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Editorial

Three-Dimensional Printing-Generated Realistic Anatomy Models and Virtual Endoscopy-Enhanced Intravascular Assessment of Pathologies

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Three-dimensional (3D) printing has become a widely used technique showing many medical applications which range from orthopedics and maxillofacial surgery to cardiovascular disease and tumor imaging.[1-10] Computed tomography (CT) or magnetic resonance imaging (MRI) data-generated 3D printed realistic models have been confirmed to accurately replicate normal anatomical structures and depict pathological changes including a demonstration of complex pathologies such as complicated cardiovascular disease.[7-11] 3D printed models also serve as a useful tool for pre-surgical planning, simulation of surgical procedures, training medical students and young doctors, and enhancing patient-doctor communications.[12-16]

Most of the current studies on 3D printing in medicine are related to the use of two-dimensional (2D) and 3D image visualizations for assessment of clinical value of patient-specific 3D printed models, whereas very little information is available about the use of 3D virtual endoscopy to assist detection of lesions which may be missed on traditional imaging examinations. Yoon et al in their recent case study presented the experience of localizing a lung cancer lesion by combining virtual endoscopy with 3D printing technology.[17] Their case refers to an endobronchial lesion which was detected in the right upper lobe on bronchoscopy, however, it was not displayed on thin slice contrast-enhanced CT images. The lesion location shown on positron emission tomography (PET)/CT did not match with bronchoscopic finding due to respiratory misregistration on PET and CT images. This led to the difficulty of deciding treatment options by the a multidisciplinary team. The virtual endoscopic visualization shows an abnormal change of the bronchial wall which corresponds to the lesion location. The team created a 3D printed airway model with anatomical structures coded with different colors. After reviewing the virtual endoscopic images and 3D printed model, the team determined the exact location of the lesion, allowing the best treatment option (photodynamic therapy) to be determined, and a successful outcome was achieved without complications. Follow-up bronchoscopy 2-months after treatment did not show any sign of a residual tumor. This unique case highlights the enhanced role of a combination of 3D printing and 3D virtual endoscopy in detecting small lesions.

Another research direction of using 3D printed models is to develop optimal CT scanning protocols for reducing radiation dose while still achieving diagnostic images. Abdullah et al developed a novel 3D printed cardiac phantom with the insertion of different filling materials.[18] The 3D printed model was placed within an anthropomorphic chest phantom and was scanned with multi-slice CT using the standard 120 kVp protocol. CT attenuations of these filling materials (contrast medium, air, oil/fat, and jelly/muscle) from the 3D printed phantom measurements were similar to those from patient's CT images. Despite the uniqueness of this cardiac insert phantom, different scanning protocols were not tested on the 3D printed model, which is a major limitation. This has been addressed by our recent research papers.

Our recent publications have further explored the usefulness of 3D printed models in developing optimal CT scanning protocols and studying the effect of different slice thicknesses on the visualization of coronary stenosis and calcified plaques with the assistance of virtual intravascular endoscopy (VIE).[19-21] Our first paper showed that we have successfully created a patient-specific 3D printed pulmonary artery model with normal anatomy.[19] A series of CT pulmonary angiography (CTPA) protocols were tested on the model with a range of kVp (80, 100 and 120) and pitch values (0.7, 0.9 and 1.2) with the aim of determining low dose CTPA protocols. The model was found to be highly accurate with <0.5% deviation in diameter measurements of anatomical structures. No significant difference was found in image quality (signal-to-noise ratio: SNR) measurements among these protocols, indicating the reduction of radiation dose by up to 75% with the use of low-dose CTPA protocol.

We extended our research in another publication by simulating pulmonary embolism in the 3D printed model.[20] A large thrombus was inserted into the main pulmonary arteries and CT scans were performed on a 128-slice dual-source CT with tube voltage ranging from 70, 80, 100 to 120 kVp, pitch value from 0.9 to 2.2 and 3.2. Image quality was assessed by measuring the signal-to-noise ratio (SNR) within the thrombus and in the main pulmonary arteries and was compared among these protocols. A low dose of 80 and 100 kVp with use of high pitch 3.2 protocols significantly reduced radiation dose (up to 80% dose reduction) without affecting image quality as confirmed by the findings (Figure 1). Image noise was increased with significantly lower SNR in the 70 kVp and high pitch 3.2 protocol. Further, we generated VIE images and demonstrated the intraluminal arterial wall and thrombus appearances corresponding to these CTPA protocols (Figure 2). When kVp is lowered to 70 and pitch is increased to 3.2, image quality is compromised because of irregular appearances noted on the arterial wall and thrombus as shown in Figure 2A. Thus, selection of 70 kVp and 3.2 high pitch CTPA protocol is not recommended due to increased image noise which affects diagnostic image quality, while low-dose CTPA such as 80 kVp and pitch 3.2 or 70 kVp and pitch 2.2 is suggested as an optimal protocol for diagnosis of pulmonary embolism.

Another publication from our group demonstrates the usefulness of 3D printed coronary artery models with a simulation of calcified plaques.[21] It is well-known that diagnostic value of coronary CT angiography (CCTA) in the visualization of calcified plaques is between low and moderate due to high false positive rate resulting in low specificity and positive predictive value (18-53%).[22-24] High spatial resolution imaging improves the diagnostic accuracy of CCTA, and this is confirmed in our study. We created 3 patient-specific coronary artery models with a simulation of calcified plaques in the left coronary arteries with different degrees of stenosis (<50%, 70-90%). The models were scanned with ultra-high resolution synchrotron radiation CT imaging with images reconstructed at different slice thicknesses comprising 0.095, 0.208. 0.302 and 0.491 mm. 2D axial and 3D VIE images were generated in these datasets to determine the effect of slice thickness on the assessment of lumen stenosis and plaque appearances on VIE. Results showed that images acquired with a slice thickness of 0.491 mm significantly overestimated the degree of coronary stenosis ($p<0.05$) when compared to other thin slice thicknesses. The calcified plaque becomes blurring as opposed to the sharp appearance observed in images acquired with thin slice thicknesses (Figure 3). Irregular appearances of plaques were noticed on VIE images reconstructed with 0.491 mm slice thickness.[21]

Figure 1. *Computed Tomography Pulmonary Angiography (CTPA) Protocols with Use of Different kVp and Pitch Values. When Pitch was Increased to 3.2, Image Noise was Increased with 70 and 80 kVp Protocols (A and B), Especially Apparent in the 70 kVp Protocol. No Significant Change of Image Quality was Noticed with 100 and 120 kVp Protocols, Regardless of Pitch Values (C and D). Arrows Refer to the Thrombus in Both Main Pulmonary Arteries.*

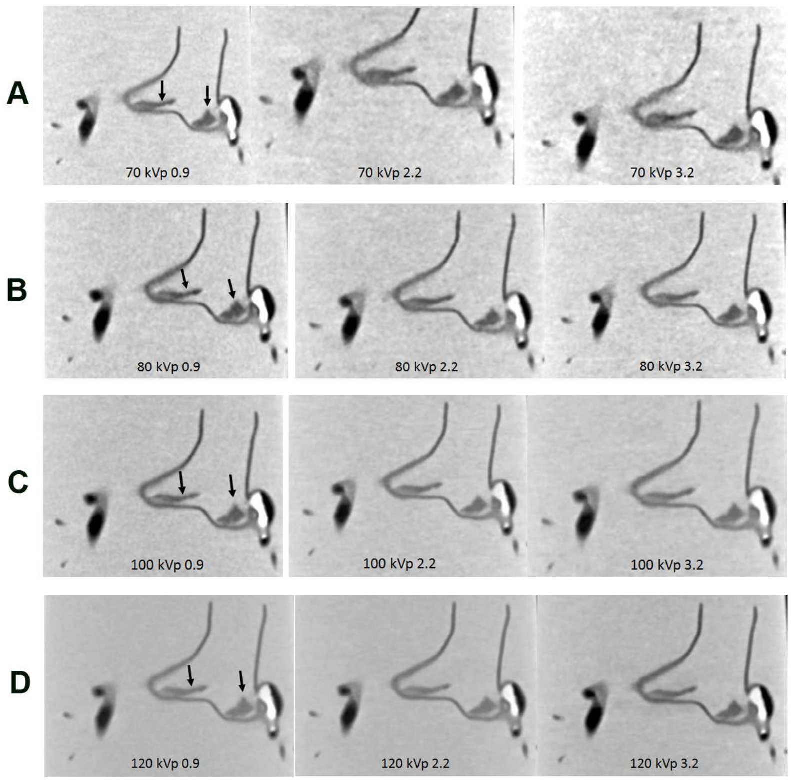


Figure 2. *Virtual Intravascular Endoscopy (VIE) of Thrombus and Pulmonary Artery Wall in Images Acquired with Different CTPA Protocols. Smooth Intravascularappearances of the Thrombus and Arterial Wall are Clearly Demonstrated with CTPA Protocols Using 100 and 120 kVp And Different Pitch Values, While the Thrombus Surface and Arterial Wall Become Slightly Irregular with 70 and 80 kVp Protocols (A-D). This Is Especially Obvious with 70 kVp and High Pitch 3.2 Protocol with Irregular Appearance of the Thrombus (Long Arrows In A) and Presence of Artifact (Arrowhead) Resulting In Disruption of the Arterial Wall (A). Short Arrows Refer to the Thrombus In both Main Pulmonary Arteries.*

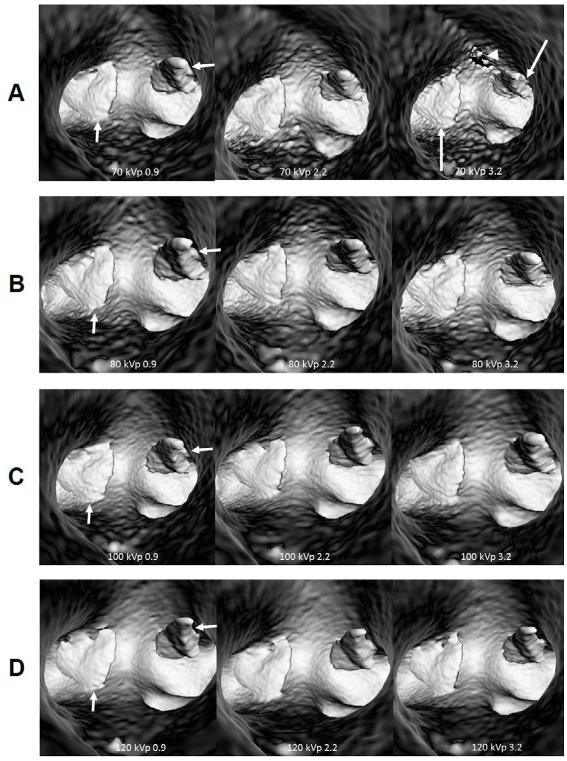
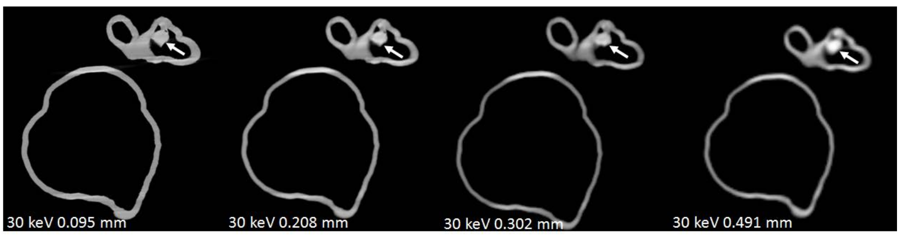


Figure 3. *2D Synchrotron Radiation Computed Tomography Images of the Coronary Model with Moderate Stenosis (<50%) Caused by Simulated Calcified Plaque at the Left Anterior Descending Coronary Artery. 2D Axial Images Acquired with a Beam Energy of 30 keV and Different Slice Thicknesses Showed that Images Reconstructed with a Slice Thickness of 0.491 mm Result in Suboptimal Visualization of the Plaque (Arrows) and Coronary Wall when Compared to Thin Slice Thicknesses (from 0.095 to 0.302 mm).*



In summary, these recent publications highlight another research direction of using patient-specific 3D printed models for investigating the optimal CT scanning protocols and determining the spatial resolution of CT images for accurate assessment of coronary plaques and associated lumen stenosis. The findings of these studies advance the application of 3D printed models in the medical imaging field such as radiation dose reduction and image quality assessment. These findings can be used to guide implementation of low-dose CT protocols in clinical practice, and develop strategies to focus on image quality assessment.

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