World Journal of Cardiovascular Diseases, 2016, 6, 1-7
Published Online January 2016 in SciRes. http://www.scirp.org/journal/wjcd
http://dx.doi.org/10.4236/wjcd.2016.61001

Enlarged and Colored Enhanced 3D Printing of Renal Artery Aneurysms for Improved Imaging and Treatment Planning

Aaron Hoffman*, **Samy Nitecki, Tony Karram, Maxim Leiderman, Igor Kogan, Guennady Yudkovsky, Amos Ofer**

Department of Vascular Surgery and Transplantation and Department of Radiology, Rambam Health Care Campus, and Rappaport Faculty of Medicine, Technion, Haifa, Israel
Email: *ahofman@rambam.health.gov.il

Received 25 November 2015; accepted 16 January 2016; published 19 January 2016

Abstract

Three dimensional printing (3D printing) technology is increasingly used to improve results in many areas of medicine. Physical models produced by this technology allow better appreciation of complex anatomical and pathologic conditions. In cardiovascular medicine and surgery, 3D modeling has been reported to be of help in treatment planning of abdominal aortic aneurysm, especially in cases of complex angulations and branching at the aneurysm neck. Here we report the use of 3D printing in cases of renal aneurysms. Enhanced 3D models of CTA images of renal aneurysms were prepared in house using common and freely available software programs, and an accurate desktop 3D printer. Eight reconstructed models were enlarged by a factor of 2 or more and then differentially painted to delineate normal arteries and aneurysmatic ones. These enhanced 3D solid models allowed visual and tactile inspection for a better appreciation of complex aneurysms. Color enhancement of these models added another dimension of comprehension, even for experienced surgeons and invasive radiologists, and allowed more accurate measurements of branch numbers, distances, and angles in space even with severe tortuosity. Endovascular use of covered stents and embolization techniques could be easily envisioned preoperatively. We conclude that enhanced, enlarged, and colored 3D printed models are a powerful tool for preoperative endovascular treatment planning of complex renal artery aneurysms.

Keywords

3D Printing, Renal Artery Aneurysm, Endovascular, Covered Stent, Embolization

*Corresponding author.

How to cite this paper: Hoffman, A., Nitecki, S., Karram, T., Leiderman, M., Kogan, I., Yudkovsky, G. and Ofer, A. (2016) Enlarged and Colored Enhanced 3D Printing of Renal Artery Aneurysms for Improved Imaging and Treatment Planning. *World Journal of Cardiovascular Diseases*, **6**, 1-7. http://dx.doi.org/10.4236/wjcd.2016.61001

1. Introduction

Renal artery aneurysms (RAA) are a rare entity with an unknown true prevalence. The reported rates of incidence varied between 0.3 - 1.3 percent of all aneurysm in large series [1]. They are usually asymptomatic but may rupture and cause severe morbidity and mortality, presumably as they become large [2]. Therefore, either open surgery or endovascular treatment is warranted in appropriate patients [3]. However, renal artery aneurysms present a real treatment challenges because of their position, size, spatial complexity, and high variability of branches [4].

Accurate preoperative measurements and stent planning in daily practice are usually based on two dimensional (2D) reconstructions of the computerized tomography angiography (CTA) images utilizing centerline based dimension measurements, or by three dimensional (3D) reconstructions of the 2D images [5]. Various software packages are available for automatic reconstructions and even for branch recognition and naming. However, in some cases of complex RAA, the real dimensions are very difficult to comprehend even by experienced surgeons and radiologists. It was felt that for those selected difficult cases, better methods should be explored.

Rapid 3D printing is a method to manufacture a desired physical 3D model from a virtual image or from computerized planning software [6]. Many commercial 3D printers are available now and they are rapidly becoming more friendly and easy to use. Some printers are even marketed as personal 3D printers. The various 3D printers available now widely vary in capabilities, build materials, sizes, and prices. They are also used to improve diagnosis and treatment in various areas of medicine and surgery [7]. In particular, this technology allows better appreciation of complex anatomic and pathologic conditions. In vascular medicine and surgery, 3D modeling may be helpful in understanding the underlying pathology. In fact, actual 3D models of aneurysms have been industrially produced from CTA images for the purpose of stent design and to train physicians and other personnel by institutions and by device manufacturing companies [8].

Therefore, we hypothesize that for patients with complex aneurysmal anatomy, an additional imaging tool, namely enhanced 3D printing technology, will improve accuracy of diagnosis and treatment planning of RAA.

2. Materials and Methods

2.1. Patients

This was a retrospective study using previously archived images of CT studies of 8 patients with RAA treated in the past in our department. There were 6 females and 2 males, ages ranged from 24 to 68, with a mean of 41 years. All 3D reconstructions were kept anonymous and no clinical decision was based on this experimental work. The work has been approved by the appropriate ethical committees related to the institution.

2.2. Personal Computer Processing

Initial preparation of the 3D model was done on a basic personal computer (PC) with access to the internal network of the hospital. The two dimensional (2D) computed tomography angiography (CTA) axial images of the RAA patients, in Digital Image Communications in Medicine (DICOM) format, were first viewed on a CT viewer of the institutional PACS (picture archiving and communication system). CT scans varied in techniques and quality but this seemed not to affect the final model. One of the best quality series is opened and then the area of interest is noted. This is the limited area that includes only a segment where the aorta with the celiac trunk, superior mesenteric artery and the renal arteries are located.

For further 3d modeling we used advanced vessel analysis (AVA), volume rendering, or surface rendering reconstructions. This action requires specialized software that can be acquired commercially or downloaded freely from a public domain (e.g. InVesalius, http://svn.softwarepublico.gov.br/trac/invesalius). In the present study we used Philips Intellispace Portal package. All bones were removed taking care to keep adjacent arteries. Lumbar arterial branches and other nonrelevant arteries were removed. Care was taken to keep and enhance accessory renal arteries. Calcifications on arteries were kept if they did not distort the lumen. Eventually, a short length of the arterial tree containing only the visceral arteries was in the ensuing model. The final image has been saved as a Standard Tessellation Language (STL) file format inside the Portal and then exported to a folder on the personal PC. The preparation time of a printable 3d STL file took typically only 15 - 20 minutes. Of note, the resultant STL file size is usually less than 1 megabyte. The completed stl file can be viewed using 3D viewer available online (http://www.3dvieweronline.com) or downloadable from the web.

2.3. 3D Printing

The 3D printer used in this study was Objet 30 Pro (Stratasys, Eden Prairie, MN, USA). It is almost desktop size and is conveniently located inside our campus and used regularly by other investigators. To produce a solid and accurate 3D RAA model we chose to use an opaque polypropylene like build material (VeroWhitePlus RGD 835, or Durus White RGD 430, Stratasys, Eden Prairie, MN, USA).

The STL file containing the previously prepared model was transferred to the printer operator via email or on a disk. The 3D model was then loaded on the printer's software, put on its virtual tray, and checked for printability. This software optimizes position on the tray and calculates the amounts of materials to be used and the time of production. It automatically converts the 3D model into sets of thin slices and plans the permanent build material and temporary support material to be removed when finished. Given the order to start printing the printer adds slices, layer by layer, from the bottom up until the whole model is finished. Total printing time depends on the model size, but for the present RAA 3D models it lasted 5 - 7 hours.

2.4. Enhancing 3D Models by Enlarging and Coloring

The diameter of the normal renal artery in an adult is about 5 mm, renal arteries branches are even smaller. RAA are considered large above 20 mm. Therefore, a real size RAA model would be un-necessarily small and fragile. The 3D printer allows easily proportionate enlargement of the basic model as required.

The basic color of the 3D model produced by this system is white. This color suits experienced surgeons and invasive radiologists who are used to watch black and white computer reconstructions of aneurysms in their daily work, and to virtually rotate and manipulate them on the computer screen. However, we repeatedly noted that other physicians, trainees and less experienced personnel, as well as the patients themselves, get a better understanding of the details of the aneurysm if the model is differentially painted for normal and abnormal findings. For convenience we chose to paint the normal part of the artery in red and the aneurysmatic parts in yellow.

3. Results

The fabricated enhanced RAA 3D models were conveniently held in hand, turned in all directions and carefully inspected from all angles. This enabled precise visualization of the real, sometimes hidden, origins and complexity of spatial relations of large and small branches entering and outgoing of the RAA. These stable physical 3D models could be studied simultaneously or separately by different members of the vascular team, for improved treatment planning (**Figure 1**).

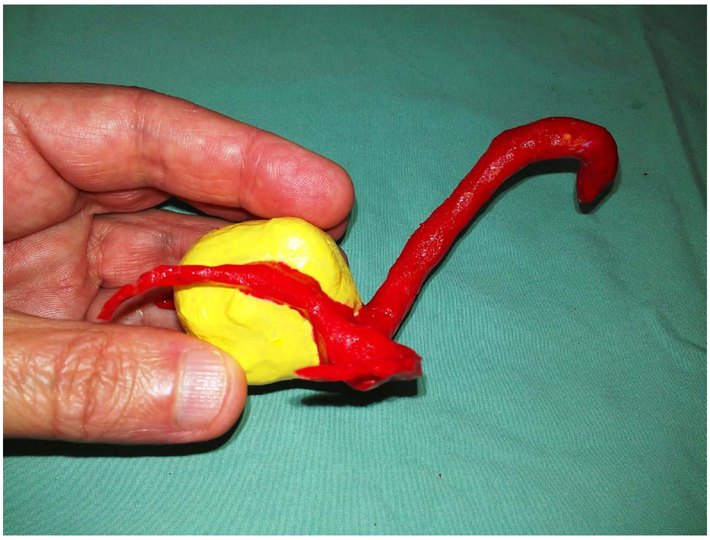

Figure 1. 3D printed, enlarged and color enhanced, physical model of a large sacular renal artery aneurysm in the hands of the vascular surgeon. Normal artery colored red, aneurysm in yellow.

Intentional enlargement of the printed model, rather than an actual size with 1:1 dimensions model, allowed a clearer physical object for palpation and manipulation and better preservation of fine branches in a more stable model (**Figure 2**).

The in house produced 3D solid models were smooth and exceptionally accurate to the millimeter range. The tactile and visual inspection of a complex RAA model were helpful in better comprehending all minute details of the disease to improve treatment plans. The models produced added significantly to all observers, including experienced vascular surgeons, invasive radiologists, and product specialist of the device manufacturers.

Many aspects of the preoperative evaluation of a complex renal artery aneurysm were changed due to new observations on a solid model. Some of these aspects are detailed as follows.

Details of Selected Case Studies

Case 1: A 68 years old man presented with unspecific abdominal pain and hypertension. A CTA was performed in the community as part of his workup. An unexpected complex right renal artery 23 × 12 mm in size was diagnosed and the patient was referred to our center. Computerized 3D reconstructions showed a very complex hilar sacular aneurysm with several branches. An enhanced 3D printed model showed finer details: The aneurysm emanated in the main renal artery after the first branch emerged. One large branch emerged at 12 o'clock of the aneurysm, and a second large branch emerged at 8 o'clock. Two more small branches were identified entering directly into the parenchyma (**Figure 3**; Video 1, May be watched at the following link https://www.youtube.com/watch?v=DEVjgXpLV-Y&feature=youtube_gdata_player)

In spite of the size, and because of the complexity of the aneurysm, no intervention was undertaken, and the patient is conservatively treated and followed.

Case 2: A 57 years old woman had an abdominal CT performed in another hospital 4 years ago, as part of staging for breast malignancy. She was also hypertensive and was well controlled with 2 drugs. A 23 mm diameter right renal sacular aneurysm was detected and she was followed conservatively. A follow-up US study suspected some enlargement of the aneurysm and a CTA was done. This showed no real change in dimensions. Computerized 3D reconstruction of the RAA was difficult to interpret because of tortuosity of branches. A 3D printed model showed a large sacular aneurysm located right at the main renal artery bifurcation. The upper branch emanates at 12 o'clock of the aneurysm and the lower branch emanates from the postero-inferior wall at 4 o'clock, it is "crawling" and adherent to the posterior wall of the aneurysm (**Figure 4**; Video 2, May be watched at the following link (https://www.youtube.com/watch?feature=player_detailpage&v=qfGObR9h3zY).

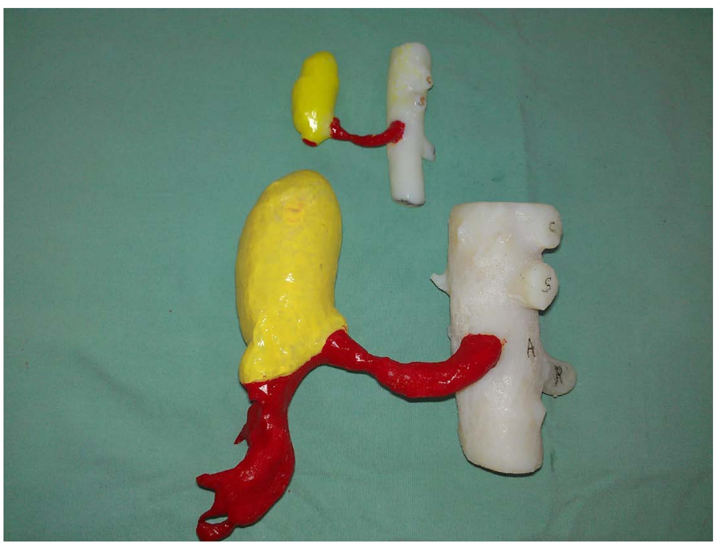

Figure 2. Two 3D printed models of the same sacular renal artery aneurysm. The upper one is actual 1:1 size, the lower one is an enlarged model for better detail appreciation. The runoff artery is now clear. Aorta is in white, normal artery in red, aneurysm in yellow. C-Celiac trunk, S-SMA (superior mesenteric artery), R-Renal artery.

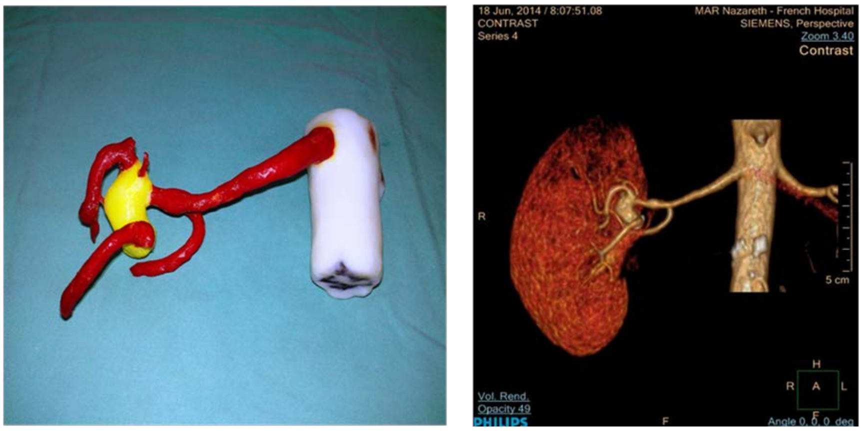

Figure 3. 3D computer reconstruction of a large hilar aneurysm (right panel) and a color enhanced 3D model of the same aneurysm (left Panel). Aorta is depicted in white, normal artery in red aneurysm in yellow.

Figure 4. An enhanced 3D model of a complex RAA looking from behind (Left panel). The model allows better visualization of the origins and courses of the branches. A conventional 3D reconstruction looking from the front (right panel) for comparison. Aorta is depicted in white, normal artery in red aneurysm in yellow.

An endovascular intervention was considered using two parallel flow diverting stents, but the patient refused. She is treated with doxycyclin and followed.

Case 3: A 36 years old man had an episode of left flank pain, hypotension and macroscopic hematuria. Workup in another hospital revealed a large left per renal hematoma. Urgent angiography showed active bleeding from an aneurysmatic renal branch which was then successfully embolized with coils to stop bleeding. CTA and 3D modeling showed additional fusiform aneurysms in 2 extra renal artery branches. Each aneurysm had small additional branches (**Figure 5**; Video 3, https://www.youtube.com/watch?v=0VEaaAeizCc&feature=youtube_gdata_player).

This patient elected to continue follow-up at his original hospital, and was lost for follow-up.

Case 4: A 41 years old woman presented with right flank pain and renovascular hypertension. Initial workup detected a 4 cm large sacular aneurysm in the main right renal artery (**Figure 2**; Video 4, https://www.youtube.com/watch?v=iyMwIfeUnsU&feature=youtube_gdata_player). Endovascular treatment was contemplated. Selective angiography confirmed a large sacular aneurysm protruding upwards, with a single runoff branch. A short covered stent (Viabahn 6 × 25 mm, Gore & Associates, Flagstaff, Arizona, USA) was placed across the neck of the aneurysm but it slipped inside the aneurysm. Therefore a second longer covered stent (Viabahn 6 × 50 mm, Gore & Associates, Flagstaff, Arizona, USA) was successfully placed across the neck with a good result of aneurysm exclusion. At 3 years follow-up his RAA is completely thrombosed, the patients is feeling well, his hypertension is controlled with 1 antihypertensive drug, and he has normal kidney function.

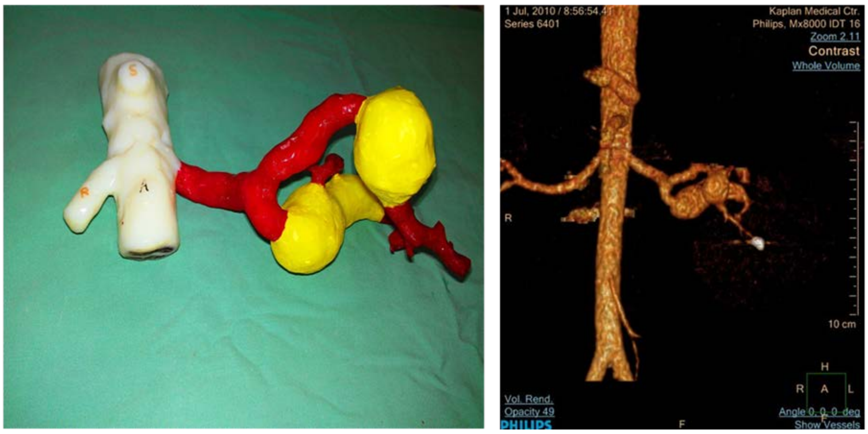

Figure 5. A solid 3D model of a case with multiple RAA, partially obscuring each other (left Panel) and the corresponding computerized 3D reconstruction (right panel). Aorta is depicted in white, normal artery in red aneurysm in yellow.

In addition to these cases, 4 more similar 3D RAA models were rapidly 3D printed so far (not shown). They are appropriate not only for planning, but also for revisions, for teaching, and for patient awareness. However, it is important to emphasize that for most small and asymptomatic, incidentally detected RAA we do not recommend interventions. Therefore, in many such patients referred to our service, no modeling and 3D printing of RAA was contemplated.

4. Discussion

Imaging of complex anatomical structures for diagnosis and treatment planning has been significantly improved in recent years by better US, CT, and MRI equipment, and better software packages for on screen visualization and reconstruction. The computer derived images can be individually inspected or projected to a medical team or any interested audience. However, in some cases computer screen images alone are somewhat limited and are not sufficient for a full understanding of the underlying pathology. Aneurysms of the cerebral and renal arteries are sometimes so complicated three dimensional structures that the usual computer reconstructions are not satisfactory for accurate diagnosis and treatment planning. A better method of visualization would be helpful in these cases [9].

Advances in both software and hardware of 3D printing technology, are now making the process of in house preparation of 3D physical models easily accessible in many medical centers. This technology is rapidly becoming common, easy to use, and even personalized. It has been previously reported that this technology may prove to be very helpful in general surgery and especially in the field of vascular medicine and surgery. The technology has been used for stent planning of aortic disease and aneurysms. Complex RAA disease is another good example, in our opinion, where 3D technology will become significant in treatment planning. As experienced vascular surgeons and invasive radiologist we would like to have a better way to inspect and even palpate the minute details of a complex aneurysm that we are going to treat. A rapidly printable 3D model will be helpful in defining important details like origin of branches, angulations, length, stenoses and more. This may determine the choice of optimal techniques and devices. Moreover, it may lead the surgeon or the invasive radiologist to avoid potentially non-feasible interventions. Thus, it is expected that 3D printing will markedly improve results of treatment in these complex RAA patients. Another interesting aspect of 3D printing is that the permanent materialization of the RAA enables readily demonstration of the vascular pathology in a self-evident way, to colleagues, to students, and to patients alike.

In this report summarizing our preliminary experience with 3D modeling technology we have demonstrated the value of 3D physical models in better comprehension of complex RAA. More important anatomical details were clarified and better retrospective and prospective techniques could be planned. Our preliminary experience is so convincing that in the future we intend to print in advance every complex vascular structure before vascular or endovascular intervention is contemplated.

Nonetheless, we would like to emphasize that 3D physical models are not generally required for most RAA cases. Computer screen based reconstructions, using the advanced software packages currently available, are sufficient in most cases and provide all anatomical and technical information needed. These imaging methods will continue to serve clinicians and will certainly improve and advance further with time. They are always invaluable in treatment planning. However, in a minority of cases, especially those with borderline anatomy, this 3D model printing technology may become a further significant tool for the decision making. 3D printing may sometimes determine the feasibility of planned endovascular techniques and will facilitate the decision how to perform the planned procedure safely and effectively.

5. Conclusion

Complex RAA can be best appreciated using enhanced 3D printing. Moreover, accurate preoperative planning may be improved for better patient outcomes. In our opinion, 3D printing advances will be of help in diagnosis and treatment planning of complex anatomical and pathological conditions not only in vascular surgery but in many other areas in medicine and surgery as well. Institutional availability and experience with 3D equipment and software, for enhanced imaging, should be encouraged.

Acknowledgements

We would like to thank Itamar Kahn for collaboration in this project. The 3D models were printed in the Workshop for fine mechanics, Rappaport Faculty of Medicine, Technion, Israel Institute of technology, Haifa, Israel.

Conflict of Interest

The authors declare that they have no conflict of interest.

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