Ukrainian Journal of Nephrology and Dialysis
Scientific and Practical, Medical Journal

Founders:
- State Institution «Institute of Nephrology NAMS of Ukraine»
- National Kidney Foundation of Ukraine

ISSN 2304-0238;
eISSN 2616-7352 **Journal homepage:** https://ukrjnd.com.ua

Nephrology School

doi: 10.31450/ukrjnd.3(67).2020.11

K. Wendo[1], R. Olszewski[1,2]

3D printing and urology: Review of the clinical applications

[1]UCLouvain, Brussels, Belgium
[2]Department of Oral and Maxillofacial surgery, Cliniques Universitaires Saint-Luc, Brussels, Belgium

Citation: Wendo K, Olszewski R. 3D printing and urology: Review of the clinical applications. Ukr J Nephr Dial. 2020;3(67):80-93. doi: 10.31450/ukrjnd.3(67).2020.11

Abstract. *Three-dimensional (3D) printing is a process that translates a 3D virtual model into its physical 3D replica. In medicine, Neurosurgery, Orthopedics and Maxillo-facial surgery were the first specialties to successfully incorporate this technology in their clinical routine, as an aid to surgical interventions.*

The study aimed to provide a clear overview of the potential areas of applications of 3D printing (3DP) for management of renal diseases, based on a review of the literature.

Method. We carried out a review of the literature according to PRISMA recommendations. We searched three databases (Medline, Scopus and Cochrane) with two specific queries: one using MeSH-terms and the second one based on free terms, all terms were related to nephrology and three-dimensional printing technology.

Results. 3D-printed models were mostly employed for the management of renal tumors and lithiasis. They provided enhanced visualization of structures and the possibility to perform procedures rehearsals which seemed to improve surgical procedures. Models were also reported to positively impact patients' understanding of their condition and the interventions. Trainees and experienced urologists also benefited from the supportive role of 3D-printed models and reported improved confidence and efficiency. Rare reports discussed their use for kidney transplantation, ureteropelvic junction obstruction syndrome treatment, nuclear medicine or cultural issues. Due to a meager data amount and heterogeneity of studies, no advanced statistical analysis was possible.

Conclusion. 3D-printed models of renal anatomical structures are feasible and are valuable tools to support renal disease management, and for educational purposes.

Article history:
Received April 08, 2020
Received in revised form April 30, 2020
Accepted June 02, 2020

Keywords: *kidney, urology, nephrology, 3D printing, education, surgery, anatomic models.*

Conflict of interest statement: the authors declared no competing interests.

Correspondence should be addressed to Kevin Wendo: kevin.wendo@student.uclouvain.be

УДК: 004.9:616.6

К. Вендо[1], Р. Ольшевський[1,2]

3D-друк та урологія: огляд клінічних застосувань

[1]Університет Каталік де Лувен, Брюссель, Бельгія
[2]Університетська клініка Сен-Люк, Брюссель, Бельгія

Резюме. *Тривимірний (3D) друк - це процес, який перетворює 3D-віртуальну модель у її фізичну 3D-репліку. Нейрохірургія, ортопедія та щелепно-лицьова хірургія були першими медичними спеціальностями, які успішно включили цю технологію у свою клінічну практику, як допоміжний засіб для хірургічних втручань. Представлений огляд літератури мав на меті визначити потенційні області застосування 3D-друку (3DP) для діагностики та лікування хвороб сечової системи.*

Методи. Аналіз наукової літератури, на основі баз даних Medline, Scopus і Cochrane, був проведений відповідно до рекомендацій PRISMA за двома конкретними запитами: 1) MeSH-терміни, 2) вільна термінологія щодо урології, нефрології та тривимірної технології друку.

Результати. 3DP моделі в основному використовувались для лікування пухлин нирок та нефролітіазу. Вони забезпечували кращу візуалізацію, що надавало можливість проводити репетиції оперативного втручання. Крім того, 3DP моделі позитивно впливали на розуміння пацієнтами їх стану та об єму втручання. У деяких повідомленнях обговорювалось використання 3DP моделі для інших інвазивних втручань в урологічній практиці та трансплантації нирки. Через мізерну кількість даних та неоднорідність досліджень, статистичний аналіз не був можливим.

Висновок. 3DP модель нирок є здійсненними та цінним інструментом для візуалізації, навчальння та лікування хвороб сечової системи.

Ключові слова: *нирки, урологія, нефрологія, 3D-друк, освіта, хірургія, анатомічні моделі.*

.

Introduction. "3D printing" (3DP), or additive manufacturing, is a technique translating a virtual image into its physical reproduction. This technology, created by Charles Hull, initially served industrial purposes. Medicine is one of its many fields of applications, 3DP is employed to reproduce physical constructs of anatomic regions [1, 2].

The printing of anatomical-specific models required several steps. First, images of the anatomy of interest are captured using Tomodensitometry (TDM), Magnetic resonance imaging (MRI) and Ultrasonography (US) [1-4].

Second, the "Segmentation": the anatomical region of interest is extracted, "segmented', from the radiological image. This process is performed by dedicated segmentation software, using an automated algorithm or manually. Multiple segmentation software are available but differ in cost, accessibility and accuracy. This step is often reported as time-consuming. Once, the segmentation is realized, the virtual model is exported into Standard Tessellation Language (STL) format which can be read by 3D printers [1-3, 5].

Kevin Wendo
kevin.wendo@student.uclouvain.be

Third, before the actual 3D printing process, an additional stage may take place: during this step, residual gaps are removed and final features of the model are fixed (color, ...). This step is realized through specific software, "Computer-aided Design" (CAD) software. Like unto segmentation software, a range of CAD software exists [6].

Fourth, the 3DP printing process occurs. Different 3D printing techniques exist but only four are usually used in for medical purposes: Fused deposition modeling (FDM), Stereolithography (SLA), Selective laser sintering (SLS) and Inkjet printing (IP). FDM: deposition of a heated and liquified thermoplastic filament slice-by-slice, followed by its cooling and hardening. SLA: successive slices of a photosensitive resin cured by ultraviolet light. SLS: sintering of successive layers of powdered material by a laser. IP: deposition of a binder solution on powdered substrate layers [3, 4, 6, 7].

Finally, a post-printing step may occur for specific arrangements (sterilization...) [2, 3].

3D printing is not a novelty in the medical field. Indeed, it has been applied and validated in neurosurgery, maxillofacial surgery and orthopedics, for preoperative planning, perioperative navigation, production of implants for in vivo implementation, and in education [2, 8]. The incorporation of 3D printing technology in nephrology is relatively new. The main application is oncologic. Indeed, teams printed 3DP models to provide enhanced visualization of 3D spatial relationships between tumoral masses and the surrounding tissues and to assess their depth. The 3DP technology was also involved in managing complex renal lithiasis due to their size or abnormalities of kidney structures (i.e. horseshoe kidneys). Patients' satisfaction as well as trainees' skill appeared to be improved by 3DP models of educational possibilities [1-5, 7-11].

To date, no systematic review neither RCT was performed to objectively evaluate the real role of 3DP. Therefore, this study aimed to objectively, based on a review of the literature, highlight the potential clinical applications of 3DP to support renal disease management, as well as its limits and future perspectives.

Methods. We used the Cochrane Handbook for Systematic Reviews of Interventions and Systematic Reviews, the Centre for Review and Dissemination's (CRD) handbook and the PRISMA Statement to conduct the review and to report appropriately findings and data of the present study [12, 13,14]. We searched the three following electronic databases using two different queries, Medline (via PubMed), Scopus and Cochrane, and used both text-free and MeSH based queries to cover a larger amount of potentially eligible elements. We employed terms relating to the nephrology field and 3D printing technology (**Supplementary file, Table S1**). The last search was performed on the 15th of May 2018. No handsearch (conference, reports) was undertaken and other sources (internet, reference lists) searched. For the study selection strategy, we used Covidence, a Cochrane Collaboration software, to perform the duplicates removal and the titles and abstracts screening, and Endnote, a reference management software.

Inclusion criteria:

- English or French written articles,
- no publication date restriction,
- both pediatrics- and adult-oriented articles,
- the articles discussing the clinical and surgical applications of 3DP in nephrology and urology,
- Contribution of 3DP for multidisciplinary management of renal diseases.

Clinical and surgical applications of 3DP were defined as follows: 1) any use of 3DP to provide support and assistance in a diagnostic, prognostic, follow-up and therapeutic approach of renal diseases, 2) therapeutic approaches include pre-interventional procedures, 3) educational applications of 3D printing. Educational applications were defined as patient education and as teaching and training of medical trainees, novices and experimented physicians in understanding and managing renal diseases.

Exclusion criteria:

- articles referring to other medical specialties or veterinarian subjects,
- articles discussing only experimental and technical aspects of 3DP in renal diseases, or any other medical and scientific field,
- articles describing technical or developmental aspects of the technique itself,
- articles underlying only 3D-Imaging approach of renal diseases,
- articles discussing experimental and technical aspects of tissue engineering in any scientific and medical fields (nephrology included),
- articles not focusing on clinical applications of 3DP in nephrology and urology.

Duplicates were automatically detected and removed after importing references into Covidence. A review of the duplicates found was undertaken manually to avoid possible wrong matches. For each element, the investigator was aware of authorship and publication details if available. Despite the use of eligibility criteria to include or exclude elements, we chose to be overinclusive at this stage.

Elements with ambiguous titles and without abstracts were included after discussion between authors. Any disagreement was resolved by discussion and unanimous consent between authors.

Each element was entirely reviewed and included after a strict confrontation with the inclusion and exclusion criteria. For each article, the investigator was aware of authorship and publication details if available. Disagreements were resolved by discussion and unanimous consent between authors.

To standardize extraction and analysis of data, we further developed a data extraction form inspired by the CRD's guidance handbook, (**Supplementary file, Table S2**). Disagreements were resolved by discussion between the two review authors.

Data were expressed as frequencies and proportions in the case of categorical variables.

Results. Search results. 295 records were identified through database searching. 109 duplicates were removed, and the 186 remaining elements were screened using the method described earlier. 60 articles were included in the full-text review assessment. Among 60 full-text articles, 22 ones were excluded and 38 studies were included in our study (Fig. 1).

Studies background. Among the included studies, 28 ones are either reported case studies of procedures or teaching reports. Other articles are review articles. The full background information is presented in Figures 2 and 3. Image data sources. Tomodensitometry appears to be the major source of image data. 1 team has reported having used both CT- scanner and MRI to acquire image data [15]. 3 studies have indicated no detail about their imaging data source [16-18]. (Fig. 2a).

Image processing. Moreover, we distinguished commercial from free and open-source segmentation software. Fig. 2b and 2c display the brand-named reported software. Zhang et al have reported the use of two different segmentation software in their study [19]. 4 studies have mentioned no imaging segmentation software which impedes a reliable analysis of their frequency of utilization [18, 20-22]. Even though they cited potential segmentation software, Dullius et al have not clearly indicated the software employed by their team[23].

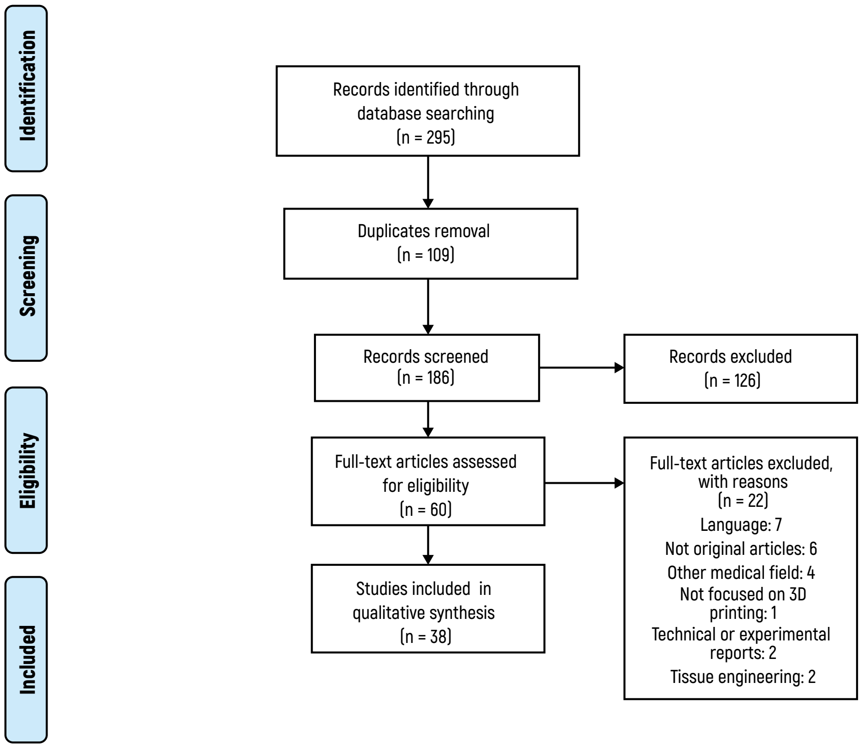

Fig. 1. Studies inclusion flow diagram (derived from PRISMA Studies Inclusion Flow Diagram).

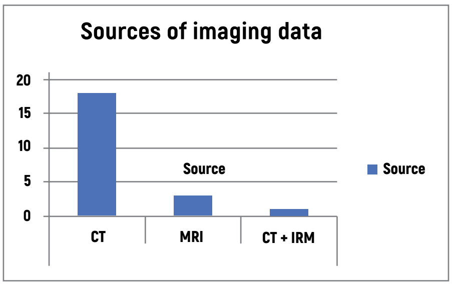

Figure 2a: Sources of imaging data

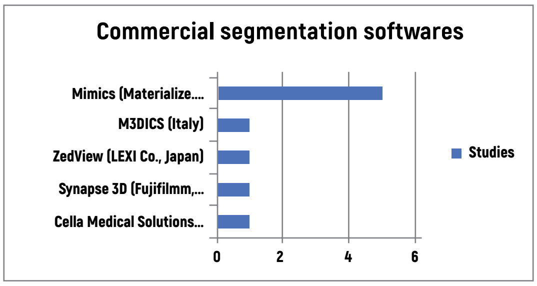

Figure 2b: Commercial segmentation software

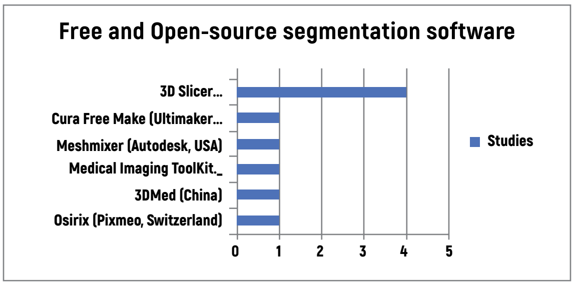

Figure 2c: Free and Open source segmentation software

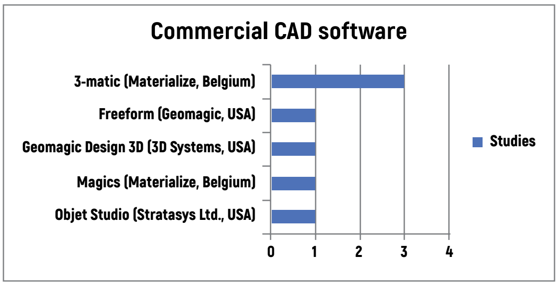

Figure 2d: Free and Open source segmentation software

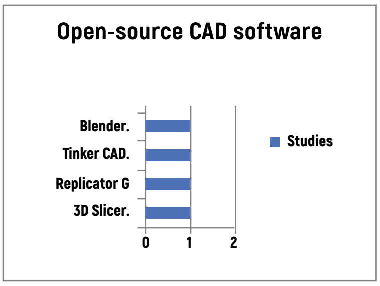

Figure 2d: Free and Open source segmentation software

Fig. 2. Background information. All parameters are expressed according to the number of studies.

Likewise, we divided the CAD software pool into 2 groups, commercial and free, and open-source. Only 10 teams have reported their use of CAD software in their 3D printing workflow [15, 24-32]. Fig. 2d and 2e show the CAD software and their frequency of use. Christiansen et al have associated two commercial CAD software in their study [26].

We also attempted to quantitatively measure the time required to process the radiological images. However, unfortunately, only 4 teams have indicated the details on the duration of their image postprocessing step: Golab et al, 2h; Wake et al, 7h; Gershman et al, 8 to 12h [24, 25, 32]. Sampogna et al have demonstrated that their first models required multiple hours which was reduced to less than an hour with the experience gained [27]. With such sparse information, any classification appeared useless.

3D printing. We exhibited the results from our analysis of the 3D printers used by the different teams. Only 16 studies communicated information concerning this parameter [15, 16, 18, 19, 22-28, 30-33]. 3 teams have indicated their 3DP models were printed with the assistance of a third-party company, 2 with 3D Systems Ltd. and 1 with Stratasys Ltd [34-36]. Fig. 3a shows the frequency of use for 3D printers. Stratasys Ltd. (USA) is the most represented brand.

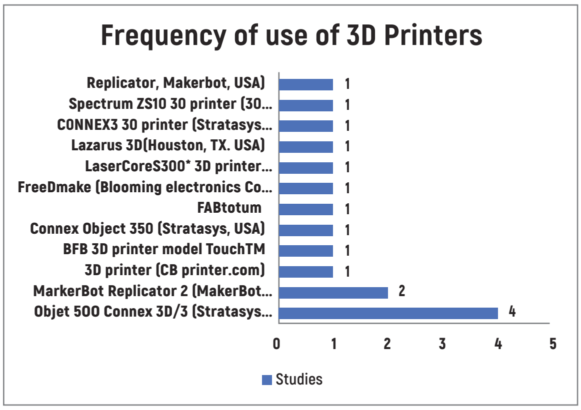

Figure 3a: 3D Printers

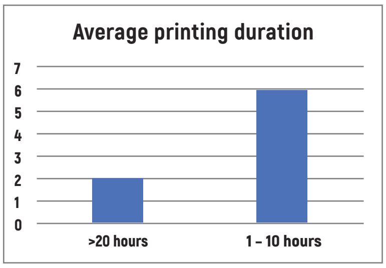

Figure 3b: Ranges of average printing duration

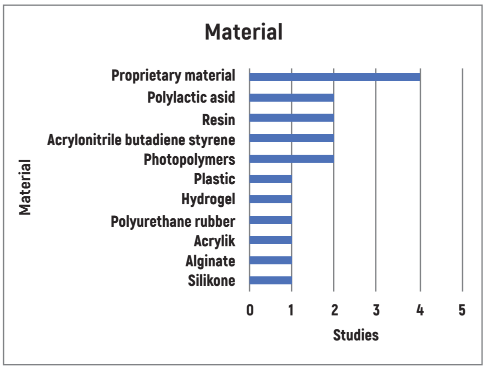

Figure 3c: Material

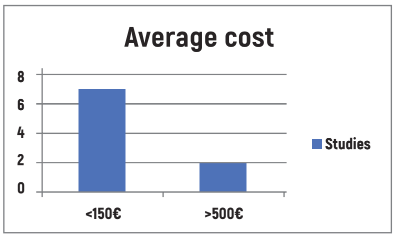

Figure 3d: Average cost

Fig. 3. Background information. All variables are displayed according to the number of studies.

Like unto image processing, we attempted to quantify the printing time. Besides, in order to classify the values of this variable, we determined ranges of time. Fig. 3b shows the average duration of the collected printing time values.

Material. Fig. 3c displays the different type of material and their frequency of utilization. Proprietary materials are the main classes employed which can complicate objective studies as the detailed composition can be inaccessible.

Cost. Only 12 studies contained information concerning the fees involved to produce their 3DP models [16, 18, 19, 21, 22, 24, 25, 30-33, 36]. Among the studies, 9 indicated the global cost. The 3 other studies have provided the following: Weng et al have indicated that each printed model cost 4$/production hour, Marconi et al have given the only cost of their printed material of 150-200€, and Turney et al have written that the "consumable" price was 9750€. No other details about this meaning were given [16, 21, 30]. Fig. 3d illustrates the ranges of cost in which we classified the different reported cost estimations. Since the limited data collection, we did not undertake any further statistical analysis as a generalization of results would be hardly reachable.

Medical Applications. Because of the restraint number of studies, we decided to divide the results according to the pathologies discussed. Most reports discussed on renal tumors and renal lithiasis. Other articles focused on renal transplantation, organ substitution, ureteropelvic junction obstruction syndrome and nuclear medicine. For clarity, we gathered common findings in Table 1.

Table 1

Benefits of 3DP models

Visual benefits of 3DP models use	Comprehension/Perception/Evaluation of normal and altered anatomy
	Visualization of location and size of the tumor, its vasculature and its spatial relationship to renal vasculature and other anatomical structures
	Assessment of NSS feasibility and preservation of healthy parenchyma
	Better localization of nephrolithiasis
Benefits of preoperative use of 3DP models	Reliable simulation of tumor excision (Prediction of tumor excision time and resected tumor volume)
	Confidence in planned strategy
	Visualization of tumor extent from different angles
	Significant reduction of blood loss during operation
	Procedures simulation
	Assessment of feasibility of planned procedures
	Helpful tool for surgical technicians and anesthesiologists
	Identifying cardinal anatomical structures
	Reduction of the operating time
	Visualization of vascular elements and their best access
Benefits of using 3DP models for team-work or decision making	Useful to choose entry points to provide best exposure
	Valuable in adjusting surgery variables
	Valuable even for experienced surgeons in complex cases
	Efficient communication tool between different specialists
	Helpful in determining the role of each member of a multidisciplinary group
Benefits of intraoperative use of 3DP models	Navigation and orientation role
	Helpful thanks to concordance between actual procedure and 3D model-based planning
	Valuable for visualization of surrounding structures, resection range
	Valuable to prevent injuries to major structures (i.e. hilum)
	Helpful to perform reconstructions
	Valuable to assess proximity to hilar vessels and collecting system
Benefits for Patients' education	Enhanced communication with physicians
	A better understanding of the disease and the surgical procedure and its related consequences
	The patient's informed consent process improvement

Adult population.

Renal tumors. As aforementioned, renal tumors represent the main area of pathologies for which urologists attempted to implement 3DP to support their surgical strategy. Therefore, we commence by analyzing the collected data on 3DP applications to manage renal cancers.

Surgery. Maddox et al have investigated the impact of 3DP models on preoperative planning of robot-assisted partial nephrectomy (RAPN) for 7 patients, by performing a surgical rehearsal and comparing their results to those contained in their RAPN database. Some differences arose: the patients included in the study had longer warm ischemia time (25 vs 21.6 min), more complex tumors (higher mean Nephrometry score), larger average tumor size, and higher pathologic stage. None of these differences were statistically significant. Those same patients showed fewer complications, fewer positive surgical margins, and shorter hospitalization, but were not significant. Only one significant difference was found: a lower estimated blood loss ($p = 0.01$) after preoperative planning with 3DP models. They have attributed the absence of differences to be likely secondary to the small cohort and limitations of the study design [**34**]. Wake et al have studied the impact of 3DP models on surgery planning and demonstrated that 3DP models led the surgeons to alter their strategy concerning the nephrectomy type (total or partial), the technical approach (open or laparoscopic procedure), the approach (transperitoneal or retroperitoneal), and the clamping. The most frequent adjustments were the approach and the clamping (30-50%). A strong concordance was observed between strategies planned with models and the actual surgical procedure. As operating surgeons had more than 12years of experience, the authors have suggested 3DP models can be helpful even for experienced surgeons [**25**]. Komai et al have reported their use of 3DP kidney models in planning minimally invasive off-clamp partial nephrectomy. Their models have been printed with a removable tumoral mass, they named this characteristic the "4D Navigation" as both surgeons and patients visualized the pre- and post-operative kidney state. They have indicated that those models help depict partial resections of important structures (i.e. vasculature, collecting system) and anticipating surgical maneuvers. They have argued that "4D Navigation" models were better than those with not-removable tumors as visualization of the tumor bed and the safety margins were possible [**28**].

Von Rundstedt et al have reported a strong similarity in tumor excision time, resected tumor volume and morphology between their patient-specific model and the actual resected tumor. They have so argued that models allowed accurate predictions of tumor resection time which can be a predicting factor for the feasibility of RAPN within a moderate ischemia time. They also have emphasized on the similar pattern of the rehearsal and the actual tumor excisions procedures [**15**]. Gershman et al have employed models for nephron-sparing surgery (NSS) and have recommended to use 3DP models only for elective complicated cases. In this context, they have indicated that models can appear very helpful to reach complete tumoral mass excision and ensure the maximal preservation of renal healthy parenchyma [**24**]. Golab et al, in two papers, have reported that using 3DP models reduced the operation time and improved patient and procedure safety [**22, 31**]. They also have indicated that their model expediated a surgical strategy approved by both cardiac and urologic surgeons [**22**] and suggested that 3DP models could serve centers not familiar with laparoscopic partial nephrectomy (LPN) [**31**].

In their study, Libby et al have printed a 3DP model of a renal carcinoma extended to the IVC, to support their management. The model depicted the localization of the tumor thrombus, which was located below the hepatic venous drainage, ensuring the surgeon that no bypass was required. They also have pointed out that the anesthesiologists also had a better understanding of the risks of the procedure thanks to the physical replica [**20**]. Zhang et al have addressed the impact of 3DP models on surgical planning in LPN by surveying experienced urologists for face and content validation of their models. The participants rated the overall usefulness, realism and usefulness in surgical planning and training with a mean score between 7 and 8 (/10). They have also reported a volume difference between the model and actual tumor specimen (the deviation was 3.4 ± 1.3 mm), potentially caused by a possible stretching of the tumor after its excision [**19**]. Porpiglia et al have tested the face and content of patient-specific 3DP models before an NSS during a congress, by surveying attending urologists. Participants highly scored (8/10) the 3DP models for their overall usefulness, their potential role in comparison to standard imaging and virtual models, their usefulness in surgical planning and their potential support in better understanding the surgical complexity. The authors have concluded that both a urologist and a radiology technician were essential to perform the manual segmentation of the renal tumor [**37**].

Education. Patients' education. Bernhard et al have specifically studied the impact of 3DP models on patients' understanding of their condition before partial nephrectomy (PN). Statistically significant improvement in their comprehension of renal basic anatomy, physiology and the surgical procedure was observed. The understanding of tumor characteristics was also enhanced without reaching statistical significance. Their overall satisfaction was also highly rated. The authors have indicated that the significative progress to understand the planned procedure illustrated the difficulty for patients to interpret CT images and the difficulty for physicians to adapt their message [**33**]. Silberstein et al have also reported that 3DP models may help patients to better understand and accept an NSS as the perception of their renal tumor characteristic is clearer [**38**]. Similarly, Porpiglia et al have reported that all patients responded favorably to the use of 3DP during the discussion with their surgeon (9-10/10) [**37**].

Medical students, residents, health professionals. Knoedler et al have investigated the impact of kidney 3DP models on medical students in characterizing renal tumors with the R.E.N.A.L. Nephrometry scoring systems. Their results showed a statistically significant improvement in students 'ability to characterize most of the properties of the renal mass in comparison to CT images alone, except for the E(Endophytic) component of the scoring system [35]. Silberstein et al have studied how 3DP models could improve trainees' understanding of renal tumors before excision. Residents demonstrated an improvement in their capacity to perceive tumor characteristics. They have reported that using translucent resins allowed them to visualize the tumor and its depth. The authors have also envisioned models being involved in the diagnosis, with percutaneous biopsies [38]. Marconi et al have explored the capacity of 3DP models to transfer anatomical knowledge by questioning medical students, expert surgeons and radiologists about some abdominal organs' anatomy, including kidneys, on 2D CT images, 3D virtual reconstructions and 3DP models. The results have shown that the number of correct answers was significantly improved by 3DP models compared with 2D scans and that participants spent less time on 3DP models than 2D scans also. The authors have also pointed out with 3DP models, radiologists marked low scores and medical students could have similar scores to theirs. The authors have hypothesized they did not have their usual landmarks or had to report anatomical details unusual for them [21]. Porpiglia et al have reported that attending participants in the congress highly rated (9-10/10) 3DP models for their potential support for patient counseling and surgical training [37].

Renal lithiasis. As only 6 studies discussed the impact of renal lithiasis management [17, 26, 30, 32, 36, 39]. Due to the heterogeneity in their endpoints and approach, we briefly expose their aims and results.

Surgery. Golab et al have performed a Percutaneous Nephrolithotomy (PCNL) using a patient-specific 3DP surgical guide (SG) for a puncture in a patient with bilateral nephrolithiasis, in a horseshoe kidney context. They have indicated that the SG reduced the time necessary to establish access (3min) to the kidney and the needle precisely reached the calculus located in the renal pelvis. The treatment was complete. They have highlighted the advantage of a printed patient-specific SG: place, angle and depth of insertion are considered altogether [32]. Christiaensen et al have compared the efficacy of five advanced imaging modalities (3DP model, 3D CAD model, a volume-rendered model on autostereoscopic 3D display, and two types of volume-rendered models on 2D screen) intraoperatively to treat a complex nephrolithiasis case (multiple stones, horseshoe kidney). Concerning the 3DP model modality, they have reported it not be advantageous during the navigation phase in the abdomen as it did not illustrate surrounding anatomical structures relevant in navigating to the kidney. But they indicated that their 3DP model to be beneficial for renal pelvis identification as it simultaneously illustrated renal pelvis and surrounding vasculature. In locating kidney stones, they only indicated that models provided some additional insights [26].

Education. Patients' education. Atalay et al have evaluated the influence of patient-specific 3DP pelvicalyceal system models on communicating information to patients before a percutaneous nephrolithotripsy. They have reported that all 5 patients included in the study demonstrated a significant improvement in their comprehension of basic kidney anatomy ($p=0.017$), lithiasis position ($p=0.02$), the planned procedure ($p=0.017$), and in understanding the potential complications related to the surgery ($p=0.015$). Their overall satisfaction with knowledge conservation have been also improved ($p=0.02$) [36].

Residents and experienced physicians. Atalay et al have assessed the impact of pelvicalyceal models on residents' understanding of pelvicalyceal anatomy before the actual PCNL procedure, for 5 patients with complex unilateral nephrolithiasis. The residents were tasked to identify landmarks (number of anterior and posterior calyces, stones locations, most adequate calix entry access) first based on CT images only and then, using patient-specific models. The results have shown a statistically significant improvement in each one of these studied items, after the models' presentation. Participants considered models beneficial for procedures planning and agreed on their potential training support for complex interventions, combined with 2D images. According to the authors, the collaboration between urologists, radiologists and bioengineers was the crucial step for model creation [39]. Ghazi et al have validated an immersive simulation platform for PCNL. The Face, Content and Construct validation was performed by 15 participants, urologists and interventional radiologists (5 experts and 10 novices) who carried out all steps of a full-immersion simulation PCNL procedure in a hybrid operating room. Face (realism) and content (educational effectiveness) validity were both considered excellent by the participants. Construct validity has been also considered as 'very good' [17]. Turney et al have created a 3DP model of a collecting system to practice PCNL access. They have indicated the model facilitated the identification of posterior and anterior calyxes and perception of their spatial orientation to renal pelvis when planning access. They also declared that a limited number of punctures (+-20) could be performed on the model without any leakage of contrast. They suggested that such a custom-model training platform could be useful for planning complex procedures and be implemented in the training program [30].

Renal transplantation. Kusaka et al have reported their use of 3DP models for renal transplantation. They have highlighted the enhanced perception of the spatial relationship between anatomic structures and the ability to accurately perform procedure rehearsals. They have also pointed out the supportive role of models with surgical planning, as surgeons shared an identical understanding of anatomy, and in obtaining informed consent. Among the limits, they have indicated costs, imaging resolution and production time [29].

Kidneys replacement. Weng et al have used 3DP generic models to replace harvested organs in a deceased young adult due to cultural customs about body integrity. This solution helped the young adult's parents accept organ harvesting [16].

Nuclear medicine. Dullius et al have reported their production of both static and dynamic renal phantoms able to simulate normal renal function. The constructs demonstrated similar results for renal scintigraphy with 99mTc-DMSA to those of normal kidneys and renal obstruction context. They envisioned their use in clinical training for renal anomalies diagnose [23].

Pediatric population.

Only 2 articles have discussed pediatric topics, the first one is a case report and the second one is an educational report.

Renal tumor. Giron-Vallejo et al have reported the use of 3DP models to support their management of a bilateral Wilms tumor in a 10-month-old infant [40]. They have explained their models depicted remaining healthy tissue which caused to alter their surgical strategy: performing a bilateral NSS instead of a left total nephrectomy and a right NSS based on 2D imaging alone. Also, they have indicated the model was a useful tool to communicate with the family and between the pediatric radiologist and surgeon. As limitations, they have reported the poor support for vascular dissection as meager vascular information was extracted from the imaging data. They have suggested future studies to assess the impact of 3DP renal tumor models on surgical procedures improvement and pediatric oncologic outcomes, and their capacity to facilitate the anticipations of frequent complications in NSS [40].

Ureteropelvic junction obstruction. Cheung et al have employed 3DP models to develop a low-cost pediatric pyeloplasty simulator platform. They tested the simulator with 24 pediatric urology fellows(novices) and 3 faculty members for a training course. Participants have been performed a right-side laparoscopic pyeloplasty on the model and a 5-0 VICRYL suture in 60 minutes. The model has consisted of a kidney, a replaceable dilated renal pelvis and a ureter with an obstructed ureteropelvic junction (UPJ), and an overlying peritoneum. The participants assigned a mean score (out of 5) between 3 and 4 for: Esthetic, Peritoneum, UPJ and Usability (use for personal skills training and teaching). Only the Overall feel criteria was score 2.82. The participants have reported the following limitations: the UPJ was easily torn, and the inaccurate wall thickness and the feature size were not realistic due to the printing material used. The authors have highlighted some advantages of 3DP in education: specific organ courses, simulation of multiple clinical situations, training with other specialties. They have envisioned to apply the same technology for other procedures, to make left-sided training possible, and to assess patients' outcome and surgical variables to develop a more solid validation of their teaching model [18].

Discussion. We attempted to highlight how 3DP might have impacted patients' outcomes and physicians' efficiency in urology so far. The results are encouraging since 3DP models were reported to be beneficial in each main reported studied field (surgery, education, ...) and in both adult and pediatric patients. In surgery, 3DP models provided operators with valuable spatial and tactile additional information on anatomic structures of interest, they seemed to improve procedures' efficiency and they facilitated multi-disciplinary decisions. In education, 3DP models tended to support patients' understanding of their respective conditions and the related procedures and risks; 3DP constructs appeared to be an aid for teaching medical students and training residents and confirmed physicians. Surgery and education are the two main fields explored, in other areas 3DP models were also reported to be beneficial for clinical incorporation. We highlighted some topics considered pertinent to the discussion.

First, in urology, CT and MRI are the sources of the most represented images as illustrated in Fig 1a. No teams indicated any issue about these modalities or any use of 3D US-derived kidney 3DP models. The relative recent incorporation of 3DP printing in nephrology can explain the absence of comments related to image data sources and their limits or unexplored potential. Also, urological teams involved in 3D printing might have directly worked on limitations reported by more experienced teams in other medical fields, reducing their learning curve with 3DP.

Second, segmentation is an operator-dependent process in which precision depends on the operator's knowledge of anatomy, his understanding of specialists' clinical demands, and his mastering of segmentation software. To this end, 2 studies involved a bioengineer to perform the image post-processing and 3DP [36, 37]. As the participation of a bioengineer to produce models was not systematic and as other teams expressed satisfaction with their models, we can cautiously argue that bioengineers, despite their knowledge of IT tools, can be replaced by other categories of operators. Radiologists seem to be the most appropriate to take the vacant seat. Indeed, they routinely process imaging data, possess anatomy and clinical knowledge and are used to collaborate with specialists and their specific terminology [2, 11]. With such a strong background, which bioengineers usually don't master at first, radiologists should not let this new technology escape. Some other teams relied on third-party companies for either or both segmentation and printing steps [2, 34, 35, 38]. This attitude might require financial resources that are not available to all. As the clinical incorporation of 3DP becomes more frequent and the printing stages are more standardized, we envision physicians (except radiologists) developing imaging post-processing skills. Such operators might involve fewer costs for the institution.

Third, as displayed in Fig 1b and 1d, Mimics (Materialize, Belgium), a commercial software, is the most used one to segment imaging data. Despite precise models produced with this software, comparative studies, including the main imaging processing software, are mandatory to objectively evaluate the efficiency-cost balance of that software. Hence, research and clinical groups, especially those discovering this technology, would determine the most appropriate segmentation software to answer their local needs, based on their resources. especially novices with this technology.

As demonstrated in Fig 2a, many different printers have been used. Comparison studies, like those discussed above for segmentation software, assessing the quality-costs balance of printers are also required to support teams in their 3D printers selection and avoid unnecessary use of various printers for identical purposes. Material selection is crucial as it impacts both the cost and potential use of a printed model [6]. As no standardization exist, different categories of material can be used to print 3DP models. Objective studies assessing the frontier between constructs produced with basic material and those made with high-quality, and potentially expensive, materials are mandatory. Indeed, such studies can guide inexperienced teams in their selection of an appropriate material. Standardization of methods might be beneficial in reaching the best balance between the accuracy required and the cost, according to patients' condition complexity.

Fourth, as indicated in the 'Image processing' section and in Fig 2b, images post-processing and printing process can be cumbersome steps and represent a limitation for the incorporation of 3DP models in clinical routine [3]. A solution to this problem could be a dedicated person which could involve additional fees. As the technology evolves, steps might become automated reducing the duration of the whole process. Indeed, Sampogna et al indicated that they reduced their image processing time by acquiring radiological images with good quality and by using established segmentation protocol [27]. Similarly, Marconi et al reduced their image processing duration thanks to a solid image acquisition protocol [21].

All case reports involved pre-procedural constructs and only 1 study created a post-procedural model [24]. As imaging technology evolves, we might explore the possibility to print 2 pre-procedural models: one that is a replica of the anatomy of interest and a second one illustrating the post-repair anatomy. Such post-operative models could guide the operative surgeon during the preoperative planning and the actual procedure as a physical visualization of the defined endpoint is available. Moreover, as surgical rehearsals are feasible on models, depending on their material properties, the perspective suggested can enhance the clinical experience of 3DP [3]. Komai et al proposed a similar option: they printed a kidney model with a removable tumor which they called '4D navigation'. This concept, which seems suited for tumoral mass, can be hardly applicable to all types of structural diseases. This possibility should be explored [28].

Fifth, a few studies demonstrated that 3DP models were more beneficial for patients 'education than conventional 2D imaging [28, 33, 36]. Larger scale studies should be undertaken to validate 3DP models as reliable communications tools. Such objective validation could support its clinical incorporation. The use of generic models should be compared to patient-specific models to highlight any difference in knowledge acquisition and retention, as generic models would involve fewer costs.

Knoedler et al have demonstrated the positive impact of 3DP models on the knowledge acquisition of medical students [35]. We envision anatomical 3DP models associated with conventional anatomy teaching to support students' learning process as physical replicas can be easily manipulated and even be brought home.

Atalay et al have highlighted the added-value of 3DP replicas for residents in urology as the simulation of clinical situations increases their confidence in their management skills [39]. 3DP offers an opportunity for clinical supervisors to teach residents in a very concrete manner the management of both frequent and rare conditions. Research groups could be created with the only purpose to promote and to develop skills training by involving 3D printing technology, like the Center for Research in Educational and Simulation Technologies (CREST) in endourology [41].

Finally, we gathered the main limitations encountered by the different teams in Table 2.

Table 2

Reported limits of 3DP models use

High cost
Small cohorts
Time-consuming technology
No assessment of 3D model impact on renal function preservation
No objective assessment of 3DP model role as a teaching tool
No objective assessment of patient counseling improvement
No objective evaluation of 3D model impact on patients' understanding of disease and therapeutic plan
Retrospective studies

Table 2 continuation

No simulation possible due to the hard plastics material.
Lack of perinephric fat and realistic blood supply
Lacking renal vasculature and collecting system details
Only certain aspect of procedures suitable for simulation
Potential segmentation difficulties in endophytic tumours

The cost was marked as a limiting factor. As Gershman et al indicated only some elective cases should be managed with 3DP models, we envision criteria to determine eligible cases for which 3DP models could improve management efficiency and potentially patients’ outcome [24]. These criteria could be established by experts, who would be experimented physicians accustomed to 3DP, and would consider local experience, disease gravity and patient’s financial resources. Such standardization would allow better control of fees. As we discuss the cases eligibility, digital 3D reconstruction strength should also be considered and investigated. Christiansen et al have reported that a virtual 3D virtual model provided more important spatial information compared with other imaging modalities, 3DP models included, in treating complex kidney stones [26]. Establishing an objective frontier between 3D virtual models and the requirement of 3DP models is essential as time and money could be spared.

Study limitation. The present study is also not without limitation. Unfortunately, our review of the literature was not strengthened by any thorough statistical analysis due to the very restraint amount of available data and to their heterogeneity in terms of strength and settings. However, despite this valuable limitation, we attempted to illustrate our findings in a way that concerned physicians can easily capture what 3DP has to offer for renal disease management. We demonstrated its contribution to custom-made and personalized treatments for both pediatric and adult patients, and we showed how its use aided residents and confirmed physicians in improving their clinical efficiency.

Future perspectives. The attempt to integrate 3DP in nephrology and urology is relatively recent. We gathered the main suggestions for further developments in Table 3.

Table 3

Future perspectives for 3DP models use

Objective validation of 3D printing impact on clinical routine by randomization
Objective assessment of 3D printing role in urological surgery
Objective assessment of 3D printing role in improving procedures performance
Objective assessment of the impact on patients’ understanding and patients’ outcomes
Objective validation of 3D model-based surgery training for residents
Larger case-control studies
Automated image segmentation
Refining image processing to increase delineation quality and resolution
Replacing high-quality and expensive 3D printers by low-cost printers
Use of materials mimicking human tissue facilitating procedures rehearsal

Larger scale studies are mandatory to validate 3DP models as clinical tools to facilitate disease management as well as educational tools for patients, medical trainees and experienced physicians [1]. Clear and well-defined segmentation and printing process protocols could reduce the duration and cost of the whole process and facilitate the clinical incorporation of 3DP [21, 27]. As virtual models can be exported as digital files, we envision virtual platforms that would facilitate sharing of those files and through them, advice and experience, like the National Institutes of Health 3D Print Exchange repository [11].

Conclusions. In the present study, we attempted to depict the actual clinical incorporation of 3D printing in urology. We exposed its reported impact in surgery, education and other fields. Objective validation, cost-quality balance and educational applications are some of the fields to investigate to facilitate the promotion of clinical incorporation of 3D-printed models. 3D-printed models of renal structures are possible and can aid and support disease management. Further studies are mandatory to validate their clinical relevance.

Conflict of Interest Statement. The authors have no conflicts of interest to declare.

Funding Statement. No funding received.

Authors' contributions. Both K.W. and R.O. contributed to the design and implementation of the research, to the analysis of the results and the writing of the manuscript.

References:

1. *Manning TG, O'Brien JS, Christidis D, Perera M, Coles-Black J, Chuen J, Bolton DM, Lawrentschuk N.* Three dimensional models in uro-oncology: a future built with additive fabrication. World J Urol. 2018;36(4):557-563. doi: 10.1007/s00345-018-2201-2.
2. *Marro A, Bandukwala T, Mak W.* Three-Dimensional Printing and Medical Imaging: A Review of the Methods and Applications. Curr Probl Diagn Radiol. 2016;45(1):2-9. doi:10.1067/j.cpradiol.2015.07.009
3. *Wake N, Chandarana H, Huang WC, Taneja SS, Rosenkrantz AB.* Application of anatomically accurate, patient-specific 3D printed models from MRI data in urological oncology. Clin Radiol. 2016;71(6):610-614. doi:10.1016/j.crad.2016.02.012.
4. *Colaco M, Igel DA, Atala A.* The potential of 3D printing in urological research and patient care. Nature Reviews Urology. 2018;15(4):213-21. doi: 10.1038/nrurol.2018.6
5. *Li C, Cheung TF, Fan VC, Sin KM, Wong CW, Leung GK.* Applications of Three-Dimensional Printing in Surgery. Surg Innov. 2017;24(1):82-88. doi:10.1177/1553350616681889
6. *Kim GB, Lee S, Kim H, Yang DH, Kim YH, Kyung YS, et al.* Three-Dimensional Printing: Basic Principles and Applications in Medicine and Radiology. Korean journal of radiology.17(2):182-97. doi: 10.3348/kjr.2016.17.2.182
7. *Özgür BC, Ayyıldız A.* 3D printing in urology: Is it really promising? Turkish Journal of Urology. 2018;44(1):6-9. doi: 10.5152/tud.2018.20856
8. *Powers MK, Lee BR, Silberstein J.* Three-dimensional printing of surgical anatomy. Current Opinion in Urology. 2016;26(3):283-8. doi: 10.1097/MOU.0000000000000274
9. *Youssef RF, Spradling K, Yoon R, et al.* Applications of three-dimensional printing technology in urological practice. BJU Int. 2015;116(5):697-702. doi:10.1111/bju.13183
10. *Westerman ME, Matsumoto JM, Morris JM, Leibovich BC.* Three-dimensional Printing for Renal Cancer and Surgical Planning. European Urology Focus. 2016;2(6):574-6. doi: 10.1016/j.euf.2016.12.009
11. *Ballard DH, Trace AP, Ali S, Hodgdon T, Zygmont ME, DeBenedectis CM, et al.* Clinical Applications of 3D Printing: Primer for Radiologists. Academic Radiology. 2018;25(1):52-65. doi: 10.1016/j.acra.2017.08.004
12. *Higgins JPT GSe.* Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0 [updated March 2011]. The Cochrane Collaboration, 2011. Available from https://handbook-5-1.cochrane.org.
13. *Dissemination. CfRa.* Systematic reviews: CRD's guidance for undertaking reviews in health care. Centre for Reviews and Dissemination; Layerthorpe, York, UK: 2009. 978-1-900640-47-3. http://www.york.ac.uk/inst/crd/pdf/Systematic_Reviews.pdf.
14. *Moher D, Liberati A, Tetzlaff J, Altman DG;* PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7):e1000097. doi:10.1371/journal.pmed.1000097
15. *von Rundstedt FC, Scovell JM, Agrawal S, Zaneveld J, Link RE.* Utility of patient-specific silicone renal models for planning and rehearsal of complex tumour resections prior to robot-assisted laparoscopic partial nephrectomy. BJU Int. 2017;119(4):598-604. doi:10.1111/bju.13712
16. *Weng JY, Wang CC, Chen PJ, Lim SW, Kuo JR.* The Application of a Three-Dimensional Printed Product to Fill the Space After Organ Removal. World Neurosurg. 2017;107:1045.e17-1045.e19. doi:10.1016/j.wneu.2017.07.149
17. *Ghazi A, Campbell T, Melnyk R, Feng C, Andrusco A, Stone J, Erturk E.* Validation of a Full-Immersion Simulation Platform for Percutaneous Nephrolithotomy Using Three-Dimensional Printing Technology. J Endourol. 2017 Dec;31(12):1314-1320. doi: 10.1089/end.2017.0366
18. *Cheung CL, Looi T, Lendvay TS, Drake JM, Farhat WA.* Use of 3-dimensional printing technology and silicone modeling in surgical simulation: Development and face validation in pediatric laparoscopic pyeloplasty. Journal of Surgical Education. 2014;71(5):762-7. doi: 10.1016/j.jsurg.2014.03.001

19. *Zhang Y, Ge HW, Li NC, Yu CF, Guo HF, Jin SH, et al.* Evaluation of three-dimensional printing for laparoscopic partial nephrectomy of renal tumors: a preliminary report. World Journal of Urology. 2016;34(4):533-7. doi: 10.1007/s00345-015-1530-7

20. *Libby RS, Silberstein JL.* Physical Model of Clear-Cell Renal Carcinoma With Inferior Vena Cava Extension Created From a 3-Dimensional Printer to Aid in Surgical Resection: A Case Report. Clin Genitourin Cancer. 2017;15(5):e867-e869. doi:10.1016/j.clgc.2017.04.025

21. *Marconi S, Pugliese L, Botti M, Peri A, Cavazzi E, Latteri S, et al.* Value of 3D printing for the comprehension of surgical anatomy. Surgical Endoscopy and Other Interventional Techniques. 2017;31(10):4102-10.

22. *Golab A, Slojewski M, Brykczynski M, Lukowiak M, Boehlke M, Matias D, et al.* Three-Dimensional Printing as an Interdisciplinary Communication Tool: Preparing for Removal of a Giant Renal Tumor and Atrium Neoplastic Mass. The heart surgery forum. 2016;19(4):E185-E6. doi: 10.1532/hsf.1500

23. *Dullius M, Fonseca M, Botelho M, Cunha C, Souza D,* editors. Three new renal simulators for use in nuclear medicine. EPJ Web of Conferences. 2014;66: 11010. doi: 10.1051/epjconf/20146611010

24. *Gershman B, Psutka SP, Matsumoto JM, King BF, Kawashima A, Morris JM, et al.* Use of Personalized Printed 3-Dimensional Kidney Models for Simulation before Nephron Sparing Surgery: Methodology and Examples from a Case Series. Urology Practice. 2016;3(2):124-33. doi: 10.1016/j.urpr.2015.05.008

25. *Wake N, Rude T, Kang SK, Stifelman MD, Borin JF, Sodickson DK, et al.* 3D printed renal cancer models derived from MRI data: application in pre-surgical planning. Abdominal Radiology. 2017;42(5):1501-9. doi: 10.1007/s00261-016-1022-2

26. *Christiansen AR, Shorti RM, Smith CD, Prows WC, Bishoff JT.* Intraoperative utilization of advanced imaging modalities in a complex kidney stone case: a pilot case study. World Journal of Urology. 2018;36(5):733-43. doi: 10.1007/s00345-018-2260-4

27. *Sampogna G, Pugliese R, Elli M, Vanzulli A, Forgione A.* Routine clinical application of virtual reality in abdominal surgery. Minimally Invasive Therapy and Allied Technologies. 2017;26(3):135-43. doi: 10.1080/13645706.2016.1275016

28. *Komai Y, Sugimoto M, Gotohda N, Matsubara N, Kobayashi T, Sakai Y, et al.* Patient-specific 3-dimensional Printed Kidney Designed for 4D Surgical Navigation: A Novel Aid to Facilitate Minimally Invasive Off-clamp Partial Nephrectomy in Complex Tumor Cases. Urology. 2016;91:226-32. doi: 10.1016/j.urology.2015.11.060

29. *Kusaka M, Sugimoto M, Fukami N, Sasaki H, Takenaka M, Anraku T, et al.* Initial experience with a tailor-made simulation and navigation program using a 3-D printer model of kidney transplantation surgery. Transplantation Proceedings. 2015;47(3):596-9. doi: 10.1016/j.transproceed.2014.12.045

30. *Turney BW.* A new model with an anatomically accurate human renal collecting system for training in fluoroscopy-guided percutaneous nephrolithotomy access. Journal of Endourology. 2014;28(3):360-3. doi: 10.1089/end.2013.0616

31. *Golab A, Smektala T, Kaczmarek K, Stamirowski R, Hrab M, Slojewski M.* Laparoscopic Partial Nephrectomy Supported by Training Involving Personalized Silicone Replica Poured in Three-Dimensional Printed Casting Mold. Journal of Laparoendoscopic and Advanced Surgical Techniques. 2017;27(4):420-2. doi: 10.1089/lap.2016.0596

32. *Golab A, Smektala T, Krolikowski M, Slojewski M.* Percutaneous Nephrolithotomy Using an Individual 3-Dimensionally Printed Surgical Guide. Urologia Internationalis. 2016. doi: 10.1159/000446291

33. *Bernhard JC, Isotani S, Matsugasumi T, Duddalwar V, Hung AJ, Suer E, et al.* Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education. World Journal of Urology. 2016;34(3):337-45. doi: 10.1007/s00345-015-1632-2

34. *Maddox MM, Feibus A, Liu J, Wang J, Thomas R, Silberstein JL.* 3D-printed soft-tissue physical models of renal malignancies for individualized surgical simulation: a feasibility study. Journal of Robotic Surgery. 2018;12(1):27-33. doi: 10.1007/s11701-017-0680-6

35. *Knoedler M, Feibus AH, Lange A, Maddox MM, Ledet E, Thomas R, et al.* Individualized physical 3-dimensional kidney tumor models constructed from 3-dimensional printers result in improved trainee anatomic understanding. Urology. 2015;85(6):1257-61. doi: 10.1016/j.urology.2015.02.053

36. *Atalay HA, Canat HL, Ülker V, Alkan I, Özkuvanci Ü, Altunrende F.* Impact of personalized three-dimensional (3D) printed pelvicalyceal system models on patient information in percutaneous nephrolithotripsy surgery: A pilot study. International Braz J Urol. 2017;43(3):470-5. doi: 10.1590/S1677-5538.IBJU.2016.0441

37. *Porpiglia F, Bertolo R, Checcucci E, Amparore D, Autorino R, Dasgupta P, et al.* Development and validation of 3D printed virtual models for robot-assisted radical prostatectomy and partial nephrectomy: urologists' and patients' perception. World Journal of Urology. 2018;36(2):201-7. doi: 10.1007/s00345-017-2126-1

38. *Silberstein JL, Maddox MM, Dorsey P, Feibus A, Thomas R, Lee BR.* Physical models of renal malignancies using standard cross-sectional imaging and 3-dimensional printers: A pilot study. Urology. 2014;84(2):268-72. doi: 10.1016/j.urology.2014.03.042

39. *Atalay HA, Ülker V, Alkan U, Canat HL, zkuvancl U, Altunrende F.* Impact of Three-Dimensional Printed Pelvicaliceal System Models on Residents' Understanding of Pelvicaliceal System Anatomy before Percutaneous Nephrolithotripsy Surgery: A Pilot Study. Journal of Endourology. 2016;30(10):1132-7. doi: 10.1089/end.2016.0307

40. *Girón-Vallejo Ó, García-Calderón D, Ruiz-Pruneda R, Cabello-Laureano R, Doménech-Abellán E, Fuster-Soler JL, et al.* Three-dimensional printed model of bilateral Wilms tumor: A useful tool for planning nephron sparing surgery. Pediatric Blood and Cancer. 2018;65(4):PDF. doi: 10.1002/pbc.26894

41. *Sweet RM.* The CREST Simulation Development Process: Training the Next Generation. J Endourol. 2017;31(S1):S69-S75. doi:10.1089/end.2016.0613