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The Utilization of 3D Printing in Preoperative Planning

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Abstract:

Successful outcomes in the operating room depend on precise preoperative planning. However, existing surgical planning methods are often limited, relying on the experiences of clinicians and medical imaging for guidance. Moreover, two-dimensional (2D) representations of anatomical structures frequently fail to capture their intricate three-dimensional (3D) nature, leaving surgeons ill-prepared for procedures. Although 3D post-processed images offer some improvement over traditional 2D images, they may still lack the necessary depth for comprehensive surgical simulation.

The field of medical 3D printing is rapidly expanding and shows promise as an innovative solution to the current challenges in preoperative planning. With the increasing adoption of 3D printing in healthcare, it is crucial for healthcare professionals to gain knowledge about these technologies and their practical applications. In this context, we present an overview of the basics of 3D printing and explore essential aspects of its workflow. We also delve into the various applications of 3D printing in preoperative planning and discuss the challenges associated with its integration.

Keywords: 3D printing, surgical preplanning, medical imaging, technology, anatomical models.

1 .Introduction:

Effective preoperative planning plays a pivotal role in ensuring the success of surgical procedures, offering the potential to reduce risks and optimize operating room efficiency [1]. The traditional approach to preoperative planning predominantly hinges on historical experiences and medical imaging, such as magnetic resonance imaging (MRI) and computed tomography (CT). However, these methods come with limitations, lacking hands-on preparation and the capacity to deliver a comprehensive three-dimensional representation of anatomical structures . Relying on two-dimensional (2D) reconstructions can leave surgeons ill-equipped for the intricacies of surgery. Although virtual three-dimensional (3D) renderings have improved preoperative planning, they often fall short of replicating the true complexity of patient anatomy, and their intangibility poses challenges for surgical simulation, particularly in complex procedures [2].

To overcome these constraints in preoperative planning, a cutting-edge solution is 3D printing, an advancing technology that allows for the meticulous layer-by-layer creation of highly detailed anatomical models [4]. Its use in clinical contexts, especially in the production of patient-specific models, has yielded promising outcomes. A systematic review unveiled that 82% of studies utilizing 3D-printed models in preoperative planning reported enhanced surgical results when compared to traditional approaches, with more than 50% of these studies noting reduced operation durations [3].

This article intends to furnish readers with a comprehensive grasp of 3D printing and its significance in the realm of preoperative planning. We will delve into the essential principles of

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3D printing, its procedural intricacies, and its diverse array of applications, while also examining the documented advantages as evidenced in existing literature. Furthermore, we will investigate the obstacles and constraints linked to 3D printing and contemplate prospective advancements that may augment its effectiveness in clinical practice.

2. Fundamentals of 3D Printing :

Facilitating the successful adoption of 3D printing in clinical settings necessitates medical professionals familiarizing themselves with the technologies, materials, and methodologies underpinning this process. The selection of a 3D printing approach depends on the intended result, as certain methods excel at reproducing specific anatomical structures. The choice of the right technique and materials is crucial for creating accurate models for clinical applications. As a result, physicians should aim to cultivate a thorough grasp of the technical aspects of 3D printing.

The process of 3D printing, also referred to as additive manufacturing or rapid prototyping, initially emerged in the 1980s within the realm of industrial and engineering applications [1]. As its capabilities continue to advance, 3D printing is progressively finding practical use in the field of medicine. This technology enables the conversion of 2D medical images into 3D printed representations. During the printing procedure, 3D printers interpret digital models as "objects" defined by surfaces and enclosed spaces. Consequently, medical images need to be transformed into compatible 3D file formats, such as stereolithography (STL) files. STL files represent surfaces as a series of triangles or "facets." To convert images like CT scans and MRIs into the STL format, anatomical structures must be meticulously segmented based on tissue and pathology. Only after completing this segmentation process can a 3D model be constructed and subsequently printed. Therefore, the creation of 3D-printed medical models can be broken down into three sequential stages:

The process involves three key steps:

- ❖ Image capture, which entails obtaining medical imaging data of the patient;
- ❖ Image segmentation and post-processing, during which 2D images are transformed into a suitable 3D file format;
- ❖ 3D printing, where the digital 3D model is materialized into a physical structure [5].

2.1 Image Capture

The precision of 3D models relies heavily on the quality of the medical imaging used in their construction [2]. Attaining high-quality image acquisition stands as a fundamental prerequisite for creating accurate 3D models. Several technical standards have been established to define image quality, such as the 2012 guidelines outlined by the European Society of Urogenital Radiology (ESUR) for prostate MRI acquisition, which underscores the critical importance of high-quality MRI in that specific context [6]. Additionally, the Radiological Society of North America Special Interest Group on 3D printing (RSNA 3D Printing SIG) has issued comprehensive guidelines regarding image acquisition for 3D printing [7]. However, substantial disparities in imaging quality persist across different institutions, leading to models with suboptimal sensitivity and specificity [6].

When generating a 3D model, any volumetric imaging modality capable of distinguishing between various tissues can be utilized. Nevertheless, CT scans are the most frequently employed imaging method for model creation due to their high signal-to-noise ratio (SNR), advantageous soft tissue contrast, and exceptional spatial resolution. In certain scenarios, multiple imaging modalities are combined to capture different aspects of the anatomy under examination (refer to Figure 1) [5]. Fine-tuning the imaging process to enhance SNR and spatial resolution is of utmost significance, with the specific adjustments varying according to each modality. Even minor alterations, such as opting for a lower slice thickness than collimation in CT scans, leading to overlap, can significantly enhance model quality [7].

Irrespective of the imaging modality chosen, it is crucial to take into account the precise purpose of the model under construction. Ideally, the volume elements (voxels) in CT data should be isotropic, meaning their dimensions should be uniform in all three spatial planes. While the dimensions in the x- and y-planes of the scan are determined by the size of the CT detector, the dimension in the z-plane, referred to as "slice thickness," offers more adjustability. Achieving an optimal isotropic voxel size is a critical determinant of producing a high-quality model. If the acquired images feature voxels that are excessively thick, the model will lack precision; conversely, if the voxels are excessively thin, the model will result in heightened patient exposure to radiation and entail substantial segmentation and post-processing time. Typically, voxel sizes should fall within the range of 0.25 mm to 1.25 mm; however, the ideal size may vary depending on the specific pathology in focus. For instance, reconstructing an orbital floor might necessitate thinner voxels compared to working with cardiac tissue. Hence, healthcare professionals should factor in the target anatomy when formulating image-acquisition protocols [5].

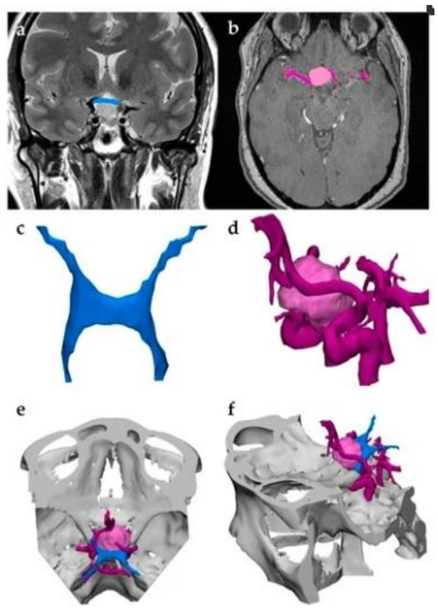

Figure 1. Multimodal Imaging for Three-Dimensional (3D) Printing: This approach was applied to visualize a brain tumor and differentiate it from the adjacent optic nerve and surrounding vasculature. (a) The optic nerve was imaged using magnetic resonance imaging (MRI) and represented in blue after segmentation. (b) Computed tomography (CT) was instrumental in delineating the neoplasm's boundaries, highlighted in pink, and identifying nearby vessels, highlighted in purple. (c, d) Subsequently, the segmented anatomical structures were transformed into stereolithography (STL) files, and (e, f) these files were integrated into a unified model for 3D printing.

2.2 Image segmentation and post-processing

Following their acquisition, medical images are typically preserved in the Digital Imaging and Communications in Medicine (DICOM) format. To generate a 3D file suitable for printing, DICOM images can be subjected to manipulation using segmentation and post-processing software packages such as MeVisLab (Mevis Medical Solutions, Bremen, Germany) or Mimics (Materialise, Leuven, Belgium). These software applications facilitate the segmentation and isolation of specific anatomical structures using a variety of techniques, including automatic, semi-automatic, and manual methods [2,8]. The selection of the technique

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is frequently influenced by the specific pathology in question. For instance, techniques like thresholding may suffice for isolating skeletal features in a CT scan due to the distinctive high attenuation characteristics of bony structures. However, the segmentation of soft tissues often necessitates additional adjustments.

The ultimate model might exhibit gaps or voids due to the varied and low signal intensity of certain pathologies and imprecise thresholding. Furthermore, challenges in 3D modeling can emerge from streak artifacts and beam hardening induced by factors like air, metallic implants, embolization coils, or dense blood. In situations where these artifacts cannot be resolved during image acquisition, supplementary segmentation techniques become indispensable (refer to Figure 2). For instance, region growing serves as a valuable tool for automated segmentation, allowing users to validate whether the chosen voxels genuinely pertain to the segmented "component." This diminishes the necessity for extensive manual adjustments or "sculpting" during the later stages of segmentation [5].

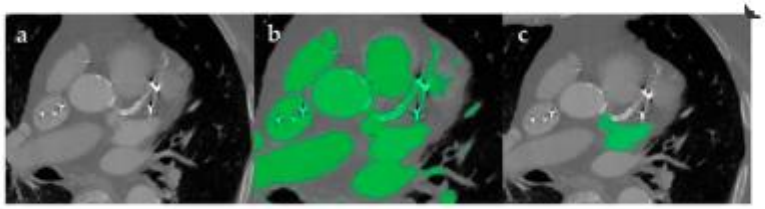

Figure 2 Dealing with Artifacts in Image Segmentation: (a) An axial contrast-enhanced CT scan of the heart displays conspicuous artifacts stemming from a metal implant and arterial calcification. (b) These artifacts undermine the efficiency of automatic segmentation through thresholding. (c) To isolate the region of interest, manual segmentation was utilized.

Upon completing the segmentation of individual DICOM images, many software packages have the capability to automatically generate a 3D STL file. This file is created using intricate algorithms, which involve processes like interpolation that consolidate the segmented regions of interest into a 3D model. Within STL files, users have the option to specify the number of triangles comprising each surface. Similar to voxel size, it's vital to take into account the anatomical characteristics of the model. An insufficient number of triangles or "facets" can result in anatomical inaccuracies. Conversely, surpassing a certain threshold for the number of triangles may not improve accuracy but can instead extend the post-processing time and lead to a rough, jagged surface. Complex, highly vascularized models might necessitate a higher threshold for the maximum number of facets compared to simpler anatomical structures [5].

While the generated 3D STL file is compatible with 3D printers, it often requires adjustments before it becomes print-ready [9]. Errors in the segmentation process can lead to imperfections in the 3D model, including gaps between facets or inverted normals, where the inner and outer surfaces of the model are swapped. Common issues with STL files arise from the necessity that every surface must enclose a space, meaning open regions of interest cannot be represented in this format. Therefore, users must manually edit the STL file using computer-aided design (CAD) software to "close" the area of interest, transforming it into a manifold structure. Additionally, the creation of supplementary components might be needed to stabilize the 3D model after printing, and CAD software can be utilized for this purpose. Employing these techniques may require a certain level of expertise to ensure correct implementation without compromising the anatomical accuracy of the model itself [5].

The RSNA 3D Printing SIG recommends that physicians meticulously document any alterations made during post-processing, classifying these changes into clinically significant and clinically

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insignificant modifications to uphold complete transparency throughout the 3D modeling process [7].

2.3. 3DPrinting

The STL file's data is used by 3D printers to segment the model into successive cross-sections. These printers then place specific regions of interest into each layer and combine them to form a physical structure [5]. In accordance with the RSNA 3D Printing SIG guidelines, each anatomical model must be printed utilising a minimum of three different layers. For example, if the smallest pathology that interests doctors is 3 mm, the layer thickness shouldn't be more than 1 mm, albeit it should ideally be considerably thinner. The required accuracy of the model dictates the ideal layer thickness [7].

There are several 3D printing processes available, which can be broadly classified as powder, liquid, or solid systems [10]. A number of considerations need to be made when choosing the best 3D printing technique for anatomical models, including availability, printing time, expense, and model purpose. We examine the five most often used and recognised technologies in this context: material extrusion, binder jetting, stereolithography, material jetting, and powder-bed fusion. Other 3D printing methods, such as directed energy deposition and sheet lamination, have fewer uses in the medical industry.

3. Clinical Applications in Preoperative Planning

The field of surgical planning has already seen the impressive efficacy of 3D printing. A comprehensive evaluation found that 3D modelling and its incorporation into preoperative planning accounted for roughly 40% of articles on the application of 3D printing in medical settings. These investigations demonstrated the beneficial relationship between patient-specific anatomical structures and 3D models, which led to shorter surgical times, lower radiation exposure, and better patient outcomes [3]. The domains of orthopaedic surgery, neurosurgery, craniomaxillofacial surgery, cardiovascular surgery, and interventional radiology were those where this influence was

3.1. Cardiovascular Surgery

The three main modalities used in cardiac imaging are echocardiography, CT, and MRI. While these techniques yield high-resolution pictures, they are not universally applicable to the wide range of morphologies associated with cardiac diseases. The inherent limitations of conventional imaging modalities present possible unexpected surgical outcomes, particularly for patients with a history of heart surgery [2]. As such, the application of patient-specific models can greatly improve a surgeon's preoperative planning. According to several studies [14, 15, 16, 17, 18, 19, 19], 3D models have already shown encouraging outcomes, particularly when it comes to surgical planning for patients with congenital heart defects including atrial and ventricular septal defects.

For example, transcatheter closure treatments for disorders such as muscular ventricular septal defects are planned using 3D-printed models based on CT angiography, which enables doctors to precisely predict catheter size prior to the surgery [20]. Notably, Ryan et al. guided surgical intervention in a neonate with tetralogy of Fallot (TOF) and pulmonary valve atresia—a severe variant of TOF that usually necessitates invasive patient morphological assessments prior to surgery—only using CT imaging and a 3D-printed model. But a viable substitute for conventional TOF diagnostic procedures is now 3D printing [21].

Beyond just helping to visualise cardiac lesions, 3D models also improve implant positioning and sizing accuracy. Several research works have highlighted the possible advantages of using 3D models to predict implant location and size during left atrial appendage

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(LAA) occlusion operations [22,23,24,25]. 3D printing can also optimise complex procedures, like replacing transcatheter valves [26, 27]. For example, thorough information on aortic morphology is necessary for transcatheter aortic valve replacement (TAVR) in order to avoid complications such as paravalvular leaks and coronary artery blockage brought on by prosthetic valve misplacement. Physical models can accurately predict the occurrence, location, and causes of complications in addition to enabling benchtop testing of prosthetic valve placement [28].Asymmetric left coronary cusp calcification and the requirement for permanent pacemaker implantation following TAVR were explained by Fujita et al. using 3D-printed models to mimic the long-term implantation of prosthetic valves in the presence of calcification. The models demonstrated how each prosthetic valve gradually shifted to the right until it eventually interfered with the heart's ability to constrict blood [29].

Current 3D printing methods are being further enhanced by ongoing innovations as the use of 3D cardiac models increases. Technological developments in 3D echocardiography have produced higher-resolution 3D models that are capable of capturing minute details of cardiac conditions, such as valvular leaks [2]. Moreover, the advancement of multi-material 3D printing presents an opportunity for more accurate surgical simulations. For instance, in one study, 3D-printed mitral valves that closely matched the physical characteristics of genuine valves were created using a combination of different elastomeric materials [30].

3.2. Neurosurgery

Determining the best strategy for surgical procedures is the main goal of 3D printing in neurosurgery [2]. A thorough understanding of the surrounding anatomical structures is necessary for this task. Because of their high contrast and spatial resolution, magnetic resonance imaging (MRI) is a useful tool for collecting large amounts of data, particularly when looking at the brain and spinal cord. The development of virtual reality simulations and 3D imaging methods has greatly enhanced preoperative planning.This is especially important because 2D renderings of these kinds frequently fall short in accurately capturing 3D depth and tactile sensations, which are very helpful to surgeons when performing real procedures [2,31]. Cutting-edge 3D printing techniques, like binder jetting, can create multicoloured models that highlight minute anatomical details that conventional medical imaging might miss. The surgical intervention's course can be crucially determined by these models [5].

Such models provide detailed representations of patient-specific vasculature, and numerous studies have demonstrated improved preoperative planning of neurovascular procedures [32, 33, 34, 35]. Microsurgical clipping is necessary for complex procedures involving intracranial aneurysms in patients, particularly when embolisation is not a practical option. This is done to restrict blood flow. In a follow-up investigation, 3D-printed models were made using CT angiography, and their ability to accurately replicate the surgical environment was assessed. These models proved useful for reproducing patient morphology, as they accurately sized aneurysm clips in comparison to the real clips used during surgery [36]. In addition, the development of 3D-printed vascular networks has allowed for the clinical and educational simulation of cerebrovascular interventions. Mashiko et al., for instance, effectively used such networks to model aneurysm clipping techniques and give trainees practical.

Patient-specific positioning is usually not taken into consideration for optimising patient evaluation when planning functional neural interventions, such as subdural electrode implantation for patients with epilepsy. Nonetheless, doctors are now able to tailor electrode arrays according to specific gyral and sulcal characteristics thanks to highly accurate 3D-printed models of patients' cerebrums. An important breakthrough for both clinical and research

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applications, Morris and colleagues have also shown that it is possible to modify the electrode density per array in order to group electrodes around particular anatomical regions of interest. For example, each array included a higher density of electrodes surrounding the motor bank of a patient's central sulcus in the study of the physiology of the motor cortex [38].

3.3. Craniomaxillofacial Surgery

Patient-specific positioning is usually not taken into consideration for optimising patient evaluation when planning functional neural interventions, such as subdural electrode implantation for patients with epilepsy. Nonetheless, doctors are now able to tailor electrode arrays according to specific gyral and sulcal characteristics thanks to highly accurate 3D-printed models of patients' cerebrums. An important breakthrough for both clinical and research applications, Morris and colleagues have also shown that it is possible to modify the electrode density per array in order to group electrodes around particular anatomical regions of interest. For example, each array included a higher density of electrodes surrounding the motor bank of a patient's central sulcus in the study of the physiology of the motor cortex [38].

Otologic treatments, like tympanoplasty, require careful preoperative planning because of the intricate morphology of the ear. In order to simulate and train surgeons on more realistic ear deformations, a number of studies have described the development of 3D-printed models [40,41,42,43,44]. Hochman et al., for example, used 3D printing to create temporal bone models and evaluated how well printed models performed surgical simulation in comparison to virtual models. When it came to accurately simulating surgical scenarios, residents discovered that the printed model worked better [41].

3.4. Orthopedic Surgery

Orthopaedic surgeons use medical 3D printing extensively in their work. A systematic review found that nearly 25% of publications discussing the advances in surgery made possible by 3D printing were related to orthopaedic surgeries [3]. Orthopaedics has made a significant investment in the surgical treatment of fractures, where 3D models have shown promise in shortening surgical times and minimising blood loss [45,46,47]. The advantages of using 3D-printed models to improve the surgical technique for distal tibial fractures were shown in one study. It was found that, upon receiving a 3D-printed model of the patient's anatomy, 74% of novice surgeons and 9% of seasoned surgeons modified their initial plate selection for distal tibial fracture surgery [48].

The creation of oncologic models for tumour resection is another use of 3D printing in orthopaedics. Because these models faithfully replicate the lesion of interest and its surrounding anatomy, they aid in the removal of tumours. Moreover, 3D printed models may help in the development of allografts that replace malignant tissue [5].

3.5. Interventional Radiology

The utilization of precise models plays a crucial role in assisting interventional radiologists in their practice. While three-dimensional renderings are valuable, they often lack the necessary spatial resolution to optimize interventional radiology (IR) procedures, especially those such as embolization, which require a comprehensive understanding of patient anatomy [49].

Apart from the previously mentioned uses of IR in cardiothoracic surgery, Giannopoulos et al. used 3D printing to model a patient's ascending aorta and aortic arch in preparation for an endovascular repair operation [50]. Moreover, testing different catheterized techniques and modelling splenic artery aneurysms were made possible by 3D printing. By being proactive, doctors could decide on the best course of action before the procedure even started, which cut

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down on the amount of time the patient had to undergo surgery and reduced their exposure to radiation.Furthermore, if tested during the surgical procedure, a few of the approaches, like coil embolisation, might have presented a risk of arterial injury [51]. Prostate artery embolisation was guided by a 3D-printed model, which effectively shows a branch of the prostate artery supplying blood to the rectum. In addition to making procedure planning easier, these models act as visual aids for patients, assisting them in understanding the relevant pathology and the intended course of treatment.

3.6. Other Interventions

Complete organ transplantation requires a thorough understanding of the anatomy of the patient prior to surgery. For a successful surgical procedure, the surrounding anatomy of the recipient and the donor must be compatible. In order to determine whether 3D-printed livers are a useful tool for surgical planning during liver transplantation, Zein et al. conducted a study. The biliary structures and vasculature of individual patients were remarkably accurately replicated by these models [52].

In a similar spirit, Chandak et al. developed paediatric kidney models through 3D printing in order to assess the viability of transplants for three patients suffering from stage 5 chronic renal failure. The inability of traditional imaging techniques to conclusively assess each patient's suitability for kidney transplantation was overcome by the 3D-printed models. These models also played a key role in determining which recipient vessel was best for anastomosis [53].

Silberstein and colleagues used 3D printing to remove renal tumours. Physicians' preoperative planning was guided by a model of the patient's kidneys and related tumours. Furthermore, these models were helpful resources for patient education because they offered a visual aid for talking about the suggested intervention [54].

Future Perspectives

Preoperative planning uses for 3D printing are numerous and growing quickly. In order for doctors to fully utilise this field's potential, they must gain a thorough understanding of its foundations. Even though 3D-printed models have already shown to be superior to traditional techniques in surgical practise and planning, there are still some issues.

As of right now, one drawback of 3D printing is its capacity to faithfully reproduce the characteristics of different tissues [2]. Though material mixing has advanced, accurately simulating the physical properties of in vivo tissue is still a challenging task. Some of these issues can potentially be resolved with bioprinting, which allows for the production of models with physiological heterogeneity while retaining control over the material's macro and micro properties [55]. 4D printing is another cutting-edge approach that combines 3D printing methods with intelligent materials that can modify their characteristics in reaction to electrical, mechanical, chemical, and thermal stimuli [56].

Nonetheless, the application of bioprinting and 4D printing in medical environments is still uncommon and encounters similar logistical challenges as conventional 3D printing. Yan and colleagues [57] have pointed out that the absence of standardised metrics for assessing 3D-printed materials also prevents the applications of 3D printing from becoming more diverse. Additionally, even though these technologies provide more accuracy, their cost makes their widespread adoption by hospitals a gradual process [4]. The entire cost of 3D printing is gradually going down as technologies become more widely available, but the initial outlay for

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setting up an in-center 3D printing laboratory and the slow rate of return on investment prevent 3D printing from being fully utilised in the medical industry [5].

The intricacy of the conventional workflow is another barrier to the wider adoption of 3D printing. To effectively use the current 3D printing technologies and software, one must possess a high degree of computer-based design expertise. To address the need for technical and medical proficiency in 3D printing, future training programmes and infrastructure development may require individual physicians to acquire a thorough understanding of the process. In certain workflows, medical professionals who confirm anatomical accuracy during segmentation and after the model's completion collaborate with engineers who generate 3D models. Even with these improved processes, though, effective communication between engineers and doctors is still necessary, and mutual understanding of the technical and medical aspects of 3D printing is still ideal until more user-friendly software is developed**.**

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