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3D Printing and Mixed Reality in Surgery: A Narrative Review

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Abstract: Three-dimensional (3D) printing and mixed reality (MR) are increasingly used in surgery, yet their complementary roles across the perioperative workflow remain insufficiently synthesized. 3D printing provides patient-specific anatomical models, surgical guides, and customized implants for physical planning and simulation, while MR can achieve interactive, spatially registered visualization and guidance in the surgical environment. A literature search was conducted in PubMed, Embase and Web of Science core collection databases from inception to September 2026, with no restrictions on the type of articles. Surgical applications of 3D printing and MR alone or in combination were considered along with related augmented and virtual reality literature. Reference lists were manually filtered for additional studies. This article reviews the applications of 3D printing and MR in preoperative planning, intraoperative guidance, surgical education and training, patient education, and postoperative evaluation. Existing evidence shows that anatomical understanding, surgical planning, visualization and guidance have potential benefits, but the results are still heterogeneous. Studies that directly evaluate combined workflows against either technology alone are still hard to find. We remain short of solid evidence regarding long-term outcomes, cost-effectiveness, and how these approaches actually perform in routine clinical practice. The main obstacles include registration accuracy, technical integration, workflow complexity, and equipment and production costs. When a surgical task requires both of these abilities, it is most reasonable to combine the two, rather than assuming that the use of dual modes has inherent advantages.

1. Introduction

Traditional surgical planning has been mostly based on two-dimensional imaging modalities and the anatomical knowledge of the surgeons [1]. But standard imaging can give limited spatial information when complex anatomical structures, pathological lesions or patient specific anatomical variations are present [2]. Three-dimensional printing allows for the fabrication of patient-specific anatomical models from medical imaging data, with benefit to anatomical visualization, preoperative planning, and surgical simulation [3-5]. Furthermore, 3D printing has found increasing application in fabricating patient-specific surgical guides, instruments and implants, broadening its utility in personalized surgical care [6,7].

Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are related but not identical technologies [8]. VR is a completely computer–generated environment that for the most part replaces the user's perception of the real world, while AR superimposes digital information onto the real environment [9]. MR also enables virtual objects to additionally reside and interact with the real environment in real time, for a more blended digital-physical visualization experience [8].

MR has been found useful for real time visualization, for navigation, for surgical education, and for intraoperative decision support [10]. Displaying patient specific virtual anatomical information overlaid on the operative environment, MR might be able to help surgeons' learning of detailed anatomical relationship and provide additional spatial guidance in some procedures [11]. Early technical validation and clinical investigation have demonstrated the potential of MR to other surgical specialties, such as neurosurgery and plastic surgery [12,13], but the clinical implementation thus far has been still limited by registration accuracy, workflow integration, equipment cost and user-related issues [14,15].

3D printing provides tangible anatomical references in planning and simulation while MR offers interactive visualization and spatial guidance, which can be potentially complementary in the various surgical workflows [16,17]. Their combined use may therefore be a step to bridge preoperative anatomical planning and intraoperative navigation [18]. However, further integration of 3D printing and MR remains at the explorative level with evidence of this to date limited to teaching studies, feasibility studies and limited clinical applications [17,18].

So far, existing reviews either discussed 3D printing and MR as individual stand-alone technologies or on a single surgical specialty. As a result, the incremental value of integrating physical patient-specific models together with interactive digital visualization throughout the various stages of surgical care, has so far not been adequately synthesized. This serves as the motivation for assessing 3D printing and MR not only on their own, but as part of an integrated perioperative workflow. Accordingly, current 3D printing and MR applications in surgical practice are summarised in this narrative review, with particular emphasis on the complementary and integrated applications for preoperative planning and intraoperative guidance,surgical education and training, patient education and postoperative evaluation. In this review, we further discuss the present clinical evidence, the technical limitations, implementation barriers, and the future applications of this emerging integrated approach.

2. Literature Search Strategy

We searched PubMed, Embase, and the Web of Science Core Collection for published articles from the start of the databases until September 2026. We used the search terms 3D printing ("3D printing," "three-dimensional printing," and "additive manufacturing"), mixed reality, augmented reality, virtual reality, and surgery-related concepts, including surgical navigation, preoperative planning, and intraoperative guidance. The literature included for consideration were those that

studied 3D printing or MR on their own, or together, as applied to surgical practice. No limitation on the type of article was implemented, and the reference lists of related articles were manually searched to find other studies. Studies addressing clinical, educational, or perioperative applications of these technologies were considered, whereas articles focused exclusively on non-surgical applications were not emphasized. AR or VR based studies were included if they presented evidence on perioperative visualisation, spatial registration, education, or comparison between MR and related technologies. When multiple publications were available addressing similar applications, priority was given to clinical and comparative studies, to systematic reviews or meta-analyses and to studies directly addressing combined 3D printing–MR workflows. The evidence was split up according to the main perioperative and educational applications while special care was taken to distinguish benefits related to the individual technologies from potential benefits arising from their combined use.

3. Application of MR Technology in Surgery

3.1. Preoperative Planning and Real-Time Navigation

MR technology has shown promise in real-time surgical navigation that provides superimposition of virtual anatomical information on the operative field [10]. By providing depth, perspective and spatial relationship information through 3D anatomical reconstruction, MR has the potential to assist surgeons to come up with a better spatial awareness of patient-specific anatomy and therefore improve on some of the limitations of standard two-dimensional imaging [11]. This might be of special significance in procedures dealing with small lesions, complex anatomical relationships or restricted surgical exposure.

MR has also been studied as a platform for pre-operative surgical planning. Perkins et al. [19] developed a patient-specific MR visualisation prototype for thoracic surgery in which users could explore reconstructed chest anatomy, and simulate lung deflation and instrument placement. This application demonstrates the potential interest of MR for surgical planning rather than for the provision of clinically validated real time intraoperative navigation. Intraoperative MR has also been investigated for 3D visualization and navigation in anatomically challenging surgical regions [20,21], with possible benefit for anatomical orientation in selected procedures [22].

However, the clinical benefits of MR-assisted navigation still have to be interpreted cautiously. A number of studies reported potential benefits in terms of procedural accuracy, surgical planning efficiency or operative time but the available evidence is still rather heterogeneous [23]. Clear differences in terms of registration method and accuracy and hardware and software platforms, the surgical application scenario and evaluation metrics limit direct comparison and reproducibility between studies [24]. Although certain studies have documented positive clinical results such as shorter operative time and fewer postoperative complications, the level of evidence for such clinical advantages is still not strong due to small sample size, fewer controlled clinical trials and lack of uniform outcome measures [11]. Therefore, the current evidence mostly favors technical feasibility and potential clinical usefulness of MR-assisted navigation, whereas its clinical value still needs to be confirmed in further, standardized, controlled clinical studies on a larger scale.

3.2. Surgical Education and Training

MR technology also holds potential for use in surgical education and training [25]. Combining virtual anatomical information with a realistic or simulated surgical setting, MR could offer the trainees an interactive environment to learn intricate anatomical relations, to practice workflow of a procedure, and to build up an intraoperative spatial judgement [26]. Compared to standard two

dimensional teaching materials, MR-based learning can provide a more intuitive three-dimensional representation of anatomy as well as interactive and spatially oriented learning [27].

In addition to teaching, MR can serve as a training aid during surgery training by using patient-specific 3D models and real-time interaction to provide visual guidance to assist the trainee during procedural simulation or supervised practice to provide case specific information [28]. Some studies do show that immersive and interactive MR-based training can improve trainees' knowledge regarding relevant anatomy and procedural workflow, and can improve some aspects of technical performance; some trainees also reported improved confidence for performing procedure [29,30]. However, as the current studies are quite different in training protocol, assessment methods, participants' experience and hardware platforms, the overall magnitude and reproducibility of such educational benefits still remain to be further verified [8].

From the complementary perspective, 3D printed models provide tactile and haptic aids to anatomy learning and procedural practice whereas MR allows interactive visualisation and spatial guidance [16]. In a randomised study in 36 medical students, Wang et al [17] observed better Objective Structured Clinical Examination scores following combined 3D printing–MR teaching vs traditional teaching. Peng et al. [30] compared 3D-printed model training only and 3D-printed model training plus MR in 16 junior physicians and observed higher puncture-related assessment scores in the combined group. Although these results provide preliminary comparative evidence, the small sample sizes and specialized educational settings render the results to be less generalizable and direct comparisons with MR alone remain scarce.

3.3. Patient Education

MR and other Augmented-reality technologies offer potentially valuable support of patient education by means of patient-specific 3D visualization of anatomy, surgical procedures and treatment information [31]. Compared to conventional two dimensional imaging based explanations, patient-specific MR visualisation might enable patients to easily and intuitively understand their own anatomy, the nature of their disease, and their planned surgical procedure [32]. This mode of visualisation might improve clinician-patient communication and patients’ understanding of the treatment-related information, and enable preoperative informed consent and shared decision making [33].

Some studies have suggested that interactive 3D visualisation might help patients to understand the related anatomical structures and diagnosis/treatment information more intuitively and in depth, and to improve the acceptance and preference for this form of education [34]. However, evidence remains limited. Current studies have focused on such short-term measures as patient understanding, satisfaction, and informed consent, and direct evidence is still lacking on whether these gains in knowledge actually translate into better postoperative adherence, recovery, or long-term clinical results [31].

So far, published work addressing MR in patient education and preoperative communication has focused on measures such as anxiousness and user experience, while objective clinical results have not been discussed in depth. In addition, due to large differences in patients, intervention, evaluation measures and technology platforms, the results are not directly comparable between studies [33]. Future research should employ common and comparable outcome measures and use prospective controlled study designs in order to further characterize the true clinical benefit of MR assisted patient education.

For patient education, the added value of 3D printing in MR could thus be the combination of a patient-specific tactile model and interactive digital visualization. Evidence that such a dual-modality presentation improves patient understanding or decision making compared to use of

either modality alone remains scarce.

4. Integration of 3D Printing and MR

4.1. Optimization of Preoperative Planning

The combination of 3D-printed models and the MR technology can potentially offer a more intuitive and handy solution for preoperative surgical planning [16]. Patient-specific 3D-printed anatomical models can help visualize complicated anatomy and preoperative surgical simulation [5], thereby supporting individualized surgical planning [7].

MR can augment 3D printed physical models further by displaying patient-specific virtual anatomical information in the form of holograms as an additional digital visualization aid in supporting complex anatomy understanding and in perioperative assistance [18]. Thereby, by spatially aligning patient-specific virtual models with the patient or the surgical environment, MR can provide additional spatial information that a physical model alone would not be able to provide completely [35]. For example, 3D-printed anatomical models can help surgeons to understand complicated pathological anatomy intuitively in preoperative planning, and MR can provide additional anatomical information like bone, blood vessel and nerves with interactive three dimensional display and in real time combining virtual model with actual operative field [36].

However, evidence on the incremental value of combining these two technologies over either technology alone is scant [35,36], because few studies have directly compared combined 3D printing–MR workflows to 3D printing alone, MR alone, or conventional preoperative planning. Variations in clinical indication, model-generation methods, visualization platforms, and outcome measures do not facilitate the direct comparison of studies.

4.2. Intraoperative Data Overlay

During surgery, MR can also be used to overlay virtual three-dimensional anatomical information on the actual surgical field, enabling the surgeon to compare preoperative plan data with the patient's anatomy in real time [37]. In complex surgery, this may further serve as a spatial guide and aid the surgeon's orientation in locating target regions and their spatial relation to related anatomical structures [22]. For example, in spinal surgery, by means of MR based visualization, preoperative three-dimensional anatomical models can be displayed over the operative field, potentially enabling the surgeon to identify key neural and vascular structures and to perform more accurate surgical manipulation [20].

A more directly integrated intra-operative workflow was shown by Lei et al. [36] in a preliminary total hip arthroplasty case, where a patient-specific 3D-printed registration instrument was secured to a selected bony landmark and allowed the MR headset to recognise external reference markers and register virtual anatomical structures to the operative field. In this application, 3D printing provided a functional registration interface for MR guidance rather than merely a separate anatomical model. This single-case report has shown only the technical feasibility, not the comparative clinical usefulness.

More generally, the intraoperative data overlay depends on the image registration and spatial tracking accuracy [24]. The mismatch between virtual models and actual anatomy may undermine the clinical utility of such guidance [14]. Although the case presented by Lei et al. [36] demonstrates a potential registration-based integration of 3D printing and MR, evidence for these combined workflows remains more limited than for the use of MR-assisted navigation alone. Whether 3D-printed registration components or anatomical models offer a clinically meaningful additional benefit can only be answered through direct comparison studies with specific accuracy

measures and defined clinical outcomes.

4.3. Postoperative Evaluation and Feedback

Ulrich et al. [38] assessed a patient-specific MR framework with 3D modeling and simulated range-of-motion analysis in a retrospective cohort of 67 total hip arthroplasties. Simulated measurements agreed well with clinical assessments, with favorable surgeon-reported usability. However, this work evaluated MR alone rather than a combined 3D printing – MR workflow. Overall, evidence for MR-assisted postoperative evaluation remains largely technical and retrospective, with scarce direct evidence for improved long-term outcomes and standardized assessment methods still lacking [11]. MR should therefore be regarded as complementary to, rather than a replacement for, conventional clinical and imaging assessment. Few studies have head-to-head compared combined 3D printing – MR workflows against single-modality or conventional assessment. Table 1 summarizes the functional roles, limitations, and qualitative evidence for 3D printing, MR, and their combined use across perioperative applications.

Table 1: Functional roles and qualitative evidence for 3D printing, mixed reality, and their combined use across perioperative and educational applications.

Surgical stage	3D printing	MR	Combined role	Main limitation	Evidence for combined use
Preoperative planning	Physical anatomical models	Interactive 3D visualization	Complementary physical and virtual planning	Unclear incremental benefit	Limited direct comparisons
Intraoperative guidance	Guides and registration aids	Real-time overlay and navigation	3D-printed registration and MR guidance [36]	Registration and tracking errors	Preliminary feasibility evidence
Education and training	Haptic training models	Interactive visualization	Hybrid physical–virtual training [17,30]	Small, heterogeneous studies	Preliminary comparative evidence
Patient education	Tangible anatomical models	Patient-specific visualization	Potential physical–digital explanations	Mainly subjective, short-term outcomes	Direct combined evidence scarce
Postoperative evaluation	Physical comparison models	Interactive postoperative assessment	Potential physical–digital review	Lack of standardized outcomes	Very limited direct evidence

Note: Combined roles include reported applications and proposed functional complementarity; proposed applications do not imply demonstrated clinical benefit. Evidence descriptions represent qualitative narrative assessments rather than formal evidence grades.

5. Future Directions

5.1. Technology Integration

As smart operating rooms and digital surgical platforms continue to evolve, closer integration of patient-specific three-dimensional models with virtual MR information may provide additional

support for individualized surgical decision-making [18,35,36]. However, broader clinical implementation of this integrated approach remains constrained by registration accuracy and by challenges related to technical and workflow integration [14,15]. In addition, equipment investment and cost-effectiveness remain important considerations for wider adoption [39].

3D printing and MR should not necessarily be regarded as competing visualization modalities, nor should they be combined routinely. Future studies should identify the surgical tasks in which combined use provides clinically meaningful benefits over either technology alone.

5.2. Clinical Research

Besides technical feasibility, some clinically meaningful outcomes including procedural accuracy, operative time, complication rates, postoperative recovery and patient-reported outcomes should be evaluated in the future. The combined use of 3D printing and MR is still at an early stage of clinical validation [36]. Across the literature included in this narrative synthesis, few direct comparative studies with combined 3D printing – MR workflows compared to 3D printing alone, MR alone, and conventional care using standardised clinical outcomes were identified. It is largely for the purpose of addressing this question as to whether dual-modality implementation offers clinically meaningful incremental benefit that such comparisons are particularly valuable.

Clinical studies with well-defined protocols, standardized evaluation criteria, sufficient sample sizes and long-term follow up will be necessary to enhance the generalizability of existing results [15]. Also cost-effectiveness should be taken into account to determine the feasibility of a wider clinical implementation [39].

5.3. Education and Training

As 3D printing and MR rapidly become part of the surgical workflow, formalised education and training for surgeons will be of growing importance [40]. Formal training programs should be set up by hospitals and healthcare institutions to assist surgeons to become competent in operating the devices, interpreting the results and fusing the technologies in clinical workflows [16].

A combination of simulation based training, and supervised hands-on practice may assist clinicians to improve the relevant knowledge and technical skills and become familiar with the relevant workflows prior to their routine clinical application [17]. In addition, the contents of the training should be updated in parallel with the continuous advances in hardware, software, and the clinical applications to ensure clinicians' familiarity with new emerging technologies [40].

Future training programs should also consider standardized competency assessment frameworks for surgeons' knowledge and practical skill in order to use these technologies in the clinical situations [17].

6. Conclusion

3D printing and MR may have distinct but potentially complementary functions in surgery. In a small clinical series involving 3D printing, VR, and MR, it was shown how 3D printed anatomical models and holographic visualization may aid surgical preparation and intraoperative anatomical understanding [18]. A case of total hip arthroplasty was presented in preliminary form, again demonstrating the use of a patient-specific 3D-printed registration instrument to bring virtual anatomy to the operative field [36]. Taken altogether, these reports suggest potential for complementarity between physical preparation and intraoperative digital guidance. Neither, however, demonstrates incremental clinical benefit over either of these technologies alone.

However, available evidence so far is still heterogeneous [23]. While several studies have reported the potential advantages of 3D printing and MR for anatomy learning, surgical planning, visualization, and procedural guidance and a few even reported shortened operative time and improved selected clinical outcomes, they are not entirely consistent across various clinical settings [11,41]. Differences in study design, surgical specialty, registration methods, hardware platform and outcome measures may contribute to heterogeneity [24]. Evidence on long-term clinical outcomes as well as cost-effectiveness remains sparse [39].

The most pertinent question for future research is thus not if 3D printing and MR can be combined, but when their physical – digital complementarity adds clinically meaningful incremental value. Comparative, multicenter studies with standardized clinical outcomes should define in which procedures combined use is warranted and in which single modality suffices. Such a task-specific approach may offer a more rigorous foundation for clinical adoption than routine dual-modality adoption.

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