protection, and preservation of neural architecture when simplified techniques were employed, compared to classical approaches. In the training studies, a significant improvement in technical performance was observed, with Greater skill transfer, improved suture quality, and reduced operating time, especially after repeated use of simulators. The artificial, synthetic, and customized 3D models allowed for the complete and reproducible execution of the fetoscopic technique, showed good correspondence with the real procedure, and were positively evaluated for realism, applicability, and educational viability.

Studies have concluded, based on in vivo experiments and surgical simulation methods, that simplified techniques for fetal correction of MMC are effective, reproducible, and potentially safer. Conclusions regarding artificial and synthetic simulators, including low- and high-fidelity models and 3D-printed prototypes, highlighted that they are effective tools for training, preoperative planning, and reducing the learning curve, offering cost-effective and ethically sound alternatives to animal models.

4. Discussion

The findings of the ten studies analyzed consistently converge with recent literature in demonstrating that both simplifying the technique and progressively using simulation models are effective strategies for improving prenatal repair of myelomeningocele (MMC).

Experimental studies in sheep models Abou-Jamra et al. (2009) and Herrera et al. (2012) showed a high success rate of correction (91%), better skin closure and spinal cord protection, reinforcing the notion that more standardized and less aggressive techniques can improve structural outcomes.

In line with the concept of reproducibility advocated by Miller et al. (2023), which reinforces that preoperative training and preparation in simulation helps teams perform complex surgeries with greater predictability. Technical simplification plays a similar role to that of a trainable protocol, making the procedure more reproducible.

In parallel, studies based on simulation, from low-fidelity and low-cost models evidenced in the studies by Tan et al. (2012) and Belfort et al. (2018).

High-fidelity, personalized artificial models described in the studies by Miller et al. (2018), Joyeux, van der Merwe, et al. (2021), Patel et al. (2021), Bevilacqua & Pedreira (2015), Ferreira et al. (2023), and Ahmad et al. (2024) corroborate evidence that simulation allows for repetitive training, preoperative rehearsal, team organization, and shortening of the learning curve. These observations were also described by da Costa et al. (2023), Spoor et al. (2023), and Kunpalin et al. (2024). Taken together, the data support that different levels of fidelity serve distinct, yet complementary, educational objectives throughout the training and consolidation of fetoscopic technique.

Despite conceptual convergence, relevant divergences emerge regarding the degree of fidelity required and the transfer of results to clinical practice. While studies with sheep (Abou-Jamra et al., 2009; Herrera et al., 2012) provide direct biological evidence on spinal cord integrity and tissue response, studies based on artificial and synthetic models focus predominantly on educational outcomes, such as perception of realism, technical performance, and operating time, without long-term physiological or functional evaluation.

In contrast to artificial and hybrid models, studies such as those by Joyeux, Javaux et al. (2021) and Ahmad et al. (2023) argue that high-fidelity live animal models offer additional advantages, especially for the retention of complex skills and three-dimensional perception, although they acknowledge ethical, logistical, and financial limitations that hinder their widespread replication. For both, high-fidelity live models and/or features such as 3D vision can strongly impact realism, skill retention, and surgical time. Thus, the divergence is not between being a simulator or not, but how faithful it is and with what features.

Spoor et al. (2023) even proposes a combination of low cost and high fidelity, suggesting that "simple" needs to be "low fidelity". Furthermore, while some studies indicate the superiority of simple simulators in transferring basic skills (Tan et al., 2012), other authors suggest that more advanced and contextual tasks may require greater anatomical and technological fidelity, demonstrating that the effectiveness of the model depends directly on the proposed educational objective.

In light of the findings, it is understood that the main advance of this series of studies does not consist in defending a single model or an isolated approach, but in the implicit proposal of a progressive, ethical, and scalable training environment for fetal MMC surgery.

The combination of simplified surgical techniques, validated experimental models, and artificial simulators of varying fidelity allows for the alignment of safety, reproducibility, and educational feasibility.

From a critical standpoint, it is essential that future studies advance the standardization of objective performance metrics, as suggested by some authors (Ahmad et al., 2024), integrating educational and technical outcomes, and exploring more systematically the transposition between simulation, experimental practice, and clinical results.

Thus, simulation ceases to be merely an auxiliary tool and begins to occupy a fundamental role in the development of fetal surgery programs, contributing to the safe training of teams and to the technical consolidation of fetoscopic repair of MMC.

5 Final Considerations

Fetoscopic repair allows for less invasive MMC closure, optimizing intraoperative efficiency and potentially reducing maternal morbidity. The possibility of creating training models may have slight variations depending on individual limitations, objectives in fetal surgery, the skills of each professional, and the technique that will most benefit the mother-fetus dyad.

Simulating surgery to develop skills in correcting intrauterine myelomeningocele using fetoscopic techniques is a very valuable training method. Although some studies use animal models, there are also studies that address artificial and high-fidelity models.

Students should be exposed to simulations of this procedure outside of the operating room to improve surgical skills and increase confidence in performing the procedures. Significant challenges remain, and future developments will involve continuous improvements in the realism, safety, and reusability of these models, along with evidence of their effectiveness in surgical training.

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