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SPECIAL ARTICLE

Evolution and Prospects of Educational Pathways in Invasive Prenatal Procedures

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ABSTRACT

Invasive prenatal procedures (IPPs) are integral to the practice of perinatology. The most commonly performed diagnostic procedures include chorionic villus sampling, amniocentesis, and percutaneous umbilical blood sampling. These techniques require precise hand–eye coordination under real-time ultrasonographic guidance. Fetal therapeutic procedures demand even more advanced skills, combining real-time ultrasound guidance with endoscopic surgical techniques. Structured training is essential to minimize procedure-related complications, particularly among less experienced operators. Teaching methods generally include simulation, animal models, mentorship–apprenticeship, and curriculum-based workshops. Simulation-based training employs both low-fidelity box trainers and high-fidelity virtual reality systems. Animal model training offers several advantages over ex-vivo synthetic simulators. Pregnant sheep provide the most realistic model for training and for developing novel in-utero surgical techniques because of their suitable uterine volume and fetal size. However, the cost and ethical concerns remain major limitations. Mentorship–apprenticeship typically begins with observation, followed by hands-on training and progressive responsibility until independent performance. Hands-on workshops offer opportunities to refresh skills in infrequently performed procedures. The advent of non-invasive prenatal testing using cell-free fetal DNA analysis has significantly reduced the number of invasive diagnostic procedures. Consequently, training programs must adapt to these changing circumstances. This article aims to assess current training paradigms, identify existing gaps, and propose future directions for skill acquisition in IPPs.

Keywords: Invasive prenatal procedures, fetal therapy, surgical simulation, medical education, ultrasound guidance, skill acquisition

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Introduction

Modern fetal medicine practice encompasses a substantial component of invasive prenatal procedures (IPPs). Over the past decades, numerous invasive techniques have been introduced for fetal diagnosis and therapy. Diagnostic procedures such as chorionic villus sampling (CVS), amniocentesis, and percutaneous umbilical blood sampling (PUBS) are performed under real-time ultrasound guidance. Inexperienced operators often require time to develop proficient hand–eye coordination. Most diagnostic procedures are performed by a single operator with minimal assistance. The acquisition of new minimally invasive techniques commonly follows the traditional surgical mentorship–apprenticeship model, wherein trainees observe expert operators performing live procedures and eventually perform the techniques under supervision(1). This time-honored model, however, limits knowledge transfer to one-on-one interactions and depends heavily on available resources, including training funds and patient caseloads.

Initial training for diagnostic procedures can be achieved using ex-vivo models. Therapeutic procedures pose greater challenges and require more advanced ultrasound-guided intervention skills. Moreover, teamwork becomes increasingly important in such settings. For instance, in fetal shunt placement, the operator must use both hands to deploy the shunt system while coordinating with the sonographer.

Fetoscopy was originally developed to guide fetal blood sampling from chorionic vessels but was soon replaced by ultrasound-guided PUBS. The treatment of twin-to-twin transfusion syndrome (TTTS) has renewed interest in fetoscopic interventions in recent years(2). Fetoscopy is now most commonly used for selective laser ablation of chorionic anastomoses, the most effective treatment for severe mid-trimester TTTS, and has opened new avenues for research and development in minimally invasive fetal surgery.

Like all new invasive techniques, these procedures are associated with a learning curve, where success rates and complication rates improve with experience. The demand for surgeons capable of safely performing these procedures is increasing. This article comprises three main sections: (1) assessment of current training paradigms, (2) identification of existing gaps and needs, and (3) recommendations for future directions in skill acquisition for IPPs. The target audience includes maternal-fetal medicine fellows, obstetric and gynecology residents, fetal medicine teams, and educators in perinatal training.

Section 1: Current Landscape of Training

The current landscape of training in IPPs is evolving under dual pressures: declining procedural volumes and rising expectations for competence prior to independent practice. On one hand, advances in non-invasive prenatal testing (NIPT) and other minimally invasive diagnostics have reduced opportunities for hands-on training. Presently, training modalities include simulation, animal models, mentorship–apprenticeship, and curriculum-based workshops.

Simulation-based training

IPPs require precise hand-eye coordination under real-time ultrasound guidance. Fetoscopic procedures combine ultrasonographic and endoscopic skills, demanding simultaneous use of both modalities. Practice using appropriate instruments is vital to reducing unnecessary maternal and fetal morbidity, as complications tend to occur more frequently during the early phase of the learning curve. Therefore, trainees must gain hands-on experience before performing these procedures under supervision.

Training should begin on models or simulators, enabling learners to practice maintaining the needle within the ultrasonic plane so that it remains visible throughout the procedure, ensuring safety[3]. Skill development can be facilitated using low-fidelity box trainers and high-fidelity virtual reality simulators. The term "fidelity" refers to how closely a simulation mimics real conditions, though its definition is not standardized in medical literature. Typically, "low fidelity" denotes simple, artificial setups, while "high fidelity" represents realistic, complex simulations[4].

Low-fidelity box trainer

Simplified models for training in invasive fetal diagnostic and therapeutic procedures can be constructed in-house. These models simulate the intrauterine environment, enabling trainees to develop proficiency conveniently. For centers where such procedures are infrequently performed, simulators help maintain technical skills[5].

A typical model consists of a plastic container with a rubber latex sheet at the base to prevent sonographic reverberation. A fresh placenta from seronegative donors is used, with the umbilical cord tied and chorionic vessels sutured at their distal ends to preserve vascular architecture. The placenta is rinsed and fixed to simulate either anterior or posterior placentation.

This model is simple, inexpensive, and effective for training in fetoscopic interventions such as selective photocoagulation of placental vessels. However, it has limitations, including biohazard risks, contamination of the endoscopic view by blood, and anatomical differences from monochorionic placentas.

High-fidelity virtual reality trainer

To address these limitations, an intrauterine endoscopic training model (Siriraj Fetoscopic Surgical Simulator™) was developed[6]. It consists of a soft rubber spherical structure representing a mid-trimester uterus with a monochorionic twin placenta mounted inside. The model allows infusion and drainage of water to simulate polyhydramnios associated with severe TTTS. It enables simultaneous sonographic and fetoscopic visualization, allowing trainees to practice mapping chorionic vasculature and handling fiber-optic scopes.

Three-dimensional printed models have recently been introduced to further enhance fidelity[7]. While these simulators allow realistic fluid manipulation and ultrasound imaging, they cannot replicate dynamic features such as fetal movement or actual laser coagulation.

Animal Model

Although simulator technologies are advancing, animal models remain valuable for training procedures that involve dynamic physiology, such as bleeding or uterine contractions. Pregnant sheep are the most commonly used species due to their uterine size and fetal dimensions, which approximate human conditions. Animal models enable trainees to manage intraoperative challenges, including amniotic bleeding, collapsed sacs, or fetal positioning, and to recognize complications such as amniotic leakage, bleeding, miscarriage, or fetal demise.

Animal models also allow testing of new interventions, such as intrauterine CO_2 insufflation or amniopatch application, and the creation of malformations like gastroschisis or meningomyelocele for corrective experiments[8-12].

Nevertheless, limitations include cost, anesthesia requirements, and ethical concerns. Sheep have a bicornuate uterus and a 145-day gestation[13]. Smaller models, such as pregnant rabbits, offer lower costs and fewer facility requirements[14]. Baboons have also been used to simulate complex fetal surgeries, such as intrauterine cleft lip repair[15].

The ethical considerations surrounding animal use necessitate strategies to minimize animal numbers, reduce costs, and prioritize the use of tissues from euthanized research animals[16].

Mentorship–apprenticeship

While simulation and animal models facilitate repetitive practice, they do not fully replicate teamwork dynamics or real-time decision-making. Direct procedural experience under supervision remains the most effective training modality[17]. Training begins with observation, progresses to assistance, and culminates in independent performance under guidance. Early procedures typically include "simple" amniocenteses or CVS cases. The number of procedures required to achieve proficiency varies, but most studies suggest diminishing returns after approximately 100 independent cases[3].

This model, however, faces limitations, including variability in trainee proficiency and ethical constraints on using certain cases for training. Although structured assessment systems exist, only a few centers have formal programs[18].

Curriculum-based workshops

Professional organizations have initiated curriculum-based workshops to address reduced procedural exposure due to NIPT and declining fertility rates[19]. Studies demonstrate that operator experience correlates with lower pregnancy loss rates[20, 21]. Simulation workshops remain valuable even for experienced providers by enabling skill maintenance in rarely performed procedures. This is one of the most important priorities for Disease-Specific Certification programs that ensure standardized care by verifying adherence to performance benchmarks and promoting interdisciplinary collaboration. These workshops facilitate sustained skill development through repeated, progressively challenging simulations with standardized performance metrics.

Section 2: Gaps and Needs

Efforts to accelerate the learning curve of IPPs persist, yet significant gaps remain in (1) competency benchmarks, (2) access inequality, (3) data-driven feedback, and (4) interdisciplinary integration.

Competency benchmarks

Despite IPPs being core components of fetal medicine training, standardized competency-based curriculum is lacking. Competence must be demonstrated through objective assessment rather than presumed based on years of experience[22]. The field is shifting toward competency-based, simulation-enhanced education, but evidence-based training standards are still needed.

Access inequality

Global disparities exist in surgical training quality and infrastructure, particularly between urban and rural areas. Key challenges include limited procedural exposure, uneven simulation access, and inadequate mentorship. International collaboration may help align best practices with local contexts[23].

Data-driven feedback

Traditional validation methods, such as logbooks and theoretical testing, inadequately measure procedural competency. Training programs are increasingly adopting structured curricula and objective assessment tools that provide real-time, data-driven feedback[24].

Interdisciplinary integration

Complex fetal therapeutic procedures require seamless collaboration among multidisciplinary teams, including anesthesiologists, neonatologists, and surgeons. Deficiencies in non-technical skills such as teamwork and communication contribute to adverse events. Multidisciplinary simulation training can mitigate these risks, though program implementation barriers persist[25].

Section 3: Future Trajectory

First-trimester NIPT has markedly decreased the demand for diagnostic IPPs despite rising maternal age at first pregnancy[26]. As with PUBS, procedures such as CVS and amniocentesis may become centralized to a few specialized centers, limiting training opportunities. However, diagnostic IPPs remain necessary for specific cases, such as Mendelian disorders and high-risk screening results. Training must therefore remain adaptable, incorporating innovations, digital credentialing, tele-mentoring, and global registries.

Innovations

Advances in ultrasound, three-/four-dimensional imaging, and endoscopic simulation increasingly allow realistic training environments with minimal patient risk. The development of digital pregnancy models, supported by recent regulatory shifts, offers potential for sophisticated in-silico fetal research[27].

Digital credentialing

Blockchain-based systems can securely and transparently record skill verification, providing globally portable credentials for procedural competence[28].

Tele-mentoring

Augmented and virtual reality (AR/VR)-assisted tele-mentoring allows real-time remote supervision of procedures, improving access to expertise. The concept, first demonstrated in the 1960s via satellite-assisted surgery, continues to evolve with modern technology[29].

Global registries

Global registries can track procedural outcomes and training efficacy through digital dashboards, identifying disparities and guiding improvement[30]. These databases are especially valuable in therapeutic IPPs, where procedural volume remains low across most centers.

Conclusion

Training in IPPs is a critical and timely issue given the evolution of fetal therapy and increasing expectations for procedural competence. Current challenges include limited procedural opportunities, curricular variability, ethical concerns, and the absence of standardized assessment tools. Future directions should emphasize the development of an internationally endorsed core curriculum, cross-institutional fellowships, scalable simulation access, and research in procedural outcomes[31]. Ultimately, fostering adaptive expertise through competence-based education will enable future fetal medicine specialists to respond effectively to evolving clinical and ethical challenges[32].

Potential conflicts of interest

The authors declare no competing interests.

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