HEART RESEARCH

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ISSN 2377-164X Open Journal http://dx.doi.org/10.17140/HROJ-4-143

Mini Review

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Volume 4 : Issue 3
Article Ref. #: 1000HROJ4143

Article History
Received: September 27th, 2017
Accepted: October 3rd, 2017
Published: October 4th, 2017

Citation
Sun Z. Three-dimensional printing in cardiovascular disease: Verification of diagnostic accuracy of 3D printed models. *Heart Res Open J.* 2017; 4(3): 66-70. doi: 10.17140/HROJ-4-143

Three-Dimensional Printing in Cardiovascular Disease: Verification of Diagnostic Accuracy of 3D Printed Models

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ABSTRACT

This article discusses the diagnostic accuracy of patient-specific 3D printed models in delineating cardiovascular anatomy and disease, with a focus on a recent paper published in the *American Journal of Roentgenology* about the accuracy of 3D printed hollow models of visceral aneurysms. Three aspects will be discussed in this review: first, 3D printed physical models are accurate in assessing the sizes and shapes of visceral aneurysms and related arteries; second, a more reliable method was implemented in this study for measurement of the diagnostic accuracy of 3D printed model to further validate the precision of 3D printing technique; and finally, 3D printed models serve as a reliable tool for replicating anatomical structures and pre-surgical simulation of endovascular treatment of aneurysmal disease.

KEY WORDS: Accuracy; Aneurysm; Cardiovascular disease; Model; Simulation three-dimensional printing.

ABBREVIATIONS: 3D: Three-dimensional; CT: Computed Tomography; MRI: Magnetic Resonance Imaging.

Three-dimensional (3D) printing is a rapidly developed technique showing great promise in medicine with increased applications reported in the cardiovascular disease.[1-12] 3D printed physical models based on computed tomography (CT) or magnetic resonance imaging (MRI) imaging data show high accuracy in replicating complex anatomic structures of cardiovascular system, ranging from delineation of anatomical details of cardiovascular system to detection of pathologies.[1-9] Furthermore, 3D printed realistic models have been shown to play an important role in pre-surgical planning and simulation of complex cardiovascular disease, in both adult and pediatric patients through clear illustration of cardiac pathologies and facilitation of the simulation.[13-17]

Before 3D printed models are recommended for routine clinical applications, it is important to ensure the accuracy of 3D printed models. This is especially important for dealing with cardiovascular disease due to the complexity of cardiovascular anatomy and a variety of cardiovascular diseases, which requires high precision of 3D printed models. Accuracy of patient-specific 3D printed models has been reported in the maxillofacial surgery using anatomic landmarks.[18-20] Similarly, good to excellent agreement has been reached between 3D printed models and original source 2D images for dimensional measurements of aortic valve, aortopulmonary artery, and aortic aneurysms.[21-25] However, in a recent study, Ho et al have indicated that the variances in aortic diameter measurements between 3D printed models and 2D contrast-enhanced CT images exceeded 1.0 mm, which is beyond the standard deviation of 1.0 mm.[26] This highlights the potential limitations of using anatomic landmarks to measure accuracy of 3D printed hollow models, such as heart models or aneurysmal models. By taking into account both sizes and shapes of the visceral aneurysms, the accuracy of 3D printed hollow models has been validated to further confirm the reliability of 3D printing technology.[27]

In their recent study, Shibata et al retrospectively analyzed 11 patients having a total

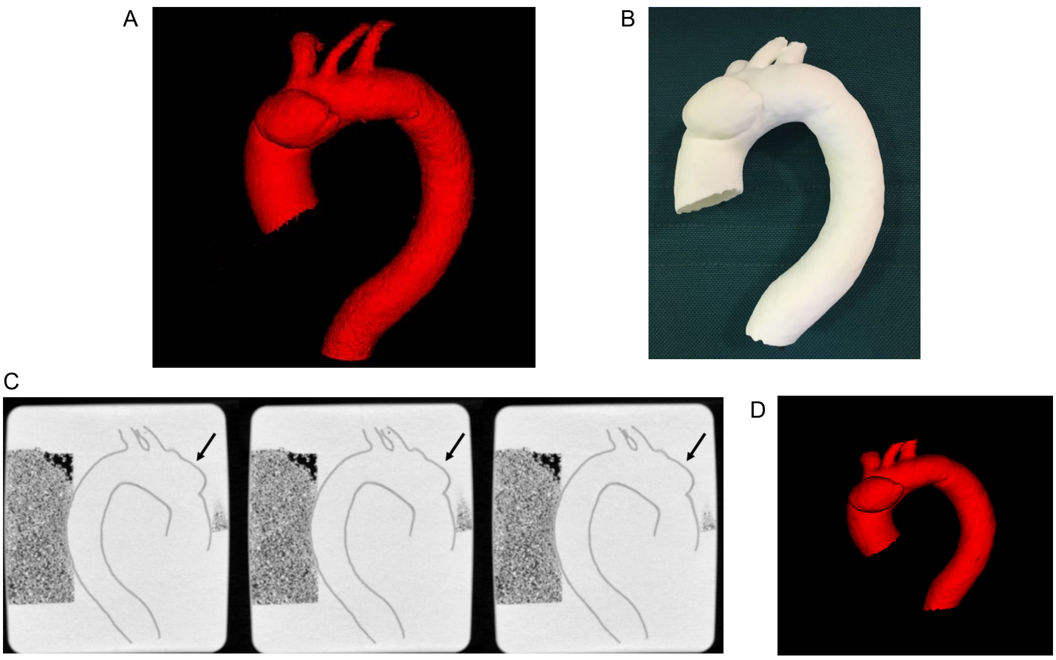
ISSN 2377-164X http://dx.doi.org/10.17140/HROJ-4-143

of 15 true visceral aneurysms consisting of splenic aneurysms (n=8), gastric aneurysms (n=2), hepatic aneurysms (n=2), epigastric, gastroduodenal and posterior superior pancreaticoduodenal aneurysms (1 for each of these arterial aneurysms).[27] 3D printed models were created from contrast-enhanced CT angiographic images which were acquired on a 320-slice CT scanner. These hollow models of visceral aneurysms were manufactured with nylon material with a layer thickness of 0.2 mm using a fused deposition melting 3D printer. The 3D printed models were scanned on a 320-slice CT scanner with slice thickness of 0.5 mm, reconstruction interval of 0.25 mm, and pixel size of 0.234×0.234 mm. The sizes and shapes of segmented aneurysms and related arteries in terms of diameters at x, y and z-axis dimensions as well as volume of the aneurysms from both patient's CT and 3D printed model images were analyzed and compared using the Dice coefficient index which allows for more accurate assessment of diagnostic accuracy. Their results showed no significant difference in aneurysm volumes between measurements from CT angiography (mean, 5168±5808 mm^3, range 138 to 18,691 mm^3) and those from 3D printed model data (5271±6279 mm^3, range 149 to 21,570 mm^3) (p=0.56). The percentage differences in volume measurement between patient's CT data and 3D printed model data ranged from 0.05 to 15.4%. A high-level of accuracy has been shown with all of the 3D printed models with the Dice coefficient index between 84.2% and 95.8%.

There are three observations that bear discussion from Shibata and colleagues' study. First, 3D printed models are highly accurate in replicating complex vascular anatomy and aneurysm when compared to the original CT angiographic images. Previous studies have reported the accuracy of 3D printed models of cardiovascular disease with good to excellent correlation between 3D printed models and original CT or MRI data.[21-25] However, these studies are limited in assessment of diameter changes in the selected anatomical regions, which failed to consider the whole shapes of vascular structures or aneurysms. Further, according to a recent systematic review, majority of the current studies compared 3D printed models with original source CT or MRI data,[12,21-24] while only a few of them compared images of the scanned 3D printed models with original source imaging data (Figure 1).[25,26] Discrepancy in measuring these dimensional diameters was shown in one of the studies with the maximal difference in vessel diameter being 3.2 mm, highlighting the limited accuracy of using diameter measurements.[26]

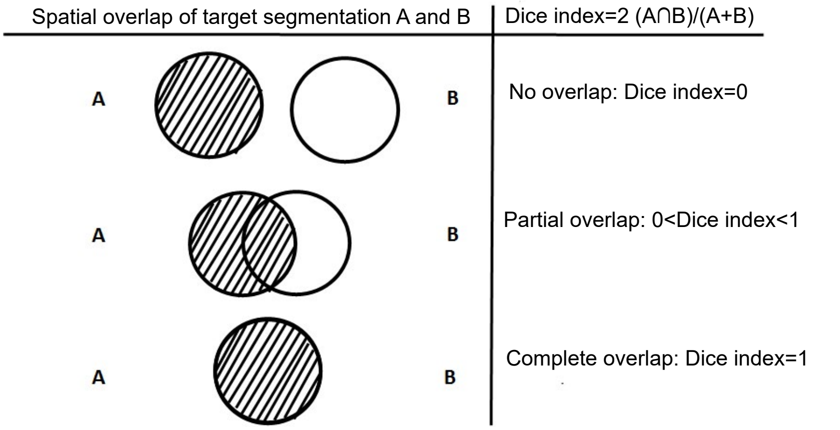
This limitation has been addressed by using a more accurate method to determine the accuracy of 3D printed models, which is the second observation from Shibata et al study. Authors used the Dice coefficient index, a reproducibility validation metric which is represented by the spatial overlap index. The Dice coefficient index is a reliable method measuring the anatomic accuracy of the models, with value 0 indicating no overlap and 1 showing identical and complete overlap between segmented geometries (Figure 2).[27-29]

Figure 1: Aortic Aneurysm in the Ascending Aorta. A: 3D Reconstruction CT Image Showing an Aneurysm in the Ascending Aaorta just Inferior to the Innominate Artery. B: 3D Printed Model Bbased on Segmentation of CT AngioGraphic Data with use of White Strong and Flexible Material. C: Coronal Reformatted Images Showing the CT Images of the 3D Printed Model Filled with Contrast Medium with Clear Delineation of the Aneurysm (Arrows). D: 3D Reconstruction CT Image of the Model Showing the Aneurysm with the same Dimension to that from the Original CT Angiographic Images.



ISSN 2377-164X http://dx.doi.org/10.17140/HROJ-4-143

Figure 2: The Dice Coefficient Index Representing Spatial Overlap and Reproducibility, where Dice Index=2 (Intersected Region)/(Sum of Region A and Region B).[28]



This method has been used to validate the segmentation accuracy in white matter lesions and the peripheral zone of the prostate gland.[28,30,31] Shibata and colleagues adopted the Dice coefficient index in their study to perform statistical shape analysis of the aneurysms and related arteries, with findings further validating the high accuracy of 3D printed models. The similar approach was used by Frolich et al who analyzed shapes of cerebral aneurysms with a high-level of accuracy in aneurysm volume measurements between 3D printed models and 3D rotational angiographic data.[29] The Table 1 summarizes the study characteristics of comparing 3D printed models and original patient's imaging data based on these two studies which used the Dice index approach to determine accuracy of 3D printed models.

The third observation lies in the fact that high accuracy of 3D printed models of complex aneurysms enables it to serve as a useful tool for pre-operative planning and simulation of cardiovascular disease. With 3D printed models integrated into preoperative planning, the efficiency of surgical interventions will be increased by decreasing operating/or interventional procedural time, reducing radiation exposure to patients during these procedures, thus improving patient outcome with reduced complications. 3D printing has been considered a valuable tool in pre-surgical planning and simulation of cerebral aneurysms according to both quantitative and qualitative assessments.[32] Further, 3D printed hollow models of cerebral aneurysms help the design of catheter device prior to the interventional procedure, therefore, contributing to development of a patient-specific treatment plan through identifying optimal micro catheter shape for coiling an aneurysm.[33] Due to difficulty in fully understanding complex cardiovascular anatomy, radiologists or cardiologists can improve their knowledge or operating skills by performing simulation of treatment procedures on the 3D printed models. Thus, a high-level of accuracy of 3D printed model is essential to achieve this goal by precisely demonstrating the anatomical details and pathological changes. This is confirmed by Shibata and Frolich's studies, although further research is needed to employ their method in the diagnostic assessment of accuracy of 3D printed models with different cardiovascular diseases.

In summary, patient-specific 3D printed models can accurately replicate cardiovascular disease, with diagnostic accuracy further enhanced with use of a more reliable method, the Dice coefficient index. This is of paramount importance for assessment of complex aneurysmal diseases due to presence of different vascular sizes and shapes. High accuracy of 3D printed models comprises an essential component for interventional radiology (ELIMINATE radiological procedures) because of widespread use of less invasive procedure, endovascular treatment in the management of the aneurysms.[34] The 3D printed models serve as a valuable tool for pre-operative planning and simulation of endovascular procedures through accurately and precisely replicating anatomical structures. Further studies with inclusion of large cohort of patients are necessary to validate these findings.

Table 1: Study Characteristics of Using Dice Coefficient Index for Assessment of 3D Printed Model Accuracy.

Studies	No. of aneurysms	Imaging technique for 3D printing	Patient aneurysm volume (mm^3) (mean±SD)	Model aneurysm volume (mm^3) (mean±SD)	Dice coefficient index (%) (mean±SD)
Shibata et al[27]	15 visceral aneurysms	CT angiography	5168±5808	5271±6279	91.1±4.1
Frolich et al[29]	10 intracranial aneurysms	3D rotational angiography	570.1±976.9	554.1±949.1	93.6±2.4

3D: Three-dimensional; SD: Standard Deviation; CT: Computed Tomography.

ISSN 2377-164X
http://dx.doi.org/10.17140/HROJ-4-143

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