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Full title: Realization of open software chain for 3D modeling and printing of organs in simulation centers: example of renal pelvis reconstruction

Short title: 3D modeling and printing of a dissectible renal apparatus in surgical simulation

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Abstract

Objective: Three-dimensional (3D) printing has many uses in healthcare such as in surgical training. It is becoming an interesting tool finding new pedagogical purposes in medical simulation. In this study, using a process consisting of 3D modeling, a simulator dedicated to pyeloplasty was designed, manufactured, and evaluated by experts.

Design: With the aid of open-source software and CAD software, 3D models of a renal parenchyma, a renal pelvis and an ureter were created. This renal apparatus was processed and crafted with additive manufacturing using soft polymer materials. Polyvinyl alcohol material was used to print the components in order to make them dissectible and to evaluate their use in surgical teaching.

Setting and participants: Seven expert surgeons evaluated the model by performing a pyeloplasty sequence established in a previous work. An evaluation grid with eight items related to surgical movement was rated on a 5 point Likert scale to assess how similar working with the model was to actual surgery.

Results: 3 items were rated with a score greater than or equal to 4 (Needle penetration, Thread-sliding, Cutting Strength). Suture strength was rated with a score above 3.5 for both renal pelvis and ureter, whereas elasticity was rated below 3. Handling and mobility properties were rated above 3 for the renal pelvis and below 3 for the ureter. The cost of the unit was \$0.30 per renal unit. The primary difference identified was a difference in elongation between polyvinyl alcohol material and real biological tissue.

Conclusions: It is feasible to generate and print a low cost upper urinary tract model from patient data imagery using environmentally friendly products that can be used effectively in surgical training. The simulator has been able to reproduce sensations related to surgical movements for a low cost. Hereafter, research into the pedagogical benefits provided to students, and through them, patients,

should be performed. 3D printing models can offer new opportunities for healthcare simulation specific to different surgical fields.

Keywords: Additive manufacturing; Medical education; Surgery; simulation ; Urological surgery; Laparoscopy

Competencies: Practice-Based Learning and Improvement, Patient Care,

Introduction

Simulation in healthcare has progressively become a major tool in the training of healthcare providers. Following recent national guidelines, academic institutions have invested in tools and manpower for the broad implementation of simulations in medical education, with the principle of “First, do no harm”,^{1,2}. Medical academic simulation centers have been developed as a priority for different targeted populations, such as undergraduate medical students, trainees, and continuous professional development for trained specialists.

This evolution benefits surgery, where the ethical and financial considerations of teaching on animal and human cadavers are significant^{3,4}, and the time required to learn in the operating room decreases^{1,5}. In procedures such as laparoscopic pyeloplasty in infants and children, the complexity of learning curve is mainly due to difficulties to acquire the skill of suturing. To overcome such difficulties, the trainees have to follow a long learning curve in the operating room leading to limitation to expand minimal invasive surgery to large number of trainees. It is already well documented that preparing trainees prior to operating room is critical to decrease the slope of the surgical learning curve⁶.

Dry-lab workshops using organ models made of plastics are increasingly considered as an alternative to the biological organs in several fields of surgery as a way to supplement actual training in the operating room⁷⁻¹⁰. However, the economic constraints involved in making these workshops available to as many learners as possible, should not take precedence over the pedagogical goal identified by teachers¹¹.

Financial and ethical constraints have been key factors in exploring the educational possibilities of three-dimensional printing (3DP)¹²⁻¹⁵. New improvements arising from the generalization of 3D modeling based on medical imaging data and 3DP may reduce such limitations, allowing professionals to directly print anatomical organs in a repeatable fashion at lower costs^{11,16} without additional tools such as molds, which requires advanced technical skills.¹⁷⁻²⁰

In this study the aim was twofold: primarily to design and print a low-cost, environmental friendly simulator depicting the upper urinary tract with abnormal anatomical variants requiring complex

surgical procedure as pyeloplasty and secondly to evaluate by experts its similarities to actual surgical procedure in humans.

Material and methods

1. Manufacturing process

To match pedagogical purposes, the model of training was designed in two parts: the first part is the parenchyma (non-flexible and non-suturable), the second part is the pelvi-ureteral part comprised of the renal pelvis, the pelvi-ureteric junction and the ureter (RP -U). This RP-U part has to be flexible and suturable.

The presented process enabled the prototypes to be manufactured on the basis of virtual models from imaging or CAD (computer-aided design) data, using appropriate materials with a 3D printer (Fig. 1).

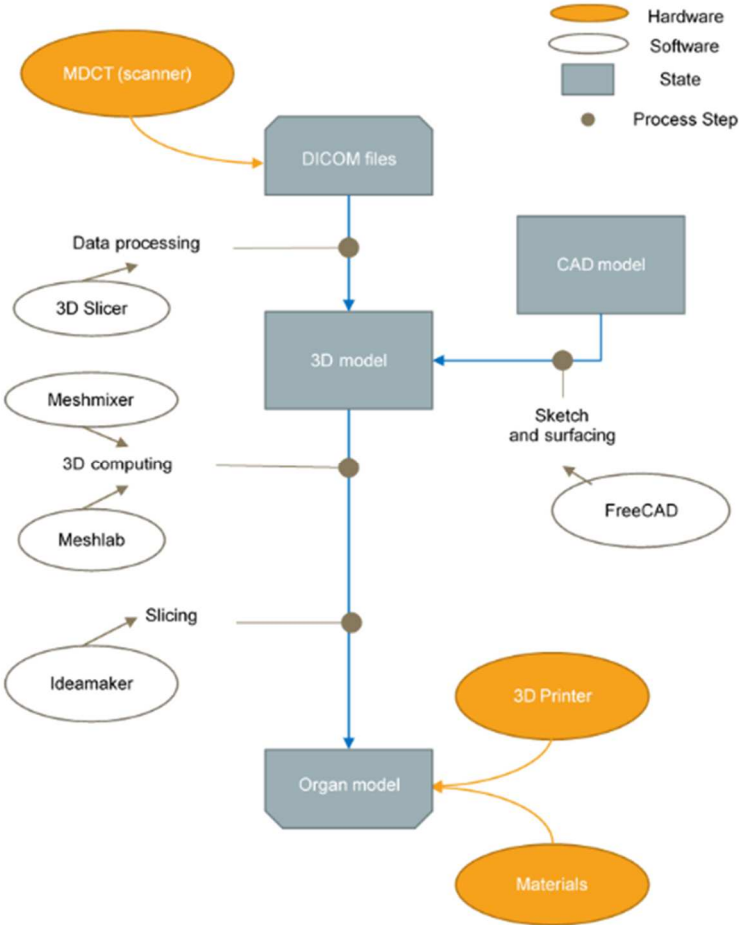


Fig 1. Workflow summary of modelization process

To create an accurate virtual model, priority was given to the quality and resolution of the radiological images. The body was sliced and encoded in the digital images and communications in medicine (DICOM) file format following data anonymization. These data were provided by the Centre de Cardiologie du Nord (Saint Denis, France). The experimental protocol conformed to the requirements of declaration of Helsinki. It was approved by the local ethics committee of Centre Cardiologique du Nord and all patients provided informed consent in written form.

Having identified the organ cluster, segmentation was carried out to extract the area of interest (Fig. 2).

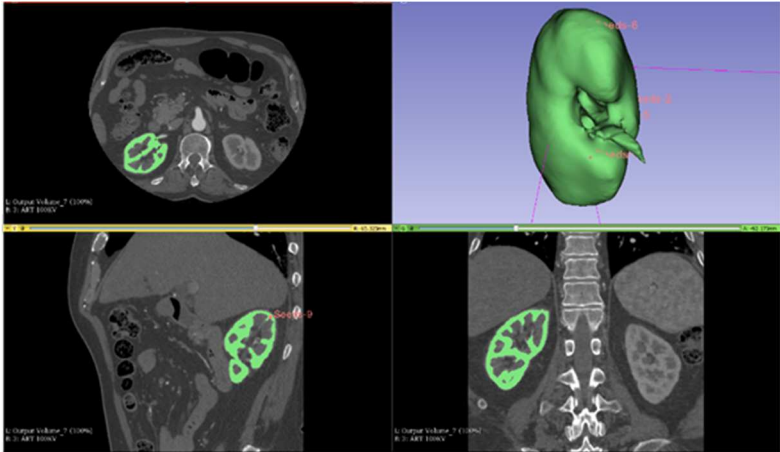


Fig 2. Segmentation of nephron using 3DSlicer region growing module

The nephron is materialized by the green pixel area.

In cases where the imagery data could not provide a model with the expected specifications regarding the pedagogical purposes and the desired pathological anatomy, CAD software provided an alternative to create custom parts for the RP-U component of our model (Fig.3). The steps of the process and associated software used are extensively described in appendix A.

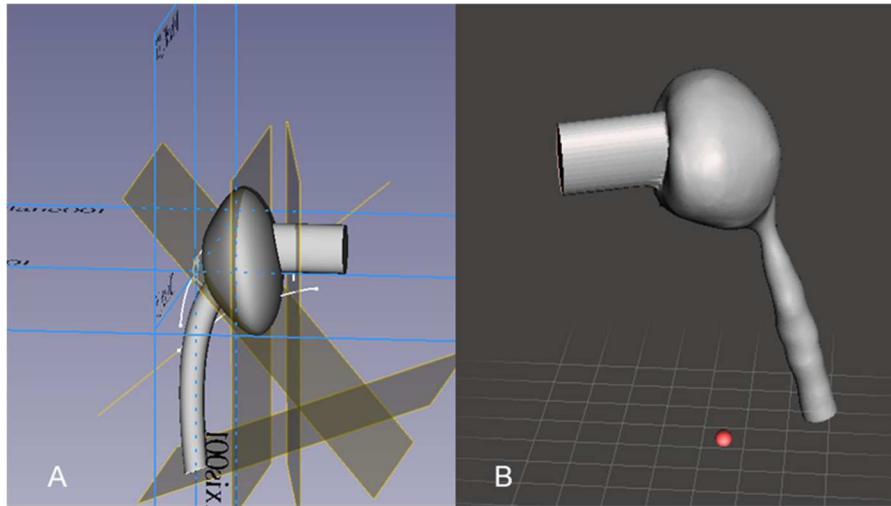


Fig.3 CAD construction of the ureter (A) Custom-made ureter and renal pelvis; (B) post-processing of CAD file

The final computing step was to slice the 3D model into movements to be executed by the printing machine to create the parts. Similar to the imagery slices, the 3D models were split once again, this time according to the thickness of a layer. The stacking of layer thicknesses materializes the volume¹³. The overall sequence of movements executed by the extruder was encoded in a G-CODE file.

For prototyping of the model of the upper urinary tract, two additive manufacturing machines helped with the embedded material extrusion process²¹. The printers Raise N2 dual plus (Raise 3D, CHINA) and Lynxter S600D (Lynxter, Bayonne, FRANCE) can extrude respectively two and three materials, alternatively, during the same printing run, with brass extrusion nozzles of 0.4 millimeters in diameter. The main printing parameters related to slicing and printing are described in appendix B.

The printing materials were selected in accordance with their availability on the market and the environmental policy of the building of the Ilumens Paris Diderot Simulation Centre. The material for printing had to be at least recyclable but preferably biodegradable. According to the application, thermoplastic urethane (TPU), which is recyclable, and polyvinyl alcohol (PVA), a hydro-soluble soft polymer, were chosen to craft the parenchyma and the ureter, respectively. Strategic points for attention included the realistic sensitive (haptic) feedback when handling and interacting with the

model. The hydro sensitivity of PVA met this demand and allowed for flexibility of the RP-U after a post-treatment which consisted of immersing them for 30 seconds in a 40°C water bath immediately followed by 10 seconds in a 99% ethanol bath. No hard chemicals were used for the post-treatment of the printed parts or to clean the machines.

2. Validity of the model

The medical and pedagogical values of the simulator have to be demonstrated with strong evidence at different levels^{22,23}. Following Messick's framework of validity, a first step was to clearly outline the pedagogical aims to reach by the student regarding the different surgeons' requests²⁴. Interviews brought to light a range of skills to evaluate, following previous work done related to the objective structured assessment of technical skill (OSATS) rating scale about suture²⁵. These elements were considered during the drafting of simulator specifications.

A first survey was committed to verify the face validity, in other words, the ability of the model to provide sensations close to what is normally experienced in the operating room. We used a grid of seven items on a 5-point Likert scale that was completed anonymously by the surgeons. They were encouraged to fill in the comment section attached. The evaluation items were defined on the cutting, stitching, and ease of handling. The model elasticity as its global behavior exposed to intensive handling were also evaluated. A score greater than or equal to 4 suggested a fidelity suitable to mimic the real conditions of surgery. Each participant had at his disposal three models to evaluate.

The procedure was performed using laparoscopic instruments, FLS trainer system (Limb & Things, USA) and Surgipro 6-0 – 70 cm suture on a CV-11 needle. None of the participating surgeons had previously tested the model.

The post-treatment was performed one hour before surgical evaluation. The RP-U was plugged into the parenchyma using adhesive gum (Fig. 6C). The assembly was set up inside the laparoscopic trainer using springs of undetermined stiffnesses (Fig. 6A-6B) to mimic the natural kidney movements. Experts did not have a limited time to carry out the simulation of the pyeloplasty.

Results

Based on the described methods, a batch of five parts depicting the renal parenchyma and thirty parts depicting the RP-U were generated for evaluation. 10 RP-U were produced using Lynxter S600D and 20 using Raise N2 Dual Plus. Renal parenchyma were produced using Raise N2 Dual Plus. The time of production is around 1hour 30 minutes for the RP-U and around 30 hours for a parenchyma.

Thanks to data from the slicer giving the weight of material used per piece and the cost of the raw material, the cost of the RP-U unit was estimated \$0.30 per renal unit. The standalone renal parenchyma was a little over \$5. (Table 1)

	Support material (PVA)	Flexible material
1 kg	75€/83.25\$	45€/51.45\$
Parenchyma	2.05€/2.34\$	3.06€/3.50\$
Renal pelvis - Ureter	0.28€/0.31\$	-

Table 1. Costing of filament materials for each model printed

(kg : Kilogram, PVA : Polyvinyl alcohol)

All surgeons performed the simulated laparoscopic pyeloplasty intervention on the model in less than an hour. Steps were defined and standardized: resection of the pelvi-ureteric junction, spatulation of the ureter, pelvi-ureteric anastomosis. All surgeons were able to complete the required surgical procedure. Surgical rating was separated according to the anatomic area between the renal pelvis and the ureter. Results of these ratings is shown in Figure 7. Three items of the content categories obtained a score greater than or equal to four points for both of the anatomic regions (A, B and D).

Little difference was seen between the renal pelvis area and ureter area on most of the items except for the elasticity (E). This item had also the lowest score, supported by comments describing a situation far from the behavior of the biological tissue.

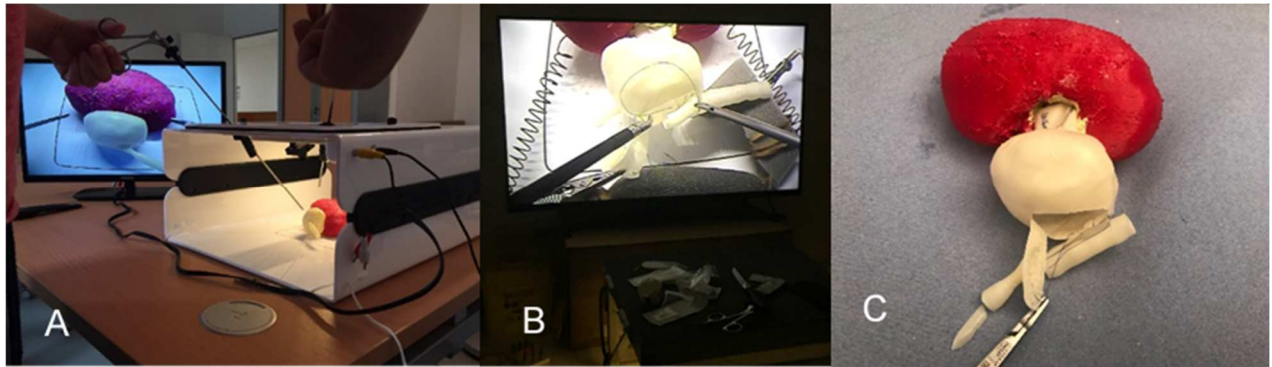


Fig. 6 (A) pyeloplasty simulator in its final form, the assembly of ureter and kidney; (B) model setup in laparoscopic simulator undergoing the surgical procedure (C) model after surgical procedure

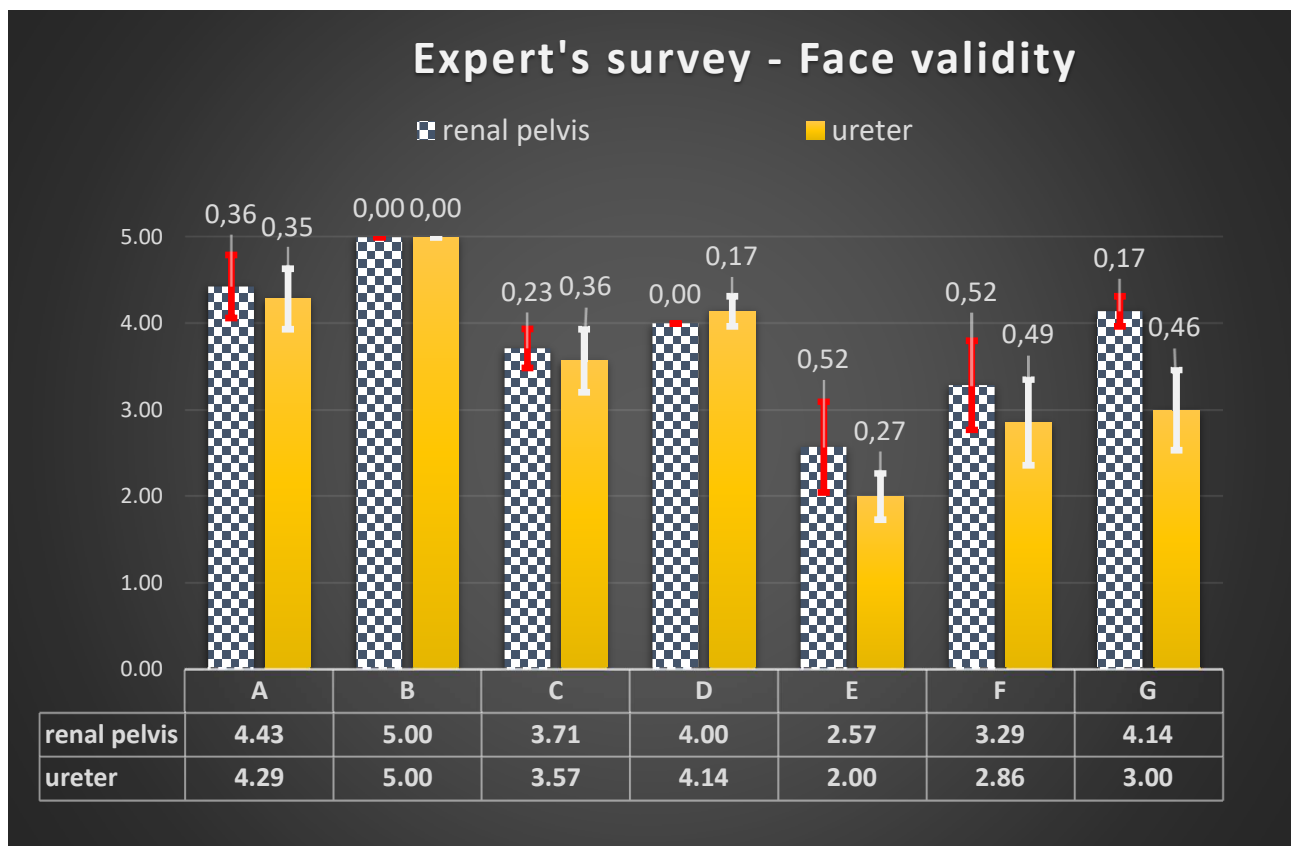


Fig 7. 5-point Likert scale to assess face validity of the simulator (Mean ± SD) (n=7)

A=Needle Insertion; B=Thread-sliding; C= Suturing strength; D= Cutting strength;

E= Elasticity (stretching); F= Handling; G= Mobility

Comments made by the experts revealed also that the penetration (A) and the thread sliding (B) were similar to the condition observed in the operating room.

The identified challenges suture strength, elasticity, and handling. About suturing strength (C), comments enlightened that some of stitches did not remain after several manipulations. They had issues remaining stable over time, especially after several attempts to place a stitch at the same location. Surgeons' comments showed a clear correlation between these three items, the lack of elasticity (E) of the RP-U resulting from excessive handling led to weakened stitches.

The adaptation of the simulators inside FLS trainer system generated several comments. Ureteral mobility has been reported to be unnatural, with the ureter retaining its cylindrical shape. Minor adaptations of the surgical procedure, without consequences for the pedagogical purposes, has been implemented in real time to solve this problem. To facilitate the handling of the ureter, the RP-U has been partially cut to release the ureter without complete dissociation with the renal pelvis. In this way, the handling of the ureter was made easier. Afterwards, the ureter has been triangularly opened in order to get a better overview for the anastomosis with the renal pelvis.

The quality and definition of the camera embedded in the laparoscopic trainer were also criticized by surgeons. Half of them referred to it as the cause of over-handling.

The outcomes of survey showed that the model met most of expectations of the most of surgical movements associated with laparoscopic pyeloplasty.

Discussion

It is feasible to generate and print a low cost upper urinary tract model from patient data imagery using environmentally friendly products that can be used effectively in surgical training.

The idea of having two separate parts, the reusable parenchyma and the singly used renal pelvis and ureter (RP-U) allowed for several successive simulation acts to be performed without discarding the parenchyma. The shapes and size of the custom-made ureter-renal pelvis and parenchyma were validated by urologist surgeons.

The pedagogical objective of the study has a double facet: qualitative, with surgical realism, and quantitative from the point of view of making a sufficient number of similar units optimally. The quantitative aspect seems to be the most mastered with costs allowing the solution to be diffused to a large public. The quality aspect is satisfactory according to the expert panel with a compromise made on the elasticity of the material, which prevents the product to fulfill all expectations, exhibiting few differences from a biological tissue. This offers a critical view and allows us to broaden the discussion on the strengths and improvements of our process.

Face validity evaluation and mimicking biological tissues

The face validity assessment enlightened the lack of elasticity of the material during surgical procedure. Elasticity, handling, cutting and penetration of the needle are all sensations perceived by the surgeons' hand receptors. This refers to the notion of haptic feedback²⁶. Previous work has shown that haptic feedback is a combination between several mechanical forces that are acting simultaneously and resulting from the interaction between the model and laparoscopic tools²⁷. An important part of these interactions relies on the mechanical properties of the material used to craft the model²⁸, hence herein using PVA.

The RP-U parts obtained by material extrusion are rigid and fragile and could not be used as initially generated. PVA is a hydrophilic polymer²⁹ that allowed us to modify its mechanical properties using the bath of water and ethanol to make it dissectible. This part of the process can be improved since drying conditions and humidity can have an impact on a hydrophilic material.

However, the delicate nature of the model was seen as a strength and formative aspect by most of the surgeons because it is similar to the criteria of real biological tissue they meet at the operating room. On the whole, the model itself demonstrates that it is capable of achieving the educational objective set by the surgeons by reproducing the sensations necessary for the implementation of an anastomosis on the ureter-pelvic junction.

In other custom simulator products in urology and pyeloplasty simulation, silicone rubbers have demonstrated their ability to mimic human tissue texture accurately, according to urologist perceptions reported in face and content validity studies^{17,18,20}. By adjusting the mixing ratio between silicone components and additives, the silicone rubbers properties are closer in terms of elongation in comparison our printed PVA part³⁰. New tools are emerging in additive manufacturing to mix and extrude silicone rubber which could remove this binding step³¹.

This milestone has been reached for a nephrectomy simulator where Maddox et al. used a jetting material technology printer to build the pathological shell structure of the parenchyma with the aid of photosensitive resins³². The shell structure was filled with a hydrogel material, and provided overall satisfaction to the expert panel evaluating the model regarding the haptic feedback.

In both cases, silicone rubbers and photo sensible resins could be criticized within the environmental policy of our laboratory in comparison of biodegradable or recyclable materials.

Determining an appropriate balance between the required haptic feedback to reach pedagogical objectives and processing convenience is the major issue requiring potential compromise in the modelization of organs³³.

Pedagogical contribution of additive manufacturing and virtualization process in simulation

Here, we presented a first project for the teaching of laparoscopic pyeloplasty by combining patient imaging and CAD. The CAD software allowed to match the anatomic specifications and the dilated shape required for the ureteral-pelvic junction for a pyeloplasty training model. The use of CAD represents an alternative to the use of patient imagery as computed tomography urography (CTU) where radiation exposure becomes a potential problem³⁴.

As a result of the early development of 3DP in healthcare education, we cannot be sufficiently objective regarding the pedagogical contribution of our simulator. The pedagogical value is still to be demonstrated with new evidence of trainee skills improvements and transfer of the new surgical procedure learned into a clinical context³⁵. The ease of replication of our production process on different 3D printers increased the capacity of our model to be utilized widespread. A wider student

audience will allow us to assess our simulator on several levels following the model of Kirkpatrick applied in the medical sciences^{36,37}. Proposing high fidelity dissectible models for a population of fellows is also a way to create engagement in learning, with better outcomes in recurrent training in a simulation centre and continuous formation³⁸. It may be a way to reduce the required years of direct mentorship in pediatric urology or improve the quality of mentorship as the mentee is beginning at a higher skill level⁶.

Economical prospection and open-source contents

Apart from the cost of materials (Table 1), the creation of the renal apparatus mostly mobilized investments dedicated to hardware material such as the 3D printer (Raise N2 Dual Plus, \$4320/4000€) and high-performance computer (DELL Precision 7720, \$3240/3000€), which can manage the 3D modeling and virtualization associated with segmentation, meshing calculus, and slicing for the printer. Points that require attention include the double extrusion, and the fact that it is mandatory to build models with sophisticated designs.

Moreover, the costs were minimized by the reusability of the parenchyma between each simulation session, with only the plugged renal pelvis being changed. The material extrusion process has generally been referenced as the cheapest technology for 3DP¹³. The economical limitations are less than those of jetting technology, using materials that are difficult to recycle and suitable only for printers of the same brand, such as photopolymer^{39,40}. The production cost of an anatomic model using jetting with hard colored multi-materials is approximately \$400 (350€) with a printer costing \$400,000 (350 000€)⁴¹. The molded silicone simulator cost, evaluated at approximately 100€ (87€), remains higher than ours²⁰.

Apart from licensing costs, open-source contents (Slicer3D, Meshlab, Meshmixer, FreeCAD) increase the number of people that can collaborate on the subject of simulators, although they may not be involved in the medicine field. The 3D volume format (STL file) can also be read and spread to a large number of users. The models created by our process are available on the intranet of the university thanks to a dedicated Moodle platform. Moreover, open-source contents encourage collaboration between simulation centers, which will be valuable for medicine studies globally. This article also

demonstrates that the future of the health field is already and will become increasingly linked to interdisciplinary efforts among engineering, physics, biology, and chemistry, resulting in exciting outcomes.

Conclusion

A printed kidney and ureter model was crafted and merged to recreate for the first time the upper urinary tract through a process from imagery data to 3D printing. This assembly of several materials can be produced in medium series and at a minimal cost, which allows for the planning and operation of further pedagogical developments. Extensive evaluation should be conducted to gain improved comprehension of the impact of our model on the skills of residents and fellows in pediatric and adult urology as final aims are increase the practice of future surgeons, and finally, to significantly reduce the length of surgical education. How to process complex shapes in additive manufacturing, such as the RP-U part, with hydrogels (biodegradable biomaterials) used in bio printing, should be investigated and tested in order to improve the model fidelity, while attempting to maintain a low cost.

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APPENDIX A

1. Imaging data

As noted by Stirling et al., optimal image resolution is obtained in most cases with computed tomography (CT) scanning¹. Preliminary implementation tests demonstrated superior quality for a slice thickness (0018,0050) of less than 1 mm^{2,3}. If the slice increment (0018,0088) is equal to the slice thickness, the entire patient body was covered³ (Fig.A.1). Display parameters with the matrix (0028,0010/0011) and reconstruction diameter (0018,1100) were available for calculating the resolution. In the 3D reference space, a pixel becomes a voxel, with a third dimension to generate a volume. If the lengths are equal in all three planes, the voxel is isotropic and processed without any spatial conversion on the axial voxel instead of the anisotropic voxel, thereby allowing the best resolution to be maintained^{3 4 5}. The technical configuration was extracted from the metadata register, where each one had an indexation following the template of 2 series of four numbers separated by a comma.

The CT scans were performed on a Discovery CT750 HD (General Electrics, USA). Data were used with a 0.625 mm (0018,0050) slicing. The slice increment was equal to the slice thickness (0018,0088). The technical parameters were as follows: 100 kV peak kilo-voltage (0018.0060) and 8 mAs exposure (0018,1152). The display parameters were defined as a 512 × 512 matrix (0028,0010/11) and reconstruction diameter of 320 mm (0018,1100). Thereafter, we obtained an

isotropic voxel of 0.625 mm in length in the three dimensions. The segmentation of the DICOM files for extracting the 3D model of the parenchyma took approximately 2 h to determine the appropriate settings, as described in the Materials and methods section. Complementary manual segmentation required approximately 1 h.

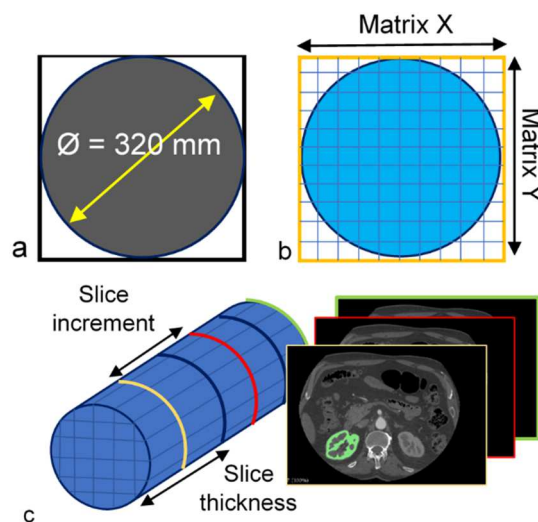


Fig A 1. Illustration of the main parameters of imagery

(a) Reconstruction diameter; (b) matrix applied on DICOM file; (c) differentiation between slice thickness and slice increment

2. Segmentation

The open-source software 3DSlicer, a platform for medical image informatics and 3D visualization, was used (v 4.8.0, Windows Platform) ⁶. We first used simple region growing segmentation (SRGS) ⁷. The procedure was supervised, meaning that 10 seeds (also known as fiducials) were placed in the different planes (sagittal, coronal, and transverse) corresponding to the desired organ. The first iterative program expanded the area from the seeds to pixels with a similar contrast. The second algorithm smoothed the inner and outer boundaries of the pixel area. Three parameters defined the segmentation: number of iterations, multiplier (standard deviation of the intensity model), and growing radius. Two parameters defined the smoothing: number of iterations and time step.

The simple region growing parameters were set to five iterations with successive values using a multiplier of 1.95. The area of the right kidney was cropped to avoid interferences with other levels of grey of the slices. The smoothing parameters were set to 0.0625 for the time step and five iterations.

The Editor module improved the iterative result achieved by the SRGS. A manual segmentation tool filled isolated holes inside the model, deleted useless areas or added missing ones. A complementary option was the Level Tracing effect tool, for detecting neighboring pixels with a similar contrast value. This value was generated by manual thresholding.

The Model Maker module was used to correlate the areas obtained in 3D. It also included an algorithm to smooth the model with a Laplacian filter. Thereafter, the virtual model was extracted in the standard tessellation language (STL) format.

Its modification is more complex than usual parts created using computer-aided design (CAD) software. To enable easier manipulation of the model resulting from Slicer3D, the simplification operation was applied, which consisted of reducing the number of triangle faces. Holes in the model, self-intersections between surfaces or isolated elements were non-manifold geometries (unrealistic shapes) that were checked.

The open-source software Meshlab (v2016.12, Windows Platform, ISTI-CNR, ITA) embedded functions to work on the meshes. The corrective actions of simplification and checking are described in Fig. A.2.

The simplification and repairing actions on the mesh took approximately 10 min to be performed with the verification steps. The merging distance threshold between vertices was set to 1 mm and applied to the model. Thereafter, double-checking with the Inspector function from Meshmixer carried out double-checking of all the geometries and issues on the nephron, and none were found.

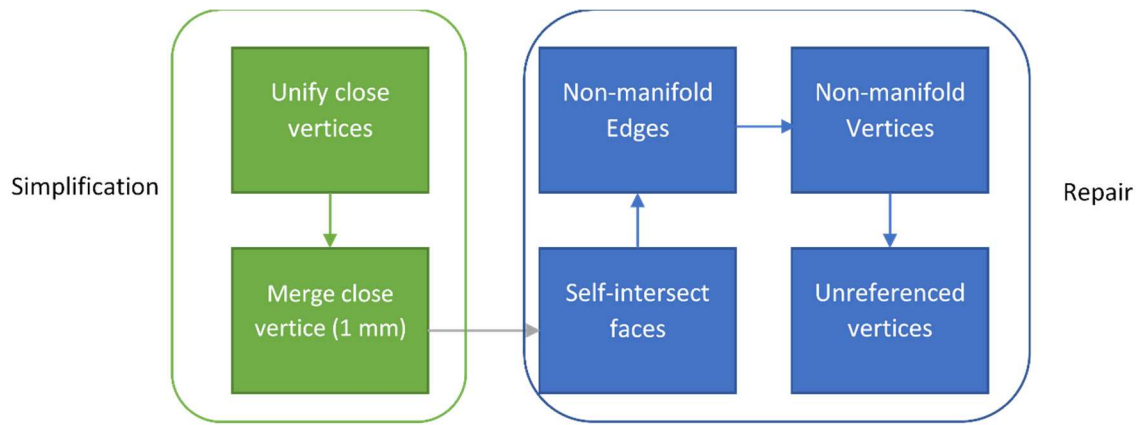


Fig A.2. Checking and optimization process of 3D model mesh using Meshlab

3. CAD modeling

We used the open-source parametric modeling software FreeCAD (v0.17, Juergen Riegel, Werner Mayer, Yorik van Havre (2001-2017), available from <http://www.freecadweb.org>) coupled with Meshmixer (v3.5, AUTOCAD, Windows Platform, USA). Inspired by anatomic literature⁸, the shapes are sketched using revolution and the sweep surface function within a FreeCAD file.

The part design of RP-U part asked different modification under supervision of the surgeon. The cumulative time of work to reach among 12 hours to get a completed version by means of FreeCAD software. Sculpting tools improved the rendering of the renal pelvis, instigating deformations and creating roughness on the outer shell using Meshmixer. This interface was used to verify if the assembly fitted properly between CAD parts and the segmented organs.

4. References

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APPENDIX B

1. Slicing

Ideamaker (v3.1.7, Raise3D, Windows Platform, CHINA) was used to generate a G-code file for the Raise N2 Dual Plus printer whereas, a custom profile designed for Simplify3D slicer (Cincinnati, OH, USA) dedicated to the Lynxter printer was used to generate G-code for this machine.

2. Prototyping

The parenchyma was made from two printed materials. The scaffoldings (Fig B.1) were made from polyvinyl-alcohol (PVA) (E-Sun, CHINA) whereas thermoplastic-urethane (TPU) (*Ninjaflex*, Ninjatek, USA) was assigned to the structure of the part.

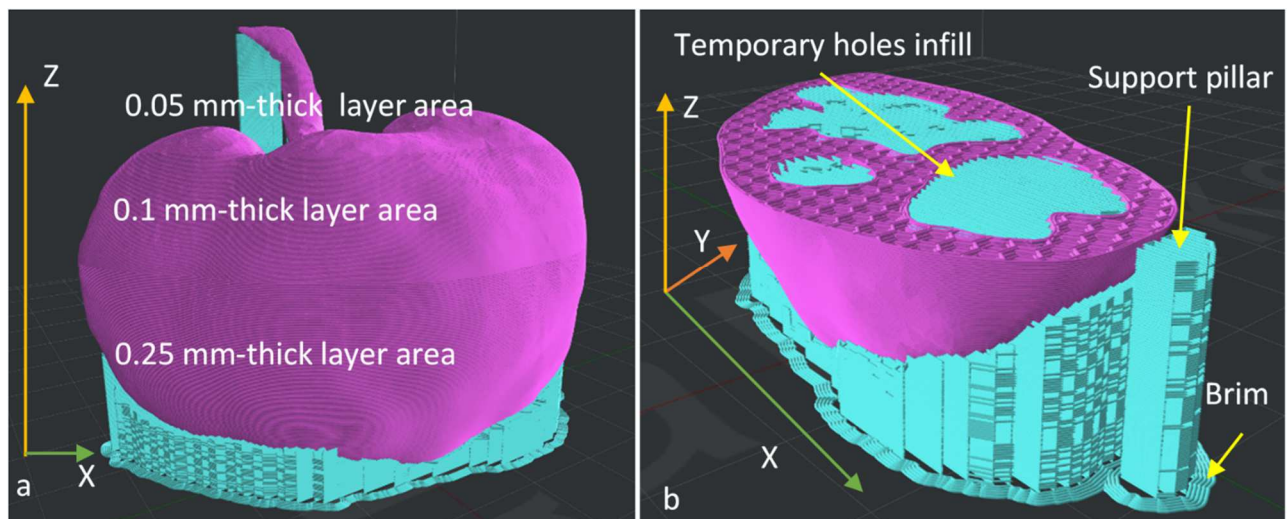


Fig B.1. Material assignment and preview extracted from the G-Code file of the parenchyma

Purple material is related to TPU, Cyan area to PVA

Parameters were optimized in order to use minimal scaffolding material. The ureter-renal pelvis (RP-U) part was made from PVA as the main structure. Below parameters allow us to print the parenchyma within 33 hours and 28 hours using Raise N2 Dual Plus depending on the infill ratios. The renal pelvis–ureter part was printed using both Raise N2 Dual Plus and Lynxter S-600D in approximately 1h30. The materials (PVA and TPU) were packaged in

filament form, with a diameter of 1.75 mm, according to the printers' specifications. After a 24h bath in water, only the permanent structure of the parenchyma made from TPU remained.

Table B.1: Printing settings for nephron

Printing settings									
FW.R (%)	L.H (mm)		F.L (mm)	SH (-)	A.R.S (mm)	S.R.S (mm/s)	Ex.S (mm)	S.Ex.S (mm/s)	Heated bed temperature (°C)
	Z	L.H							
120	0-50	0.25	0.2	1	1	25	0.5	10	50 °C
	50-70	0.1							
	70-80	0.05							

FW.R: Flow rate of material; L.H : Layer heights as function of kidney height of Z; F.L : First layer height; SH: Number of shells (envelopes); A.R.S: Amount of retraction when a switch of extruder occurred; S.R.S :Speed of retraction when a switch of extruder occurred; Ex.S: Amount of material added in addition to retraction amount on extruder used after switch; S.Ex.S: Amount of material added in addition to retraction amount on extruder used after switch.

Table B.2: Material settings for printing of nephron

Material settings													
TPU							PVA						
P.S (mm/s)	IF (%)	T (°C)	A.R (mm)	S.R (mm/s)	Ex (mm)	S. Ex (mm/s)	P.S (mm/s)	IF (%)	T (°C)	A.R (mm)	S.R (mm/s)	Ex (mm)	S. Ex (mm/s)

15	40/25	235	1	15	1	15	15	30	195	1	15	0.5	15
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P.S: Printing speed; IF: Infill; T: temperature of each material; A.R: Amount of retraction; S.R: Speed of retraction; Ex: Extra restart amount; S.Ex: Extra restart speed.

Table B.3: Printing settings for ureter

General settings								
FW.R (%)	L.H (mm)	F.L (mm)	SH (-)	A.R.S (mm)	S.R.S (mm/s)	Ex.S (mm)	S.Ex.S (mm/s)	Heated bed temperature (°C)
100	0.1	0.2	1	NA	NA	NA	NA	50 °C

Table B.4: PVA settings of printing for ureter

PVA						
P.S	IF (%)	T (°C)	A.R (mm)	S.R (mm/s)	Ex (mm)	S. Ex (mm/s)
15 mm/s	0	195	0	0	0	0

Supplementary Material:

S1 5-point Likert scale

S2 OSATS suture assessment (French Adaptation)

S3 Kidney 3D Model (STL)