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Mini Review

Artificial Intelligence–Assisted Three-Dimensional Modeling as a Dynamic Decision-Support Framework for Surgical Planning

Luís Fernando Rosati Rocha [1,*], Ana Paula de Carvalho Miranda Rosati Rocha [2], Ana Luiza de Carvalho Miranda Rosati Rocha [3], Luís Eduardo Miranda Rosati Rocha [4], Filipe Moll de Souza Rocha [4]

[1] Department of General Surgery, Fluminense Federal University (UFF), Rio de Janeiro, Brazil.
[2] Department of Radiology, Fluminense Federal University (UFF), Rio de Janeiro, Brazil.
[3] Pardini Institute, Rio de Janeiro, Brazil.
[4] Faculty of Medicine IDOMED, Rio de Janeiro, Brazil.

* Correspondence: lfrosati@yahoo.com.br.

Abstract: Artificial intelligence (AI)–assisted three-dimensional (3D) modeling has expanded the role of medical imaging in surgical planning; however, its clinical value is often conflated with advanced visualization rather than true decision support. This Mini Review critically examines AI-driven 3D modeling as a precision tool for surgical planning, emphasizing the distinction between static anatomical reconstructions and dynamic, intelligence-driven systems capable of adapting to intraoperative conditions. Beyond classical convolutional neural networks, contemporary architectures such as Vision Transformers and diffusion-based models are discussed, highlighting their implications for generalizability, uncertainty estimation, and robustness. Attention is given to imaging standardization, algorithmic responsibility, economic thresholds for adoption, and the persistent gap between visualization and quantifiable surgical benefit.

Keywords: Artificial Intelligence; Three-Dimensional Modeling; Surgical Planning.

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1. Introduction

The transformation of volumetric imaging into actionable surgical information represents one of the most consequential developments in modern high-complexity surgery [1]. Patient-specific three-dimensional reconstructions derived from computed tomography and magnetic resonance imaging have been increasingly incorporated into preoperative planning across multiple specialties. Nevertheless, enthusiasm for AI-assisted 3D modeling has often preceded critical appraisal. Reported benefits such as improved spatial understanding or reduced warm ischemia time are frequently attributed to artificial intelligence without clear distinction between algorithmic inference and enhanced graphical representation. This distinction is fundamental, as most clinically deployed systems remain static and preoperative in nature, offering limited resilience to intraoperative tissue deformation and organ displacement [2].

Accordingly, this Mini Review adopts a critical perspective, examining not only technological advances in AI-assisted segmentation and reconstruction, but also unresolved challenges related to dynamic modeling, imaging standardization, liability, and cost-effectiveness.

2. Materials and methods

This Mini Review was conducted as a critical narrative synthesis of literature, an approach suited to emerging technologies whose clinical implications extend beyond

quantitative performance metrics [3]. The objective was to integrate technical, clinical, ethical, and organizational dimensions of AI-assisted 3D modeling in surgical planning. A structured search was performed in PubMed/MEDLINE, Scopus, and Web of Science, covering publications from January 2014 through March 2026. Search terms included 'artificial intelligence', 'three-dimensional modeling', 'segmentation', 'surgical planning', 'Vision Transformer', 'diffusion model', and 'augmented reality'. Eligible studies comprised narrative and systematic reviews, clinical observational studies, prospective trials, and translational reports explicitly addressing surgical application.

3. Evolution of AI Architectures in Surgical 3D Modeling

Convolutional neural networks, particularly U-Net–based architectures, constituted the first generation of AI-assisted segmentation in surgery and remain widely used due to their stability and reproducibility [4]. However, their reliance on localized receptive fields limits generalizability across heterogeneous imaging protocols. More recent architectures incorporate Vision Transformers and hybrid CNN–Transformer models, enabling improved capture of long-range spatial dependencies and contextual relationships within volumetric data [5]. Diffusion-based models further extend this paradigm by introducing probabilistic segmentation and uncertainty-aware reconstructions, a critical feature when small anatomical structures carry disproportionate surgical risk [6].

4. Static Visualization Versus Dynamic Surgical Modeling

Despite algorithmic advances, most AI-assisted 3D models currently used in clinical practice remain static anatomical maps generated from preoperative imaging. Once surgical exposure begins, organ shift, deformation, and loss of physiological constraints progressively erode the spatial validity of these reconstructions [2]. Emerging efforts integrating biomechanical simulation, physics-informed neural networks, and real-time intraoperative imaging represent a conceptual shift toward dynamic modeling. Although largely investigational, such approaches delineate the boundary between illustrative visualization and true AI-driven surgical decision support.

5. The Standardization Paradox in Imaging Acquisition

Automated segmentation demonstrably reduces interobserver variability; however, it simultaneously amplifies inconsistencies inherent to imaging acquisition. Without minimum international standards for surgical-grade CT and MRI protocols, AI-driven 3D modeling risks becoming a precise reproduction of systematically biased data rather than a tool for precision surgery [7].

6. Algorithmic Responsibility and Structured Implementation Pathways

In surgical environments, algorithmic omissions may have direct clinical consequences. If an accessory vessel or critical structure is not identified during segmentation, responsibility cannot be attributed solely to the algorithm or the surgeon. Structured implementation pathways are therefore essential and should include surgeon-in-the-loop validation, explicit visualization of algorithmic uncertainty, standardized reporting of model limitations, and institutional credentialing processes. Such safeguards mitigate the risk of over-reliance while preserving the benefits of AI augmentation [1, 8].

7. Augmented Reality Integration: Technical Limits and Clinical Reality

Although augmented reality has been widely promoted as a natural extension of AI-assisted 3D modeling, its clinical adoption remains limited. Persistent challenges related to registration latency, depth perception errors, and misalignment between virtual overlays and deformable anatomy have prevented AR systems from achieving reliable intraoperative performance. These limitations help explain why, despite more than a

decade of technological development, AR-guided surgical navigation has not become standard of care in most academic centers.

8. Economic Considerations and the Clinical Tipping Point

The economic justification for AI-assisted 3D modeling is unlikely to be universal. Its value proposition is strongest in anatomically complex, high-risk procedures, where modest reductions in operative time, ischemia duration, or complication rates translate into disproportionate downstream benefit [9].

9. Discussion and Conclusion

Collectively, current evidence suggests that AI-assisted 3D modeling functions primarily as a facilitator of surgical planning rather than a deterministic driver of outcomes. The absence of dynamic adaptability, standardized imaging, and robust cost-effectiveness data explains why these technologies remain selectively adopted rather than universally integrated into surgical practice. AI-assisted three-dimensional modeling should be regarded as a transitional decision-support framework whose clinical relevance depends on the convergence of dynamic modeling, surgical-grade imaging standards, uncertainty-aware algorithms, and structured implementation pathways. Bridging the gap between enhanced visualization and quantifiable surgical benefit remains the central challenge for widespread adoption.

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