Development and Educational Impact of a Low-Cost 3D-Printed Amniocentesis Simulator for Obstetrics and Gynaecology Resident Training: A Prospective Interventional Study

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Abstract

Background: Amniocentesis is a technically demanding ultrasound-guided invasive procedure that requires precision and experience to minimize complications. Opportunities for hands-on training are limited because of ethical concerns and patient safety. Simulation-based education offers a safe alternative for skill acquisition. We developed a low-cost, reusable 3D-printed amniocentesis simulator and evaluated its impact on procedural performance among postgraduate trainees.

Methods: A prospective pre–post interventional study was conducted among ten obstetrics and gynecology postgraduate residents. Participants were assessed using a structured seven-step performance checklist before simulator training and again after structured practice on the 3D-printed model. Total performance scores were compared using paired t-test. Effect size and 95% confidence intervals were calculated.

Results: Mean performance score increased from 26.6 ± 2.32 before training to 56.1 ± 2.02 after training. The mean improvement was 29.5 ± 2.76 points. Paired t-test showed a highly significant difference ($t(9)=33.8$, $p<0.0001$). The 95% CI for improvement was 27.5–31.5. Effect size was extremely large (Cohen's $d=10.7$).

Conclusion:

The 3D-printed simulator produced substantial improvement in technical competence and represents an affordable, scalable solution for procedural training in fetal medicine programs.

Keywords: Simulation training, amniocentesis, 3D printing, medical education, procedural skills, obstetrics training

Introduction

Amniocentesis continues to serve as the definitive invasive diagnostic procedure for prenatal genetic evaluation despite advances in non-invasive screening techniques.[1–3] Although considered relatively safe when performed by experienced operators, the procedure carries recognized risks including membrane rupture, infection, fetomaternal hemorrhage, and procedure-related pregnancy loss.[4–6] Evidence indicates that complication rates are closely associated with operator skill, number of needle passes, and procedural accuracy.[7]

Traditionally, procedural competence has been acquired through supervised practice on patients. However, this apprenticeship-based model poses ethical and safety concerns, particularly during early learning phases. Invasive procedures performed by inexperienced trainees may increase patient anxiety and procedural risk. Consequently, simulation-based medical education has gained prominence as a strategy to facilitate deliberate practice without compromising patient safety.[8–10]

Multiple systematic reviews have demonstrated that simulation improves technical performance, procedural confidence, and skill retention across medical and surgical specialties.[9–11] Within obstetrics, ultrasound-guided procedures demand precise spatial orientation and fine motor coordination, skills that benefit from repetitive, structured training. Despite this, commercially available obstetric simulators are often expensive and not readily accessible to many teaching institutions, especially in developing countries.

Advances in 3D-printing technology provide opportunities to develop anatomically realistic, low-cost, and reproducible training models. Such locally fabricated simulators may enable wider adoption of structured procedural training while maintaining affordability. Indian training centers have increasingly reported the usefulness of simulation-based approaches for ultrasound education and procedural skill development.[12,13]

The present study describes the development of a novel low-cost 3D-printed amniocentesis simulator and evaluates its effectiveness in improving procedural performance among postgraduate residents.

Materials and Methods

Study design and setting

This prospective paired interventional study was conducted in the Department of Obstetrics and Gynaecology at Saveetha Medical College and Hospital, Chennai, India. The design involved within-participant comparison of performance before and after simulator-based training.

Participants

Ten postgraduate residents undergoing fetal medicine training were included. All participants had prior theoretical knowledge of amniocentesis but limited independent hands-on experience. Written informed consent was obtained.

Development of the simulator

A reusable amniocentesis training model was fabricated using 3D-printing technology. The simulator was designed to replicate the abdominal wall layers, uterine cavity, amniotic sac, and fetal position. Materials were selected to ensure ultrasound compatibility and realistic tactile resistance to needle insertion. The model permitted repeated punctures and allowed real-time ultrasound visualization during practice. The overall objective was to create a durable, cost-effective, and easily reproducible training tool suitable for routine institutional use.

Training protocol

The study was conducted in two phases:

Baseline assessment (without simulator):

Residents performed the procedural steps following conventional instruction.
Performance was objectively scored using a standardized checklist.

Simulator training phase:

Participants then underwent structured practice sessions using the 3D-printed model. Faculty provided demonstration, supervision, and immediate feedback. Multiple attempts were permitted to facilitate deliberate practice.

Outcome assessment

Performance was evaluated using a seven-step procedural checklist encompassing probe positioning, identification of amniotic pocket, needle alignment, insertion technique, safe advancement, fluid aspiration, and overall handling. Each step was scored numerically and summed to obtain a total performance score.

Statistical analysis

Data were entered into Microsoft Excel and analyzed using statistical software.
Continuous variables were expressed as mean ± standard deviation. Paired t-test was used to compare pre- and post-training scores. Effect size was calculated using Cohen's d. A p-value <0.05 was considered statistically significant.

Results

All ten residents completed both assessments.
Individual pre- and post-training scores are presented in **Table 1**.

Table 1. Pre- and post-training total performance scores of postgraduate residents

Participant	Before training	After training	Difference
PG1	28	57	29
PG2	30	57	27
PG3	29	57	28
PG4	27	54	27
PG5	28	57	29
PG6	27	55	28
PG7	23	56	33

PG8	**25**	**52**	**27**
PG9	**25**	**58**	**33**
PG10	**24**	**58**	**34**

Descriptive statistics demonstrated a substantial increase in overall performance following simulator training, as shown in **Table 2**.

Table 2. Descriptive statistics of performance scores

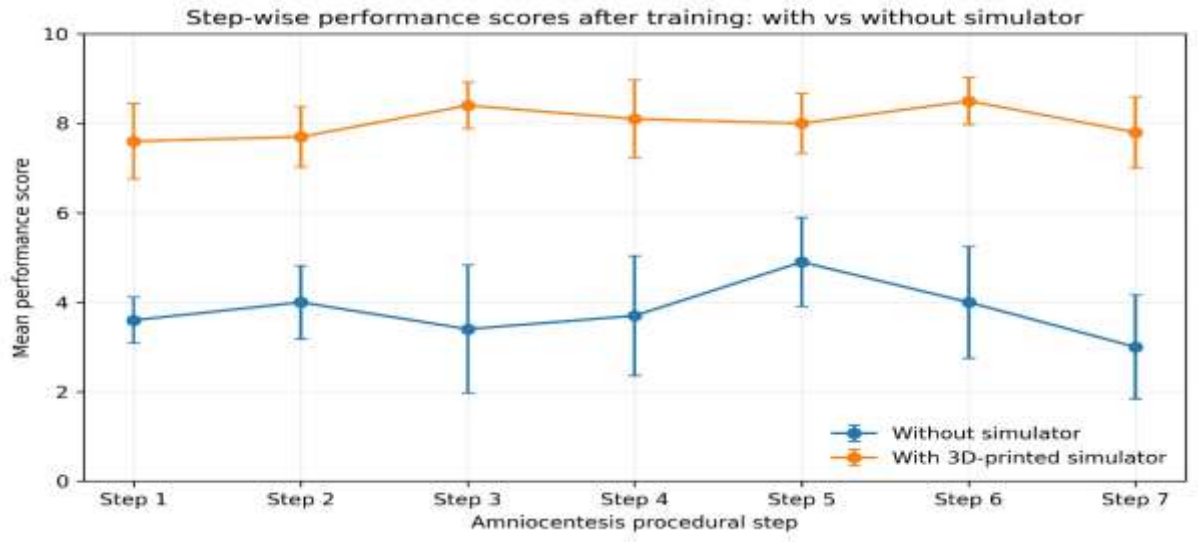
Parameter	Before training	After training	Mean improvement
Mean score	**26.6**	**56.1**	**29.5**
SD	**2.32**	**2.02**	**2.76**
Minimum	**23**	**52**	**27**
Maximum	**30**	**58**	**34**

Inferential analysis confirmed that the improvement was statistically significant. Paired comparison revealed a highly significant difference between pre- and post-training total scores with a very large effect size, indicating a strong educational impact of the simulator intervention (**Table 3**).

Table 3. Comparison of pre- and post-training performance scores

Variable	Mean ± SD	t value	df	95% CI	p value	Effect size (Cohen's d)
Before training	**26.6 ± 2.32**	**33.8**	**9**	**27.5– 31.5**	**<0.0001**	**10.7**
After training	**56.1 ± 2.02**					

Step-wise performance trends demonstrated consistent improvement across all seven procedural components, with post-training scores markedly higher for each step (**Figure 1**).



Discussion

The present study demonstrates that structured practice using a low-cost 3D-printed amniocentesis simulator significantly improved procedural performance among postgraduate trainees. Improvement was observed uniformly across all participants and across every procedural step, suggesting a generalized enhancement of technical competence rather than isolated gains.

Simulation provides an environment where trainees can repeat complex tasks, receive immediate feedback, and refine technique without patient risk. Previous literature consistently supports the role of simulation in improving procedural skills and clinical outcomes.[9–11] Our findings align with these observations and extend the evidence to amniocentesis training.

Importantly, the affordability of the model represents a practical advantage. Commercial simulators may be prohibitively expensive for many institutions, limiting their integration into routine curricula. In contrast, 3D-printed models can be fabricated locally at low cost, replaced easily, and customized according to training needs. Such scalability is particularly relevant for teaching hospitals in low- and middle-income countries.[12–14]

The very large effect size observed indicates not only statistical significance but also meaningful educational benefit. From a patient safety perspective, improved procedural competence may reduce multiple needle attempts and potentially lower complication rates during clinical procedures.

Strengths

The paired study design minimized inter-individual variability, objective scoring enhanced reliability, and the low-cost nature of the simulator supports real-world
applicability.

Limitations

The small sample size and single-center design may limit generalizability. Long-term skill retention and clinical outcome measures were not evaluated.

Future directions

Multicenter studies assessing clinical translation of simulator-acquired skills and longterm competency retention are warranted.

Conclusion

The low-cost 3D-printed amniocentesis simulator produced significant and consistent improvements in procedural performance among postgraduate residents.

Incorporation of such simulation tools into routine training curricula may enhance competency while ensuring patient safety.

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