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Review

Virtual and augmented reality systems and three-dimensional printing of the renal model—novel trends to guide preoperative planning for renal cancer

Claudia-Gabriela Moldovanu [a,b,*]

[a] *Department of Radiology, Municipal Clinical Hospital, Cluj-Napoca, Romania*
[b] *Department of Radiology, Emergency Heart Institute "N. Stancioiu", Cluj-Napoca, Romania*

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Abstract *Objective:* This study aimed to explore the applications of three-dimensional (3D) technology, including virtual reality, augmented reality (AR), and 3D printing system, in the field of medicine, particularly in renal interventions for cancer treatment.

Methods: A specialized software transforms 2D medical images into precise 3D digital models, facilitating improved anatomical understanding and surgical planning. Patient-specific 3D printed anatomical models are utilized for preoperative planning, intraoperative guidance, and surgical education. AR technology enables the overlay of digital perceptions onto real-world surgical environments.

Results: Patient-specific 3D printed anatomical models have multiple applications, such as preoperative planning, intraoperative guidance, trainee education, and patient counseling. Virtual reality involves substituting the real world with a computer-generated 3D environment, while AR overlays digitally created perceptions onto the existing reality. The advances in 3D modeling technology have sparked considerable interest in their application to partial nephrectomy in the realm of renal cancer. 3D printing, also known as additive manufacturing, constructs 3D objects based on computer-aided design or digital 3D models. Utilizing 3D-printed preoperative renal models provides benefits for surgical planning, offering a more reliable assessment of the tumor's relationship with vital anatomical structures and enabling better preparation for procedures. AR technology allows surgeons to visualize patient-specific renal anatomical structures and their spatial relationships with surrounding organs by projecting CT/MRI images onto a live laparoscopic video. Incorporating patient-specific 3D digital models into healthcare enhances best practice, resulting in improved patient care, increased patient satisfaction, and cost saving for the healthcare system.

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* Department of Radiology, Municipal Clinical Hospital, Cluj-Napoca, Romania
E-mail address: moldovanucg@gmail.com (C.-G. Moldovanu).
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1. Introduction

Recent advancements in computer power and manufacturing technology have revolutionized imaging capabilities, enabling the generation of three-dimensional (3D) digital models from two-dimensional (2D) images [1]. This breakthrough has paved the way for widespread availability and application of virtual reality (VR), augmented reality (AR), and 3D printing systems in various fields, including medicine [1,2]. The utilization of specialized software enables the transformation of 2D images into 3D digital models, resulting in substantial enhancements in the comprehension of anatomy, more precise evaluation of pathology, and improved surgical interventions [2]. The creation of a patient-specific 3D printed anatomic model, can be used for many applications including preoperative planning, intraoperative guidance, trainee education, and patient counseling [1,3].

The term "virtual reality" emerged in 1960 with Morton Heilig's patent for the Telesphere Mask, the first head-mounted display [4]. VR involves the complete substitution of the real world with a computer-generated simulation of a 3D environment [4]. In the realm of renal cancer, the advances in 3D modeling technology have sparked considerable interest in their application to partial nephrectomy (PN) [5]. On the other hand, "augmented reality" refers to digitally created perceptions that overlay onto the existing reality, enabling the interaction with augmented elements [6]. "3D printing", also known as additive manufacturing, involves the construction of a 3D object based on a computer-aided design (CAD) model or a digital 3D model [7].

The utilization of 3D-printed preoperative renal models proves beneficial for surgical planning, as it provides a more reliable assessment of the relationship between the tumor and vital anatomical structures like renal vasculature and the collecting system [8]. Placing a physical 3D printed renal model in the hands of surgeons enables them to observe the actual anatomy firsthand, reducing the risk of misinterpretation and enabling better preparation for the procedure [9]. Furthermore, AR technology empowers surgeons to visualize patient-specific renal anatomical structures and their spatial relationships with surrounding organs by projecting CT/MRI images onto a live laparoscopic video [10].

Incorporating patient-specific 3D digital models at the point of care enhances best practices, leading to improved patient care, increased patient satisfaction, and cost savings for the healthcare system [11]. This report provides an overview of the principles underlying 3D renal models and outlines the necessary steps to obtain accurate patient-specific models. It also explores the application of 3D printed models in preoperative planning for renal cancer, discusses the barriers to clinical adoption, and outlines future challenges to support renal interventions.

2. General principles

The ability of a surgeon to develop a well-thought-out surgical plan is crucial for optimizing intraoperative performance, reducing surgical complications, and improving patient outcomes [12]. However, for surgeons who are not experienced in interpreting 2D medical images, assessing complex anatomical structures and pathology can be challenging [13]. Developing a 3D model can assist the surgeons in comprehending the intricate anatomy, establishing their surgical approaches, determining dissection planes, and predicting maneuverability in advance [14]. In the case of PN, accurately identifying the precise location of a tumor is of utmost importance [12]. Even experienced surgeons may encounter difficulties in identifying tumors, particularly small endophytic ones [12].

3. General workflow to create a patient-specific anatomical model

Volumetric medical imaging has played a pivotal role in the advancement of medical 3D models over the years [14]. Among the available imaging modalities, CT is the most commonly used for generating 3D anatomical models [15]. MRI offers excellent soft tissue contrast without the use of ionizing radiation, but its implementation for creating 3D anatomical models presents challenges and requires significant time due to the inherent low signal-to-noise ratio and presence of imaging artifacts [16]. 3D ultrasound data can also be utilized, but their use is even more challenging due to the non-tomographic nature of ultrasound acquisition [17].

In order to generate a patient-specific and anatomically accurate model for VR, AR, and 3D printing applications, the workflow involves a complex process comprising several steps (Fig. 1), which are described below.

3.1. Image acquisition

Digital Imaging and Communications in Medicine (DICOM) files cannot be directly used as input anatomical models for the creation of 3D models [18,19]. Irrespective of the chosen imaging modality, the quality of input data remains a critical limitation in the image processing workflow [19,20]. To generate a 3D anatomical model, it is essential to optimize the image acquisition parameters for quality. However, this can be challenging as imaging studies are typically performed before a model is ordered. Important considerations include high spatial resolution, volumetric data acquisition, multi-phase contrast, artifact reduction, and small slice thicknesses [20,21].

It is not recommended to repeat imaging solely for the purpose of producing a 3D model as it is cost-prohibitive and

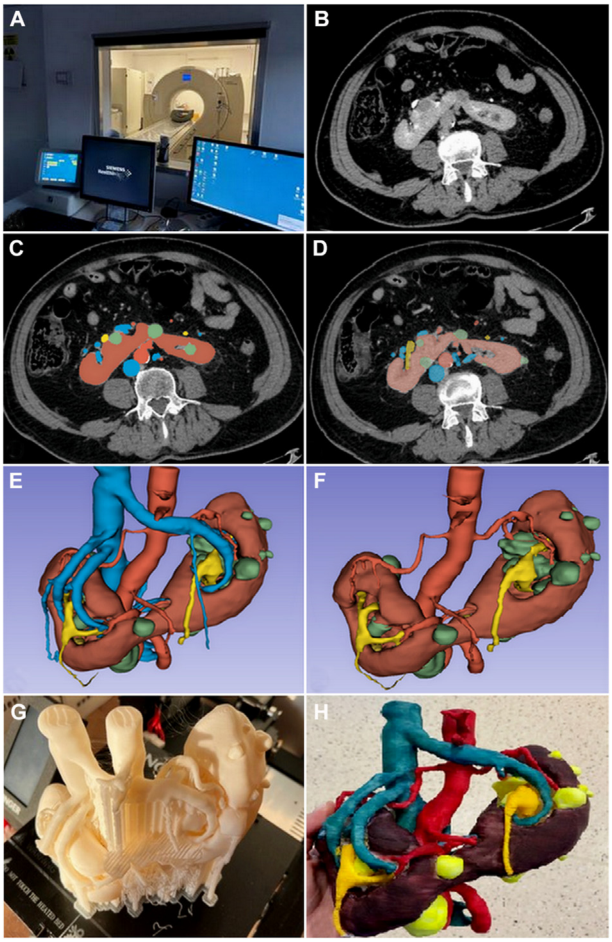

Figure 1 General overview of a three-dimensional printing workflow. (A and B) Image acquisition—high resolution volumetric dataset including CT, MRI, or ultrasound; (C and D) Image segmentation to create individual object for anatomy of interest; (E and F) Computer-aided design model to prepare for printing, create digital models, and smooth and verify objects to ensure anatomical accuracy; (G and H) A three-dimensional printing to print model using desired materials and remove support material.

increases the radiation dose to the patient if another CT scan is performed [20]. The DICOM volumetric dataset is exported to an independent image post-processing workstation, where it is utilized for subsequent steps in generating 3D anatomical models [15,18,20]. Converting the DICOM file to printable formats involves an elaborate process that requires multiple steps, which will be outlined below.

3.2. Image segmentation

Image segmentation is a crucial step in generating an accurate patient-specific 3D anatomical model [22,23]. Its primary objective is to partition a volumetric medical image into distinct anatomical regions or pathology [23]. This process relies on assessing the similarity and discontinuity of pixel values [22]. In the case of creating renal cancer models, separating anatomical regions of interest (ROIs) are delineated for the normal kidney, tumor, renal artery, renal vein, and collecting system [20].

Segmentation can be performed through various methods, including manual, semi-automatic, fully automatic, and semantic approaches [24]. Manual segmentation involves the operator tracing the ROI on each image slice, making it a subjective, time-consuming, challenging, and skill-dependent process that necessitates specialized training [24,25]. Fully automatic segmentation, on the other hand, employs algorithms such as thresholding, edge detection, and region growth to automatically assign boundaries [26,27]. Despite advancements in computing methods, accurately segmenting images using fully automatic methods remains challenging due to factors like indefinite boundaries, intensity inhomogeneity, and anatomical variations across subjects [28]. Fully automatic segmentation methods have shown efficiency in cases where the contrast is sufficiently high (*e.g.*, for bones) [28,29]. However, when the contrast is insufficient (*e.g.*, for differentiating between soft tissue), fully automatic segmentation methods tend to be inaccurate [29]. In such cases, a semi-automatic approach is often required, which involves a combination of algorithms that are manually verified [25]. This approach ensures more precise segmentation by incorporating human intervention and expertise [25].

Deep learning methods have emerged as a prominent research area in the medical image analysis [24,31]. Semantic segmentation involves the task of labeling each pixel in an image with a corresponding class [24]. Convolutional neural networks (CNNs) are currently the most popular neural network models for image processing. CNNs have the ability to learn from image data without human intervention, making them highly effective [30—32].

While medical image segmentation is gaining traction, there is limited literature on kidney tumor segmentation [24,31,33—45]. However, published works have proposed various methods for segmenting kidney tumors, including recurrent neural networks, enhanced feature resolution, feature coding, up-sampling/deconvolution, feature enhancement, spatio-temporal clustering, and approaches based on Markov random fields and conditional random fields. In recent times, the performance of deep learning algorithms for renal tumor segmentation has improved due to the availability of more training data and utilization of sophisticated CNN architectures and training methods [24].

Regardless of the segmentation method employed, it is crucial to optimize it for a specific dataset, a process that requires time and expertise [46]. In the creation of renal cancer models, it is necessary to segment the normal kidney, tumor, renal artery, renal vein, and collecting system, assigning separate anatomical ROIs [46] (Fig. 2). The segmentation results in a volumetric ROI, which serves as a valuable modeling tool for generating surface meshes [46].

3.3. CAD modeling

In the field of medicine, CAD systems have the capability to produce 3D printed anatomical guides, molds, and customized devices for patients [47]. Furthermore, CAD is utilized for analysis and simulation purposes as well [47,48]. Several post-processing software programs are

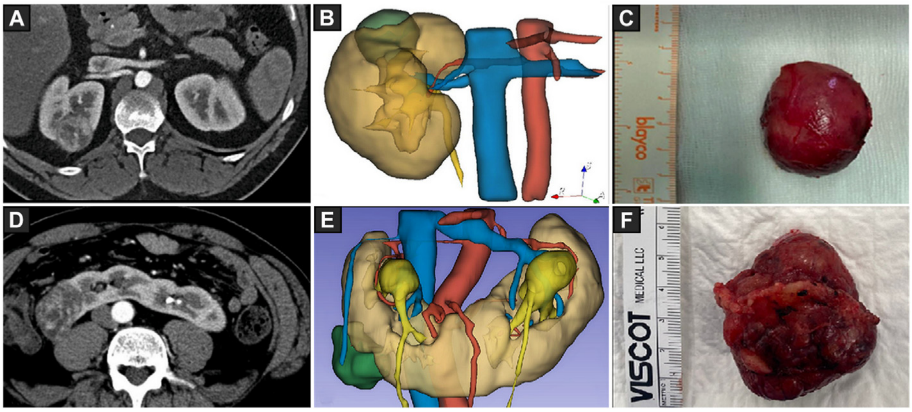

Figure 2 Three-dimensional virtual reality models of two renal tumors. (A—C) The first renal tumor: (A) Image acquisition, corticomedullary phase CT scan, axial plane of a patient with a right kidney tumor; (B) The corresponding CAD model; (C) Surgical resection specimen; (D—F) The second renal tumor: (D) Image acquisition, corticomedullary phase CT scan, axial plane of a patient with a right kidney tumor developed on a horseshoe kidney; (E) The corresponding CAD model; (F) Surgical resection specimen. CAD, computer-aided design.

used in hospitals to refine surface meshes for 3D printing, AR, and VR, including 3-matic, Materialise Magic, 3ds Max, Fusion 360, Inventor, Maya, MeshMixer, Blender 3D, Geomagic Freeform, MeshLab, Rhinoceros 3D, Solidworks, and Computer-Aided Three-Dimensional Interactive Application [46—50]. The CAD software employs various principles to generate objects, including solid modeling (the most frequently utilized method), surface modeling, parametric modeling, and 3D surface scanning [49,50].

To ensure that a patient-specific anatomical model is suitable for 3D printing, several steps need to be followed [47]. First, the segmented anatomical ROI must be carefully designed and prepared [51]. Next, these segmented regions are converted into 3D file formats that are compatible with the specific 3D printing slicing software used by the vendor [52].

Commonly used file formats for 3D printing are vendor-neutral and represent the 3D geometry through a triangulated polygon mesh surface, accompanied by node and vector data [47,51,53,54]. Some of these formats include standard tessellation language, alias wavefront object, VR modeling language, ZPR (a file format created by Z Corporation), additive manufacturing, and 3D manufacturing format [47,51,53—55]. These formats allow for accurate representation and communication of the anatomical structures to the 3D printer [51,53]. The standard tessellation language is widely recognized as the standard file format for 3D printing [47,51,54,55].

This file format allows for a reduction in file size and provides the ability to include additional data such as units, color, lattices, and textures [53]. VR modeling language files also incorporate similar color and texture information [54]. During the preparation phase, regardless of the file format, minor adjustments may be required to optimize the model for 3D printing [47,51,54,55]. In some cases, significant modifications might be necessary to facilitate intervention planning [47]. The CAD software is often utilized for the model analysis, digital planning, and surgical simulations [47,48]. Moreover, personalized surgical guides, templates, and molds can be designed using the CAD software [47].

4. Printing patient-specific anatomy

One aspect of 3D printing that has had a significant and immediate influence on the healthcare ecosystem is the utilization of 3D printed anatomical models [51]. Numerous studies and publications have highlighted the benefits of incorporating printed anatomical models in surgical planning [5,8,9,14,20,21,24,46—49,51,55,56]. 3D models have proven invaluable in improving the visualization of the kidney's arterial vasculature, aiding in perioperative surgical planning for robotic PN, particularly for complex renal masses [57,58]. The use of these models resulted in a notably lower rate of patients requiring global ischemia compared to 2D images [57,58]. Additionally, 3D VR offered a superior comprehension of tumor characteristics such as location, endophytic growth, and vascular relationships prior to surgery, leading to a higher likelihood of recommending nephron-sparing surgery [57—59]. Moreover, 3D virtual models (VMs) outperformed traditional 2D imaging in accurately assessing the surgical complexity of renal masses based on nephrometry score or category [60,61]. This superiority stemmed from the enhanced visualization of tumor depth and its interactions with intrarenal structures offered by the 3D VM [60,61]. This was further validated by the heightened precision of the 3D VM in predicting postoperative complications [60,61]. Moreover, a recent study demonstrates that using mathematical algorithms for 3D VMs allows for precise identification of kidney perfusion areas, optimizing the effectiveness of selective clamping and minimizing adverse impacts on renal function [62]. Ukimura and his team [63] highlighted the practical utility of 3D printing in planning the management of the renal pedicle and clamping during PN. Their findings indicated an enhanced understanding of intra-renal vascular anatomy and its interactions with the kidney tumor, facilitated by this technology [63]. Another study by Von Rundstedt et al. [64] showcased a noteworthy correlation between the 3D model and surgically removed tumor in terms of morphology and volume. This correlation was demonstrated through comparable biometric outcomes obtained from simulated surgical procedures and actual *in vivo* operations [64].

The trifecta criteria encompasses a negative surgical margin, absence of perioperative complications, and a warm ischemia time of ≤25 min [65]. Some studies demonstrated that utilizing a 3D kidney model during robot-assisted PN resulted in a high rate of TRIFECTA success [65,66]. Regardless of the level of surgeon's experience, the use of 3D models showed promise in enhancing surgical planning efficiency and reducing the likelihood of needing to convert to radical nephrectomy during surgery [65,66]. Additionally, adopting a 3D-guided approach to PN promoted adoption of selective clamping and improved the prediction of achieving TRIFECTA outcomes even when treating complex tumors with less-experienced surgeons [65,66].

The emergence and accessibility of specialized platforms like the MyMedics cloud system and ICON3DTM have greatly simplified the utilization of 3D models, which are now seamlessly integrated across multiple phases of surgery, encompassing preoperative evaluations, patient consultations, and intraoperative guidance [67]. The MyMedics cloud system facilitates the sharing of CT/MRI images and grants users direct entry to completed 3D models crafted by hospital engineers [67]. Furthermore, the platform empowers users to tailor the model by incorporating presurgical information such as resection planes or clamping strategies [67]. These modifications can be saved within the cloud system for subsequent use during surgery [67]. The ability of the cloud-based platform to store both 2D and 3D images also fosters collaboration among specialists through remote teleconsultation [67].

These 3D models serve as valuable supplements to traditional imaging modalities like MRI, CT scan, and X-ray [47,48]. The writing group representing the Radiological Society of North America Special Interest Group on 3D printing has developed a comprehensive literature-based guideline document [68]. These recommendations have undergone thorough vetting and have been voted on by the active membership of the Special Interest Group [68]. This guideline document serves as the first comprehensive reference for the implementation of 3D printing in clinical practice and outlines appropriate scenarios for various clinical applications [68]. Created by the members of the Radiological Society of North America Printing Special Interest Group on 3D printing, this consensus guideline document serves as an initial point of reference for standardizing methods and clinical applications in the field of 3D printing [68].

The intricate nature of normal anatomical structures, coupled with the absence of straight lines, smooth edges, and 2D interfaces in the human body, often poses challenges in understanding normal anatomical relationships [5,68]. To address this, 3D models have proven to be valuable in visualizing and comprehending complex anatomical structures, particularly in medical training [69—71].

Research studies have demonstrated the effectiveness of 3D printed models in teaching intricate surface anatomy and as an alternative approach to traditional didactic instruction [70,71]. These models offer a practical and tangible means of enhancing learning and understanding in medical education [70,71]. Estimating surface anatomy and its correlation with underlying structures can be challenging when relying solely on standard cross-sectional imaging techniques [71]. An example of utilizing 3D printing to enhance the visualization of complex anatomical relationships involves vascular structures, including both common and less common anatomical variants [69,71]. For instance, in standard anatomy, the left renal vein typically crosses in front of the aorta when connecting to the inferior vena cava [5,71]. However, it is crucial to recognize significant vascular variations such as retroaortic and circumaortic renal veins [5,71].

Advanced 3D visualization can greatly benefit surgeons and patients with giant renal tumors by facilitating a better understanding of the complex relationship between the aorta, the inferior vena cava, and renal vessels [5,69—71]. Variant anatomy poses challenges in comprehending these relationships, and the utilization of advanced 3D visualization techniques can provide valuable insights [5,71]. Similarly, the number and length of renal veins and arteries are important factors to be considered in presurgical imaging [71]. Demonstrating these aspects accurately to surgeons using only 2D sectional anatomy can be difficult [5,71]. Therefore, 3D printing provides a valuable tool to depict these intricate details and aid in surgical planning and decision-making [5,69—74].

5. Applications of a patient-specific model for renal interventions in renal cancer

In general, the primary clinical objective of VR and AR systems in kidney interventions is to enhance patient outcomes. The literature highlights several more specific objectives addressed through VR or AR assistance, including facilitating precise tumor resection, ensuring safe renal clamping, assisting in selective arterial clamping, and minimizing the risk of postoperative leakage resulting from an open urinary tract [5,56,69—74].

Accurately understanding tumor localization, proximity to the collecting system, and vascular invasion can be challenging when relying solely on 2D visualizations of CT or MRI data [75,76]. Preoperative planning plays a crucial role in ensuring optimal patient outcomes in renal cancer surgery. It involves careful consideration of significant patient co-morbidities while placing emphasis on the surgeon's understanding of the intricate spatial relationships among the different anatomical components involved [76].

Intensive research is currently focused on developing personalized medical and surgical approaches tailored to individual patients [75,76]. In the field of kidney oncologic surgery, the optimization of perioperative outcomes heavily relies on gaining a comprehensive understanding of the specific surgical anatomy of each case [75]. The recent advancements in 3D VM technology have sparked a growing interest in their application in robotic minimally invasive surgery for kidney tumors [56,76].

6. Barriers to clinical uptake

There are various challenges associated with VR or AR support in the field of urology [75–77]. The process of generating 3D models for simulation purposes can be highly time-consuming [56,76]. Furthermore, incorporating an AR overlay that accounts for organ motion presents additional complexities [75,76]. Methods like manual image registration, which aim to address this issue, require additional resources and can potentially disrupt the intraoperative workflow [74–76]. These challenges may partly explain the comparatively slower implementation of AR systems in urology compared to other fields [75,76].

The integration of 3D models into clinical practice and standard of care faces two significant barriers, namely the associated costs and time required to create the models [74–76].

Accuracy of the models and proper co-registration play a crucial role, especially when using them for real-time surgical navigation. In the context of co-registration for incision planning and intraoperative guidance, it is essential to account for patient motion and deformation [75,76].

7. Future directions in urology

The potential applications of 3D printing in the field of urology are continuously expanding [74–79]. There is a growing emphasis on creating physical models of patient anatomy using 3D printing technology to improve patient comprehension, enhance surgical planning, and provide realistic simulation training [78–80].

We perceive 3D printed models as an innovative tool that holds potential for the preparation and planning of intricate surgical procedures, offering utility that can be applied to various urological surgery [75–78]. Furthermore, 3D printed models can also prove beneficial for surgical trainees, including medical students, residents, and fellows [79,80]. In the operating room, surgeons face the challenge of balancing their time between teaching learners, optimizing patient care, and achieving surgical efficiency [80]. Therefore, medical educators are constantly seeking strategies and tools to aid in the education of surgical trainees [79,80]. 3D images and models have been employed to assist trainees in learning and comprehending patient-specific anatomy for their own surgical planning purposes [70,74]. Moreover, by utilizing materials that resemble human tissue, 3D models can be employed in simulation-based training, allowing surgical procedures to be taught, learned, and practiced outside of the operating room environment [70,74,79,80].

CAD is a robust tool that holds a significant importance in various aspects of medical 3D printing and modeling [75,76]. It extends its capabilities from creating basic anatomical models to assisting in computer-assisted surgeries, designing personalized implants, and developing computational and *in vitro* simulation models [76]. The integration of CAD technology significantly enhances patient care [76]. Moreover, as 3D CAD continues to advance, enabling improved simulations of patient-specific tissue and fluid dynamics, coupled with ongoing progress in printable tissue development, it is anticipated that the transplant industry will experience a revolutionary transformation in the future [78].

Irrespective of the number of developments that prove to be sustainable in the long run, the advancements in urology demonstrate the freedom to innovate and quickly prototype facilitated by 3D printing [79,80]. While bioprinting holds significant potential for patient-specific grafts in the future, we believe that the combination of rapid prototyping, network sharing, and idea development is the reason why 3D printing will continue to play a crucial role in ongoing surgical innovation [78].

In the coming years, it is anticipated that robotic surgery will become more affordable. Given the advancements in technology, it is expected that VR, AR, and 3D modeling will frequently be integrated into robotic surgical procedures [56,78].

8. Conclusion

The utilization of 3D VMs holds great promise for enhancing the safety and outcomes of renal interventions in the future. Additionally, these models serve as valuable tools for physicians to educate patients and their families about the disease and treatment procedures. It is anticipated that with the reduction in costs, 3D technology will become more widely adopted as a standard of care in the field of medicine.

Conflicts of interest

The author declares no conflict of interest.

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