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Review

Simulation-based surgical training: methods, technologies, and perspectives

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Abstract
Simulation-based training has emerged as a cornerstone of modern surgical education, addressing critical challenges such as patient safety, ethical considerations, and limited training hours. This study explores the scope, technological advancements, and future perspectives of surgical simulation training. High-fidelity simulations, including VR and robotic systems, offer immersive and realistic training experiences. Innovations like augmented reality, 3D printing, and integrated simulation laboratories have enhanced skill development, decision-making, and teamwork in complex surgical scenarios. Meta-analyses confirm that simulation training reduces operative times, decreases errors, and improves patient outcomes. While cadaver and animal models remain integral, their limitations have driven the adoption of cost-effective alternatives. Future trends include metaverse-based platforms and patient-specific simulations, promising more accessible and individualized training solutions. As surgical simulation technologies evolve, their role in fostering proficient surgeons and enhancing patient care outcomes will continue to expand.

Keywords
surgical training, simulation, patient safety, educational technology

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Introduction

Simulation in surgical education has become a vital tool to address issues such as patient safety, ethical concerns, and limited working hours [1-3].

New generations, having grown up in an era of rapid change and instant access to information through the internet, often seek more efficient ways to acquire complex skills, such as surgical techniques. Studies suggest that simulation-based training provides an effective approach to address this need, significantly shortening the learning curve for the majority of surgical procedures [4].

When patient safety was assessed in training cases under the training program used simulators, postoperative morbidity and mortality rates were not higher than those observed in procedures conducted by experienced surgeons. Furthermore, trainees who achieved the proficiency benchmark during the training program were able to perform complete surgeries under supervision without causing additional adverse effects to patients [5].

Simulation technologies provide surgical trainees with opportunities to enhance technical skills, manage complex scenarios, and develop teamwork abilities [6]. This study focuses on the scope, importance, technological advancements, and future perspectives of surgical simulation training.

Scope of Surgical Simulation Training

Simulations offer a secure environment for surgical trainees to develop a variety of skills. Low-fidelity simulators facilitate the learning of basic surgical techniques, while high-fidelity models realistically simulate complex surgical procedures.

For instance, cadaver models are considered the gold standard in surgical training due to their realistic tissue properties. However, their high cost and limited availability have driven the development of alternative methods [2,7]. VR and robotic systems have emerged as transformative technologies in surgical training, effectively addressing limitations associated with traditional methods like cadavers and animal models. VR offers immersive, repeatable simulations for developing technical and decision-making skills, while robotic systems, such as the da Vinci simulator, provide hands-on training for minimally invasive surgeries. These technologies enhance precision, reduce errors, and allow for performance tracking through objective metrics, making them indispensable tools in modern surgical education [8].

Importance of Surgical Simulation Training

Surgical simulations offer benefits far beyond the development of technical skills. They play a pivotal role in enhancing patient safety, boosting surgical confidence, and improving overall operational efficiency. By providing a controlled environment for repetitive practice, simulations allow trainees to refine their techniques without risking patient harm. This is particularly crucial in high-stakes surgeries where even minor errors can have significant consequences. Meta-analyses have shown that incorporating simulation-based training into surgical curricula reduces operative times, decreases the frequency of errors, and leads to better patient outcomes [9]. These findings underscore the value of simulation as an essential component of modern surgical education.

Additionally, simulations foster critical non-technical skills such as crisis management, decision-making under pressure, and effective teamwork. These competencies are indispensable in real-world scenarios where unexpected challenges often arise. Augmented reality systems like virtual interactive presence and augmented reality (VIPAR) exemplify the potential of advanced technologies to enhance these capabilities. By enabling remote collaboration, VIPAR creates an interactive platform where experienced surgeons can guide trainees through complex procedures in real time. This approach not only improves individual performance but also cultivates cohesive team dynamics, which are vital in multidisciplinary surgical environments [7,10].

Moreover, simulations provide measurable outcomes, offering educators the ability to objectively assess and monitor progress. Trainees can identify areas for improvement through immediate feedback, while structured assessments ensure that learning objectives are consistently met. In this context, surgical simulation bridges the gap between theory and practice, making it an indispensable tool for preparing surgeons to deliver safer and more effective care.

Current Approaches in Surgical Simulation Technologies

Advancements in simulation technologies have made training processes more effective. This section explores these innovations under eight subheadings.

• Virtual Reality (VR) Simulators: VR simulators are crucial for developing hand-eye coordination, tissue sensitivity, and operational skills. Tools like LapSim and da Vinci Skills Simulator are widely used in laparoscopic and robotic surgical training [8]. The advantages of VR systems include repeatability and objective performance measurement.

• Augmented Reality (AR) and Telesurgery: AR provides real-time guidance, while telesurgery technology enables experienced surgeons to offer remote training. The VIPAR system is a groundbreaking example, facilitating coordination in complex procedures [11].

• 3D Printing and Patient-Specific Models: 3D printing technology allows the creation of patient-specific anatomical models, enabling surgeons to plan complex procedures. These models optimize surgical workflows, particularly in neurosurgery and cardiac surgery [2,7].

• Robot-Assisted Simulators: Robotic surgery has taken simulation training to the next level. The da Vinci system enables training for minimally invasive surgeries. However, the high cost of these systems underscores the need for more affordable solutions [12]. (Proietti et al., 2024). It highlights the importance of implementing comprehensive laparoscopic training programs. Early, frequent, and well-structured training initiatives are crucial for fostering the development of proficient laparoscopic surgeons [13,14].

• Cadaver Models: Cadavers remain widely used in surgical training due to their close representation of human anatomy. Pressurized cadaver tissues are particularly valuable for vascular surgeries and trauma training. Nonetheless, high costs and limited availability pose challenges to their widespread use [2].

• Animal Models: Animal models play a significant role in the development of surgical skills. However, ethical concerns and anatomical differences from humans limit their application [7].

• Simulation Applications and Mobile Training: Mobile applications provide surgeons with tools to simulate various procedures. For instance, Touch Surgery offers a user-friendly interface to help surgeons learn procedural steps [15]. This study shows that students can achieve comparable cognitive and technical learning outcomes.

• Integrated Simulation Laboratories: Modern simulation laboratories combine cadaver models, VR systems, and 3D printers to create multidisciplinary training environments. These labs integrate diverse technologies to standardize training processes [10].

Future Perspectives in Surgical Simulation Training

The future of surgical simulations involves the integration of metaverse-based educational platforms, patient-specific models, and robotic systems. Metaverse technology can strengthen individual learning processes by providing interactive training experiences with virtual patients [11].

Additionally, the development of cost-effective and accessible solutions will expand the applicability of simulation training. Advanced simulation laboratories are expected to play a central role in surgical education [10].

Conclusion

Surgical simulation technologies have become a cornerstone of modern surgical training. These training methods enhance technical skills, ensure patient safety, and improve operational efficiency. With the integration of innovative technologies and cost-effective solutions, the impact of surgical simulations is expected to grow in the future. This evolution in surgical education will lead to improved individual learning processes and better patient outcomes.

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Scientific Responsibility Statement

The authors declare that they are responsible for the article's scientific content, including study design, data collection, analysis and interpretation, writing, and some of the main line, or all of the preparation and scientific review of the contents, and approval of the final version of the article.

Animal and Human Rights Statement

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data Availability Statement

The datasets used and/or analyzed during the current study are not publicly available due to patient privacy reasons but are available from the corresponding author on reasonable request.

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Conflict of Interest

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