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A 3D model of the renal vasculature — a joined result of the corrosion casting technique, micro-CT imaging and rapid prototyping technology

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Abstract: Three-dimensional (3D) printed model of the renal vasculature shows a high level of accuracy of subsequent divisions of both the arterial and the venous tree. However, minor artifacts appeared in the form of oval endings to the terminal branches of the vascular tree, contrary to the anticipated sharply pointed segments. Unfortunately, selective laser sintering process does not currently permit to present the arterial, venous and urinary systems in distinct colors, hence topographic relationship between the vascular and the pelvicalyceal systems is difficult to attain. Nonetheless, the 3D printed model can be used for educational purposes to demonstrate the vast renal vasculature and may also serve as a reference model whilst evaluating morphological anomalies of the intrarenal vasculature in a surgical setting.

Key words: renal vasculature, corrosion cast, micro-CT, rapid prototyping.

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Introduction

Vascular anatomy of the human organs has been frequently studied by the means of corrosion casting technique. Corrosion casts show the way that blood vessels penetrate an organ, as well as further branching pattern of both the arteries and veins that is clinically important in everyday practice of namely interventional radiologists [1–3].

Corrosion casts are supplementary to formalin cadaver specimens that by themselves present a whole spectrum of morphological features, characteristic to a particular organ [4, 5]. However, corrosion casting is superior in demonstrating spatial configuration and architecture of the studied anatomical entities. Henceforth, various injection techniques have been frequently used in anatomical research in the past and are still in use these days as required, albeit in some cases they can be substituted by virtual reconstructions obtained from radiological imaging data.

Contemporary innovative technologies allow for a combination of medical imaging, virtual 3D reconstruction and computer aided modeling, finalized by manufacture of immensely accurate three-dimensional anatomical models which disclose morphological features of real structures of the human body, as well their pathologies (e.g. tumor, aneurysm), thus facilitating surgical planning [6–10]. Different methods apply whilst creating anatomical models, however it is the 3D printing that has become the most popular and widely used technique in the field of medicine. Up to date, 3D printed models appeared to be helpful in understanding the anatomy of the liver, lungs, prostate, heart, brain, as well complex cranial bones, namely the sphenoid and temporal [11–13].

The purpose of this study was to create a 3D printed model of the renal vasculature using corrosion casting of the human kidney in order to demonstrate the intrinsic arterial and venous renal systems in regard to the pelvicalyceal system. Henceforth, the authors briefly presented benefits and constraints related to the manufactured corrosion casting replica when using 3D printing technology.

Materials and Methods

Three-dimensional model of the intrarenal vasculature was prepared based on micro-CT scans of the corrosion cast of a human kidney, obtained by the injection-corrosion method utilizing synthetic plastic polymer. The corrosion cast of the human kidney was derived from the Department of Anatomy of the Jagiellonian University, Medical College, and was prepared in the seventies of the XXth century [14]. The corrosion cast of the human kidney (Fig. 1A) with completely injected vascular and urinary entities (arteries in red, veins in blue, and the pelvicalyceal system in light brown color) was subjected to the micro-computed tomography analysis to obtain a series of imaging data (2D micro-CT scans) that were then combined into the volume data used for creating 3D model of the renal vasculature. For this purpose, the kidney corrosion cast was scanned using the Nanotom 180N device (GE Sensing & Inspection Technologies Phoenix X-ray Gmbh) equipped with Hamamatsu detector (2300 × 2300 pixels). The following working parameters of the X-ray tube applied: $I = 250$ µA and $V = 70$ kV. The reconstruction of the scanned sample with the spatial resolution of 60 µm was performed with the aid of the GE software datosX ver. 2.1.0 using the Feldkamp algorithm dedicated for cone beam X-ray CT. The post-reconstruction data treatment (denoising, cropping and 16 bit to

8 bit conversion) was performed by the means of the VGStudio Max 2.1 software (http://www.volumegraphics.com/en/products/vgstudio-max/).

The imaging data was processed with the aid of the CT-Analyzer software (http://www.bruker.com/en/applications.html) that allowed for generation of a stereolithography file (STL file), containing the 3D mesh model of the kidney corrosion cast (Fig. 1B). Due to the extreme size of the initial STL file (1.55 GB) and the huge number of the triangles comprising the mesh (31 653 060), the MeshLab software was used (http://www.meshlab.sourceforge.net) for final adjustments of the mesh model. The final mesh of triangles comprised 1 831 342 facets and 812 678 vertices, was stored in the STL file which size has been reduced to 89 MB.

The replica of the kidney corrosion cast was manufactured from the polyurethane material (Flexa) in the process of selective laser sintering using the Sinterit Lisa 3D printer.

Quality of the 3D printed replica was evaluated by visual exploration of the anatomical details observed on the kidney corrosion cast in juxtaposition to the replicated structures in the process of 3D printing (Table 1). Therefore, transillumination technique was applied to compare the perception of deep vascular and urinary structures of the human kidney. For this purpose, both the kidney corrosion cast and its printed replica were placed on a piece of plexiglass, fixed above the beam of intense white light emitted by the LED lamp, and photographed. The obtained digital images were analyzed to find out potential similarities and discrepancies between the appearance of the anatomical structures observed on the corrosion cast and the 3D printed replica.

Length, width and thickness measurements were taken on both the printed replica and the original corrosion cast using a digital calliper. However, the intention of the present work was to evaluate the ability of printing technology to replicate complex vasculature mesh rather than recreate the exact size of the kidney corrosion cast. Therefore, only absolute measurements of both specimens were presented (Table 2). Nonetheless, potential sources of deviations between the methods were not analyzed because they basically relate to the fact that printed replica has been scaled-up during the printing process.

Results

Anatomical details of the renal vasculature demonstrated by the corrosion casting were replicated accurately by the 3D printed model (Fig. 1C), manufactured by the laser sintering technology. Upon visual inspection, the printed model of the vascular anatomy of the kidney showed considerable resemblance to the corresponding corrosion cast. Both main divisions of the renal artery (segmental, interlobar and arcuate arteries, and corresponding renal vein tributaries), as well as their minor branches, have been adequately replicated in the printed model. However, there were discrepancies found between the printed replica and the original corrosion cast in terms of the exact reproduction of the morphological appearance of the renal vasculature (Table 1), and the ability to observe its relationship towards the pelvicalyceal system. Although the printed 3D model includes complete intrinsic vascular pattern (both arteries and veins) of the human kidney, detailed distinction, and differentiation of the subsequent divisions of the blood vessels is difficult for visual assessment due to the monochromatic material used for manufacturing the arteries and veins, as well as the renal urinary structures (the calyces, renal pelvis, ureter). Color painted structures on the model would further enhance the visual perception, thus improve comprehension of their topographical arrangement, and facilitate tracking them inside the organ. However, it was not attained in our case. Moreover, the applied 3D printing technology did not adequately reproduce terminal branches of the vascular tree due to their abnormal rounding, which appeared as small bubbles or protuberances in the printed replica (Fig. 2). In the original corrosion cast, the terminal divisions of the vascular tree were thin segments, sharply ended. Such artifacts probably resulted from melting of the polymer powder subjected to the sintering process that forms a solid model from the thermoplastic material heated by the laser energy.

A high-intensity light transmitted through the corrosion cast of the kidney allowed to observe more details of the intrarenal vasculature compared to the printed replica, which transmitted less light through itself due to the specific material properties used for replicating the intrarenal structures in the process selective laser sintering (Fig. 3). Thereby, the original corrosion cast demonstrates much better intrarenal segmental anatomy than the printed replica, related to spatial distribution of the blood vessels towards the pelvicalyceal system.

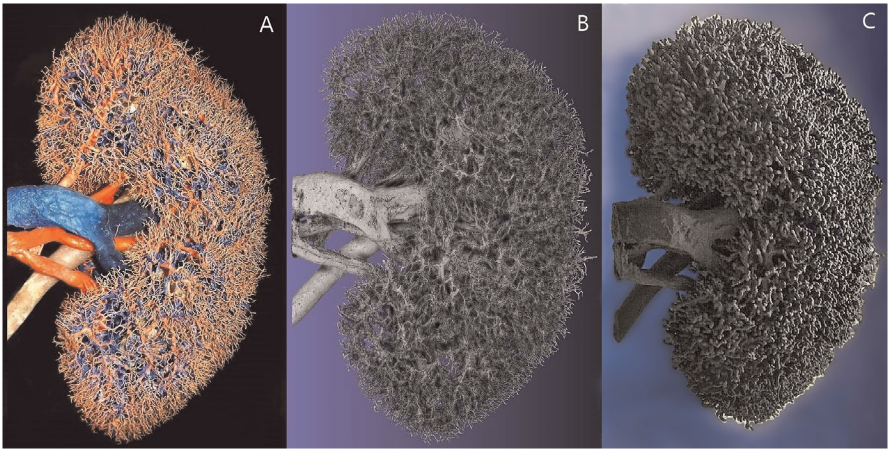

Fig. 1. A — Photograph of the corrosion cast of the human kidney showing complete vasculature surrounding the pelvicalyceal system (arteries in red, veins in blue, ureter in brown). **B** — The 3D mesh model of the intrarenal structures obtained from micro-CT scans of the kidney corrosion cast. **C** — The replica of the kidney corrosion cast obtained from the mesh model (B), materialized by the 3D printing.

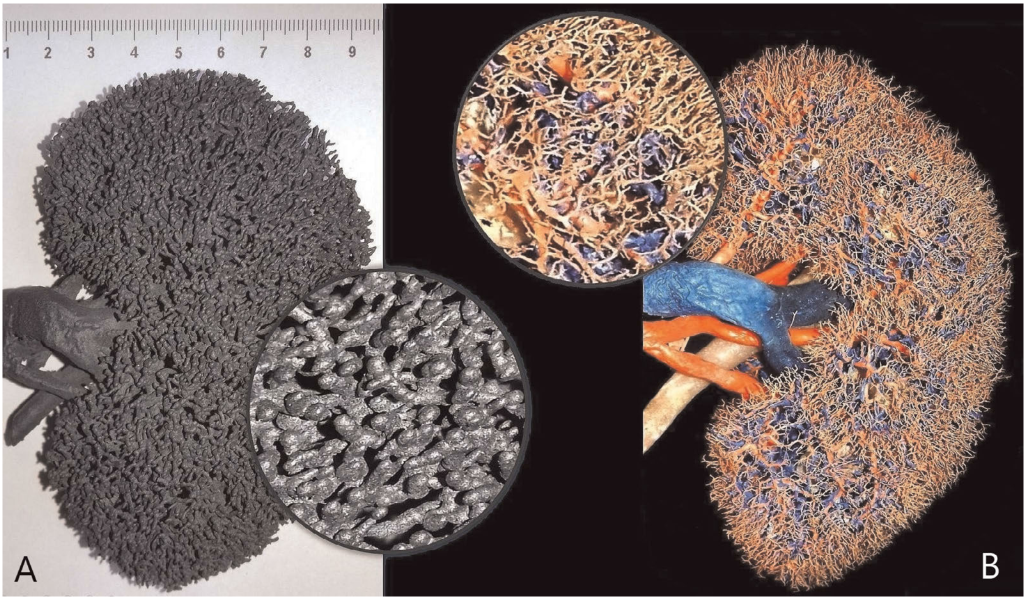

Fig. 2. Close up of the artifacts (bubbled endings of the terminal branches) that appeared in the printed replica (**A**), instead of sharp segments existing in the original corrosion cast (**B**).

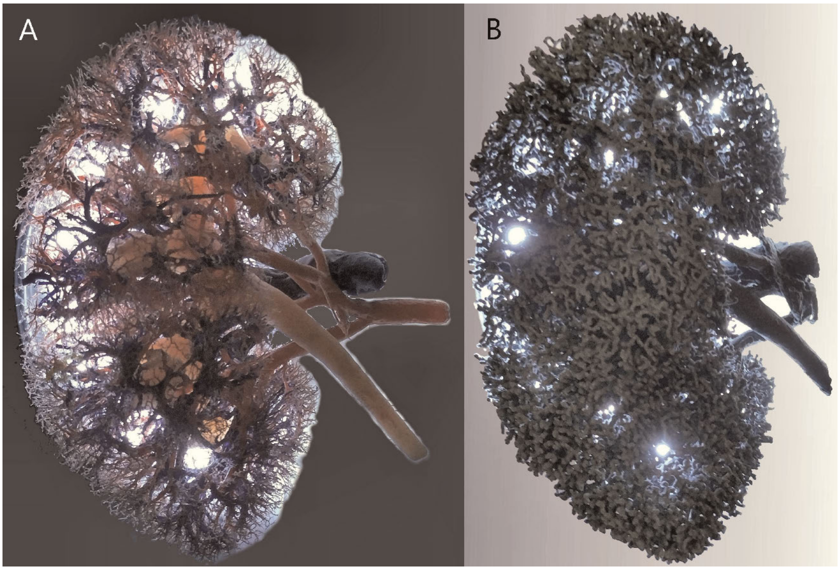

Fig. 3. Effect of transillumination performed on the kidney corrosion cast (**A**) and its printed replica (**B**). Illuminated corrosion cast reveals position of the pelvicalyceal system and the surrounding vasculature. Such a spectacular effect has not been attained on the printed replica.

Table 1. Similarity of the vascular and urinary structures observed on the printed replica versus the original kidney corrosion cast scored in a three-stage scale by visual observation.

Morphological features	Printed replica	Corrosion cast
Pre-hilar appearance of the renal vein, artery and ureter	satisfactory	satisfactory
Appearance of the renal hilar structures	moderate	satisfactory
Ability to distinguish arteries from veins in the intrarenal vascular mesh	unsatisfactory	satisfactory
Appearance of the uttermost divisions of the blood vessels (diameters in the range of 1 mm)	unsatisfactory	satisfactory

Table 2. Dimensions of the printed replica of the kidney versus the original corrosion cast obtained from measurements as presented in Fig. 4.

Dimension (in millimeters)	Replica	Corrosion cast
Length	112	97
Width above the hilum (A)	67	57
Width at the hilum (B)	47	42
Width below the hilum (C)	60	51
Thickness	49	40

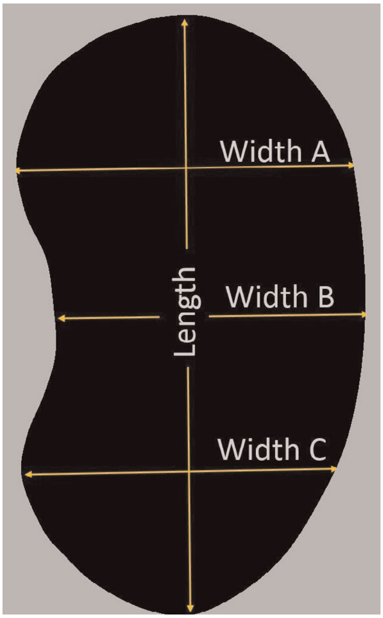

Fig. 4. A schematic drawing of the linear measurements performed on the kidney corrosion cast and its printed replica. Thickness was defined as the greatest distance between two points found on the anterior and posterior surface of the kidney, measured perpendicularly to the length.

Discussion

The intrinsic blood vessels of the human kidney are arranged in a very complex system which was recognized with the help of corrosion casting methods [15–18]. Both arteries and veins form a dense mesh of bifurcated vessels, originating from each other. The arteries entering the renal hilus reveal several orders of divisions, causing the original diameter of the main renal artery to decrease from approximately 5 mm to 0.1 mm at the distal divisions.

The corrosion cast of the renal vasculature provides a direct insight into the spatial arrangement of the arterial and venous tree, and their relationship to the pelvicalyceal system. However, manufacturing its 3D printed replica is not a trivial task and requires technologies which are capable of replicating details from the macroscale to the microscale, with a spatial resolution comparable to the natural arrangement of the anatomical structures. The ideal solution for manufacturing such model appeared to be the combination of the corrosion casting technique, micro-CT scanning and rapid prototyping technology. It resulted in the creation of an accurate 3D model that presented the angioarchitecture of the human kidney to a similar extent to the native endocasts of the vascular tree.

The corrosion casts of the renal vasculature are delicate specimens because they are usually made of the polyester that is fragile in the solid phase. Handling such specimens may be destructive for them, particularly for the tiny segments of the vascular tree which length and diameters are in the range of a few millimeters. The 3D printing technology seems to be indispensable for producing numerous accurate replicas of the corrosion casts that can be viewed repeatedly during anatomy teaching without the fear of destroying the original specimens. It should be emphasized that preparation of the vascular corrosion cast is a time-consuming, complex procedure that requires skills and laboratory facilities.

It is relatively easy to accomplish a solid model with the 3D printing process, though the process may take a few or even several hours. Notwithstanding, it does not require an excessive involvement of a person inspecting the model production, except for preparation of the printable 3D triangle mesh that is a template for the solid model. The aforementioned task may be difficult and time-consuming (remeshing, detection and elimination of defects from the mesh e.g.: degenerate and non-manifold elements, self-intersections, closing unwanted holes, appropriate adjustment of the parameters for control mesh smoothing and decimation), particularly in case of large input data representing an object to be printed in high spatial resolution [19–20].

Another benefit relates to the possibility of manufacturing enlarged replicas compared to the original corrosion casting specimen, as the latter's dimensions do not allow for a clear presentation of minute anatomical details. This can be particularly helpful whilst teaching anatomy of the complex meshes of the blood vessels or other tubular structures, namely the biliary tree branching through the liver. Moreover, a 3D printed, tangible anatomical model is regarded more efficient for anatomy teaching than a 3D virtual model, observed only on the computer screen. High fidelity of anatomical details revealed on the printed replica of the original corrosion cast provides the opportunity for utilization of such models for educational purposes, as well as for practicing surgical procedures performed on the kidney in a safe, controlled environment.

Limitations of the study

The authors perceive a few limitations related to manufacturing replicas of the kidney corrosion cast utilizing 3D printing technology based on the selective laser sintering process. The applied in this study 3D printing allowed for manufacturing of the replicas of the kidney corrosion cast, however the final product did not correctly reproduce all anatomical features of the terminal branches of the arterial tree, as presented in the original specimen. Moreover, this printing method did not permit to replicate veins, arteries and urinary entities located inside the kidney in different colors. This is particularly cumbersome trying to present spatial distribution of the subsequent divisions of arteries and tributaries of the veins, because these vessels form a very dense vascular mesh with the smallest segments ranging approximately 0.5–1.0 mm visible both on the original corrosion cast and the printed replica. Thereby, educational value of the printed replica seems to be limited to demonstration of the density of the vascular mesh but without possibility of easy distinction of arteries from veins, except vessels entering the renal hilum in their most common order: the renal vein in front of the renal artery, and the ureter positioned most posteriorly. Furthermore, if the original kidney corrosion cast is transilluminated, the bright light can highlight the pelvicalyceal system surrounded by the injected blood vessel, and thus clearly demonstrates the anatomical relationship of these structures inside the kidney. Such demonstration could not currently be attained utilizing the printed replica.

Conclusions

The 3D printed replica of the kidney corrosion cast shows a whole spectrum of anatomical details, characteristic to the branching pattern of the renal vasculature. Such models can be a valuable help for anatomical education and serve as demonstrative tool for practicing surgeons in the field of urology. Hence, 3D printed models of the renal vasculature obtained from the radiographic data may be used as reference models for the evaluation of vascular anomalies of the kidneys.

Conflict of interest

The authors declare no conflict of interest nor any financial interest associated with the current study.

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