



Personalized 3D printed coronary models in coronary stenting

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Background: 3D printing has shown great promise in cardiovascular disease, with reports mainly focusing on pre-surgical planning and medical education. Research on utilization of 3D printed models in simulating coronary stenting has not been reported. In this study, we presented our experience of placing coronary stents into personalized 3D printed coronary models with the aim of determining stent lumen visibility with images reconstructed with different postprocessing views and algorithms.

Methods: A total of six coronary stents with diameter ranging from 2.5 to 4.0 mm were placed into 3 patient-specific 3D printed coronary models for simulation of coronary stenting. The 3D printed models were placed in a plastic container and scanned on a 192-slice third generation dual-source CT scanner with images reconstructed with soft (Bv36) and sharp (Bv59) kernel algorithms. Thick and thin slab maximum-intensity projection (MIP) images were also generated from the original CT data for comparison of stent lumen visibility. Stent lumen diameter was measured on 2D axial and MIP images, while stent diameter was measured on 3D volume rendering images. 3D virtual intravascular endoscopy (VIE) images were generated to provide intraluminal views of the coronary wall and stent appearances.

Results: All of these stents were successfully placed into the right and left coronary arteries but 2 of them did not obtain wall apposition along the complete length. The stent lumen visibility ranged from 54 to 97%, depending on the stent location in the coronary arteries. The mean stent lumen diameters measured on 2D axial, thin and thick slab MIP images were found to be significantly smaller than the actual size ($P < 0.01$). Thick slab MIP images resulted in measured stent lumen diameters smaller than those from thin slab MIP images, with significant differences noticed in most of the measurements (4 out of 6 stents) ($P < 0.05$), and no significant differences in the remaining 2 stents ($P = 0.19-0.38$). In contrast, 3D volume rendering images allowed for more accurate measurements with measured stent diameters close to the actual dimensions in most of these coronary stents, except for the stent placed at the right coronary artery in one of the models due to insufficient expansion of the stent. Images reconstructed with sharp kernel Bv59 significantly improved stent lumen visibility when compared to the smooth Bv36 kernel ($P = 0.01$). 3D VIE was successfully generated in all of the datasets with clear visualization of intraluminal views of the stents in relation to the coronary wall.

Conclusions: This preliminary report shows the feasibility of using 3D printed coronary artery models in coronary stenting for investigation of optimal coronary CT angiography protocols. Future studies should focus on placement of more stents with a range of stent diameters in the quest to reduce the need for invasive angiography for surveillance.

Keywords: Coronary stent; diameter; kernel; lumen; model; three-dimensional (3D) printing; visibility; visualization

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Introduction

Coronary computed tomography angiography (CCTA) is a widely used less-invasive modality in the diagnostic assessment of coronary artery disease. Due to technological improvements in CT scanning techniques, CCTA has demonstrated high diagnostic accuracy in determining coronary stenosis and serves as a reliable gatekeeper for excluding obstructive coronary stenosis, even in patients with high heart rates (1-7). Coronary stenting is a commonly performed less invasive procedure following percutaneous coronary intervention for the treatment of patients with significant coronary artery stenosis, while stent patency and presence of in-stent restenosis is increasingly evaluated with CCTA, according to several systematic reviews and meta-analyses (8-13). Despite reported high sensitivity and specificity of CCTA, the clinical application of CCTA for evaluation of coronary in-stent restenosis remains questionable because of beam-hardening artifacts which result in high false positive rates, leading to low positive predictive value, especially when assessing stents with diameter less than 3.0 mm (14,15).

The recent introduction of third generation dual-source (DSCT) with improved spatial and temporal resolution has enhanced the visualization of coronary stent lumen and increased the diagnostic value of CCTA in detecting in-stent restenosis based on *in vitro* phantom and patient studies (16-19). Furthermore, use of different convolution kernels or postprocessing image reconstructions have been shown to reduce beam hardening or blooming artifacts associated with metal stent components, thus improving the diagnostic image quality of CCTA in coronary stenting (20,21). The purpose of this study was to simulate coronary stenting by placing coronary stents with different diameters into the three-dimensional (3D) printed coronary artery models and acquire images on the third generation DSCT scanner. The innovative aspect of this study lies in utilizing personalized 3D printed models to simulate the coronary stenting procedure and scanning the models with latest CT scanner with images reconstructed with different imaging parameters. 3D printing is increasingly used in medical applications with promising reports in the domain of congenital heart disease and aortic disease (22-30). To the best of our knowledge, this is the first study using 3D

printed coronary models with stents inserted inside the coronary arteries for determining the feasibility of coronary stenting procedure.

Methods

3D printed coronary artery models

Patient-specific 3D printed coronary models were created using de-identified CCTA images with models printed by soft and elastic material, TangoPlus. Details about these 3D printed models were reported in our previous publication (31). In brief, each model has right coronary artery (RCA) and left coronary arteries (either left anterior descending-LAD, or left circumflex-LCx or both of these branches). *Figure 1* shows these 3D printed coronary models that were used in the experiments.

Coronary stent placement

Six balloon expandable expired coronary stents with different diameters and lengths were used to simulate coronary stenting. Stent details are summarized in *Table 1*.

Each stent was placed into the 3D printed coronary artery to simulate the interventional procedure for treatment of coronary artery disease. Although the stents were not visible from the outside of the model, all were deployed according to recommended balloon inflation pressures on the instructions for use (IFU). Optimal deployment was therefore assumed as it could not be directly visualized. Of the 6 coronary stents, 2 were placed at the RCA (proximal and distal segments) in the model 1, and 1 in RCA and 1 in distal LAD in the model 2, 1 in RCA and 1 in proximal LCx in the model 3. The models were placed in a plastic container which was positioned on the CT scanner table parallel to the z-axis. *Figure 2* shows 3D volume rendering images of stent locations in the 3D printed coronary artery branches.

Coronary CT scanning protocols and image reconstruction

CT scan was performed on a 192-slice 3rd generation DSCT scanner (Siemens Force, Siemens Healthcare, Forchheim, Germany) without using electrocardiographic gating due to

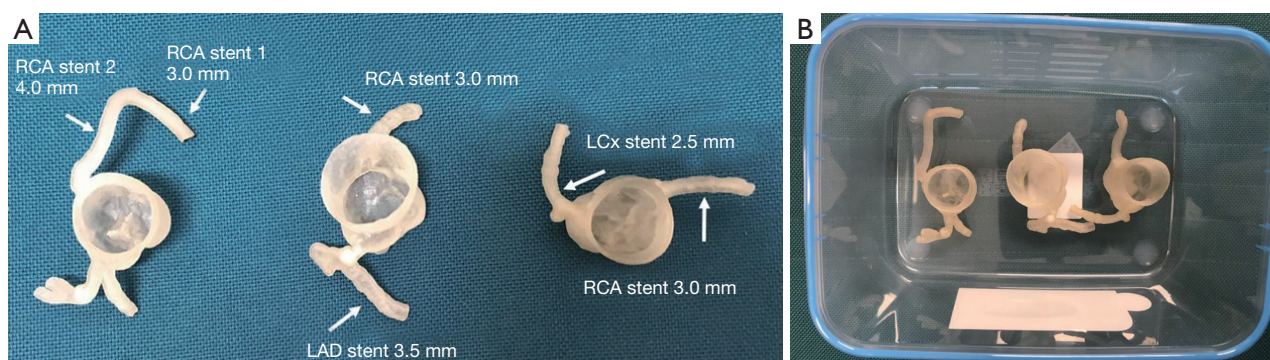


Figure 1 3D printed coronary artery models used for simulation of coronary stenting. (A) Three models comprising right coronary artery (RCA) and left anterior descending (LAD) and left circumflex (LCx) with stents inserted into the artery branches; (B) the models were placed in a plastic container for CT scans. Arrows refer to the locations where stents with different sizes were placed.

Table 1 Details of coronary stents placed in the 3D printed coronary models

Stent location in the coronary arteries	Stent details			
	Diameter	Length	Balloon pressure	Stent manufacturer
Model 1				
RCA-stent 1	3.0 mm	30 mm	16 atm	Medtronic AVE BeStent™ 2
RCA-stent 2	4.0 mm	18 mm	16 atm	Biocompatibles Biodiv Ysio™
Model 2				
LAD	3.5 mm	11 mm	16 atm	Biocompatibles Biodiv Ysio™
RCA	3.0 mm	24 mm	16 atm	Medtronic AVE BeStent™ 2
Model 3				
RCA	3.0 mm	12 mm	16 atm	Boston Scientific Promus PREMIER™
LCx	2.5 mm	24 mm	8 atm	Medtronic AVE BeStent™ 2

LAD, left anterior descending; LCx, left circumflex; RCA, right coronary artery.

the static nature of the models. The following parameters were used for scans: beam collimation: $2 \times 192 \times 0.6$ mm with gantry rotation of 250 s, tube potential of 70 kV and tube current of 20 mA with resultant CT DIvol of 0.06 mGy and dose length product (DLP) of $2 \text{ mGy} \cdot \text{cm}^{-1}$.

All images were acquired with a slice thickness of 0.5 mm and 0.25 mm reconstruction interval, resulting in the voxel size of $0.25 \times 0.25 \times 0.25 \text{ mm}^3$ for volumetric data. Images were reconstructed with advanced modelled iterative reconstruction (ADMIRE) algorithm using the level 3 strength.

For visualization of both coronary artery and stent lumen, two sets of axial images were reconstructed with smooth kernel (Bv36) and sharp kernel (Bv59). Images (2D

and 3D) reconstructed with smooth kernel were used for assessment of coronary artery lumen with stents placed in the coronary arteries, while images reconstructed with sharp kernel (only 2D axial images) were used for evaluation of stent details, especially in the coronary stenting regions where multiple stent wires overlapped resulting in significant beam hardening artifacts.

Further to the use of different reconstruction kernels, images were reconstructed with thick slab maximum-intensity projection (MIP) and thin slab MIP images with corresponding parameters of 3.0 mm slice thickness and 1.5 mm reconstruction interval, 1.5 mm slice thickness and 0.75 mm reconstruction interval, respectively. This aims to determine the effect of different MIP reconstructions on

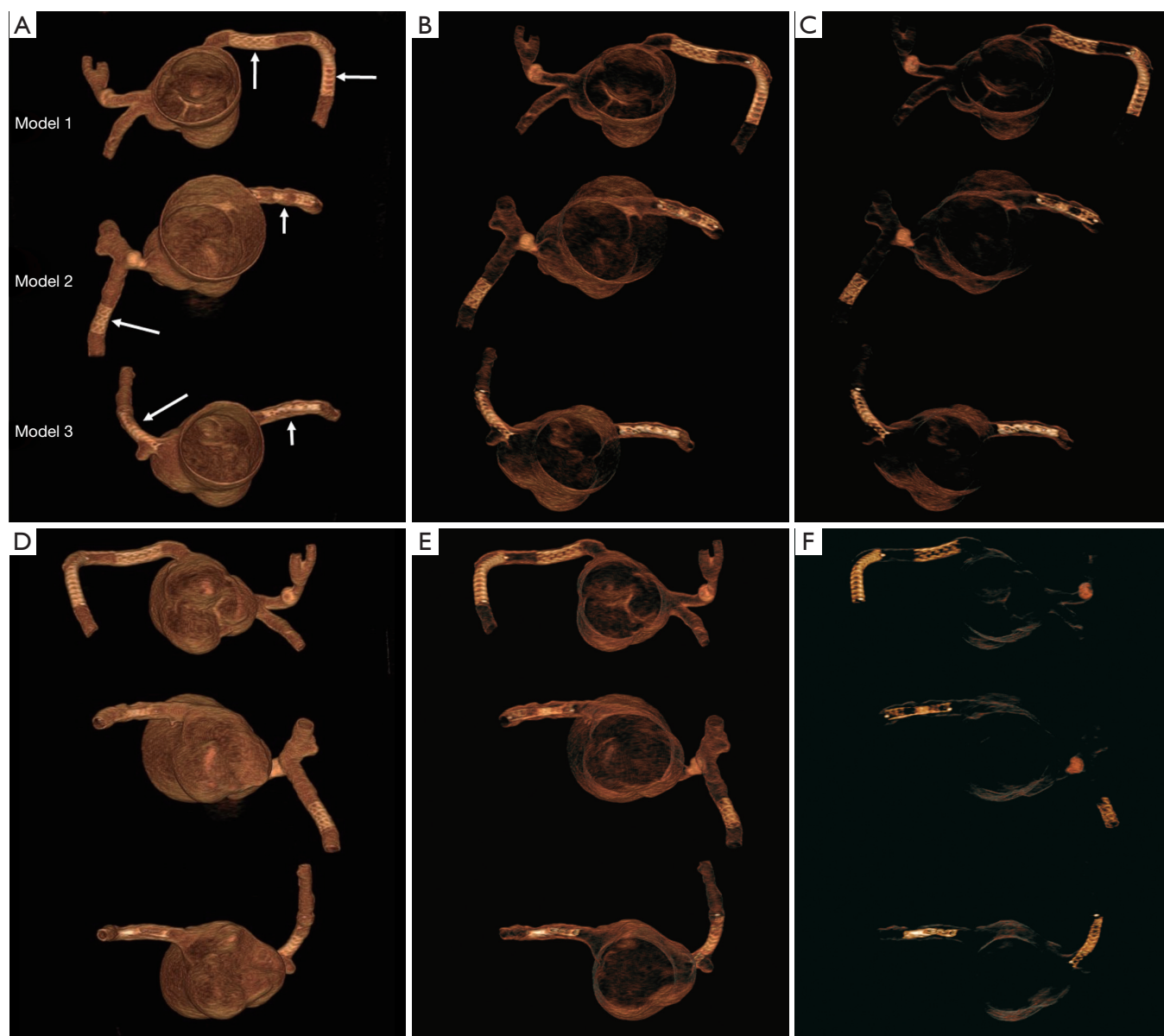


Figure 2 3D volume rendering of 3D printed coronary models with stents. (A,B,C) Anterior views of volume rendering images with windowing adjusted to show the stent and coronary wall together, then to only viewing the metal stent components; (D,E,F) posterior views of volume rendering images with windowing adjusted to show the stent and coronary wall, then to only viewing the metal component details. Arrows indicate the stents in these coronary artery branches.

the visualization and assessment of coronary stent lumen.

2D and 3D image visualization and assessment

CCTA images in digital imaging and communications in medicine (DICOM) format were transferred to a separate workstation for image postprocessing and analysis. 2D and

3D volume rendering reconstructions were performed using an open source RadiAnt DICOM viewer (64-bit) with measurement of stent lumen and stent diameter on 2D axial and 3D volume rendering images (*Figure 3*). All measurements were performed by an observer with more than 15 years of experience in interpreting cardiac CT images. Three measurements were repeated at each stent

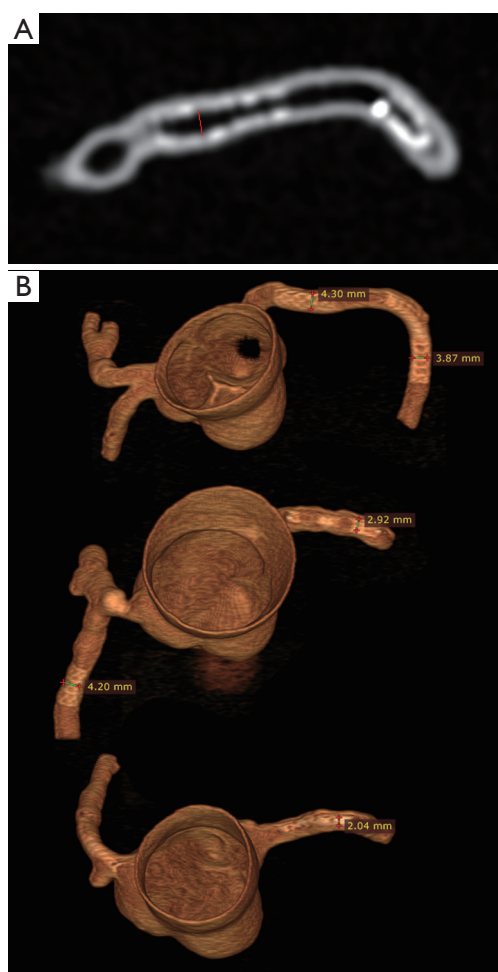


Figure 3 Measurements of stent lumen and stent diameters. (A) Measurement of stent lumen on 2D axial image; (B) measurement of stent dimension on 3D volume rendering image.

location with the mean values used to minimize intra-observer variability.

3D virtual intravascular endoscopy (VIE) views were also generated using a commercially available software Analyze 12.0 (AnalyzeDirect, Inc., Lexana, KS, USA) in the images reconstructed with soft kernel Bv36 algorithm to provide intraluminal views of the coronary stents in relation to the coronary wall for determining the position of stent placement, stent patency and configuration. Details of producing VIE images have been well described in our previous studies (32–35).

Statistical analysis

Quantitative variables were expressed as mean $\pm$ standard

deviation. A two-tailed T test with P value <0.05 was used to determine statistical significance. All statistical analyses were performed using SPSS 24.0 (IBM Corporation, Armonk, NY, USA).

Results

The mean stent lumen diameters measured with different image reconstructions are presented in Table 2. The stent lumen visibility ranged from 54% to 97%, depending on the location of the stent in the coronary arteries. Three stents gave high visibility between 72% and 97%, with more than 86% visibility assessed by these reconstruction images in the LCx stent in the model 3. Relatively low visibility was seen in the other 3 stents ranging from 54% to 77%, in particular in the two stents which failed to achieve wall apposition consistently along their length resulting in the lowest visibility.

The lumen diameters were found to be significantly smaller than the actual sizes when measurements were performed on 2D axial, thin and thick slab MIP images ($P<0.01$). In contrast, volume rendering images allowed for more accurate measurements with measured stent lumen close to the actual dimensions of these coronary stents, except for the stent placed at the RCA in model 2, with similar measurements among these 2D and 3D reconstructions ($P=0.65$ – 0.94). This is mainly due to the reason that the stent was not fully expanded in the model during deployment.

Thick slab MIP images resulted in measured stent lumen diameters smaller than those from thin slab MIP images, with significant differences noticed in the measurements of the 4 stents in the models 1 and 2 ($P<0.05$), with no significant differences in the remaining 2 stents in the model 3 ($P=0.19$ – 0.38). Figure 4 shows visualization of coronary stents with images reconstructed with thin and thick slab MIP. Significant improvements of assessing stent lumen are observed in most of the images with use of thin slab MIP as opposed to the thick slab images.

Stent lumen visualization was significantly improved in images reconstructed with sharp kernel algorithm, and this is especially apparent in the evaluation of stents at the RCA in the models 1 and 3 ($P=0.01$). Figure 5 shows 2D axial images reconstructed with smooth kernel Bv36, while Figure 6A are 2D axial images reconstructed with sharp kernel Bv59, with clear visualization of the right coronary stent in the model 3. Figure 6B shows the 3D volume rendering view of metal stent components with use of sharp

Table 2 Dimensional measurements of coronary stents based on 2D and 3D image reconstructions

2D/3D views	Model 1		Model 2		Model 3	
	RCA-stent 1	RCA-stent 2	LAD stent	RCA stent	LCx stent	RCA stent
2D axial (mm)	2.37±0.17	3.28±0.09	3.41±0.05	2.23±0.08	2.25±0.12	2.20±0.12
Thin slab MIP (mm)	2.59±0.17	3.48±0.08	2.93±0.06	2.16±0.08	2.23±0.07	1.88±0.12
Thick slab MIP (mm)	2.31±0.08	2.94±0.11	2.52±0.25	1.63±0.30	2.16±0.14	1.96±0.05
Bv 59 (mm)	2.37±0.03	3.52±0.04*	3.46±0.01	2.35±0.04	2.19±0.07	2.57±0.09*
VR (mm)	3.46±0.12	4.23±0.06	3.65±0.06	2.14±0.29	2.70±0.05	2.85±0.17

* indicates statistically significant difference between Bv59 and Bv36 measurements ($P=0.01$). LAD, left anterior descending; LCx, left circumflex; MIP, maximum intensity projection; RCA, right coronary artery; VR, volume rendering.

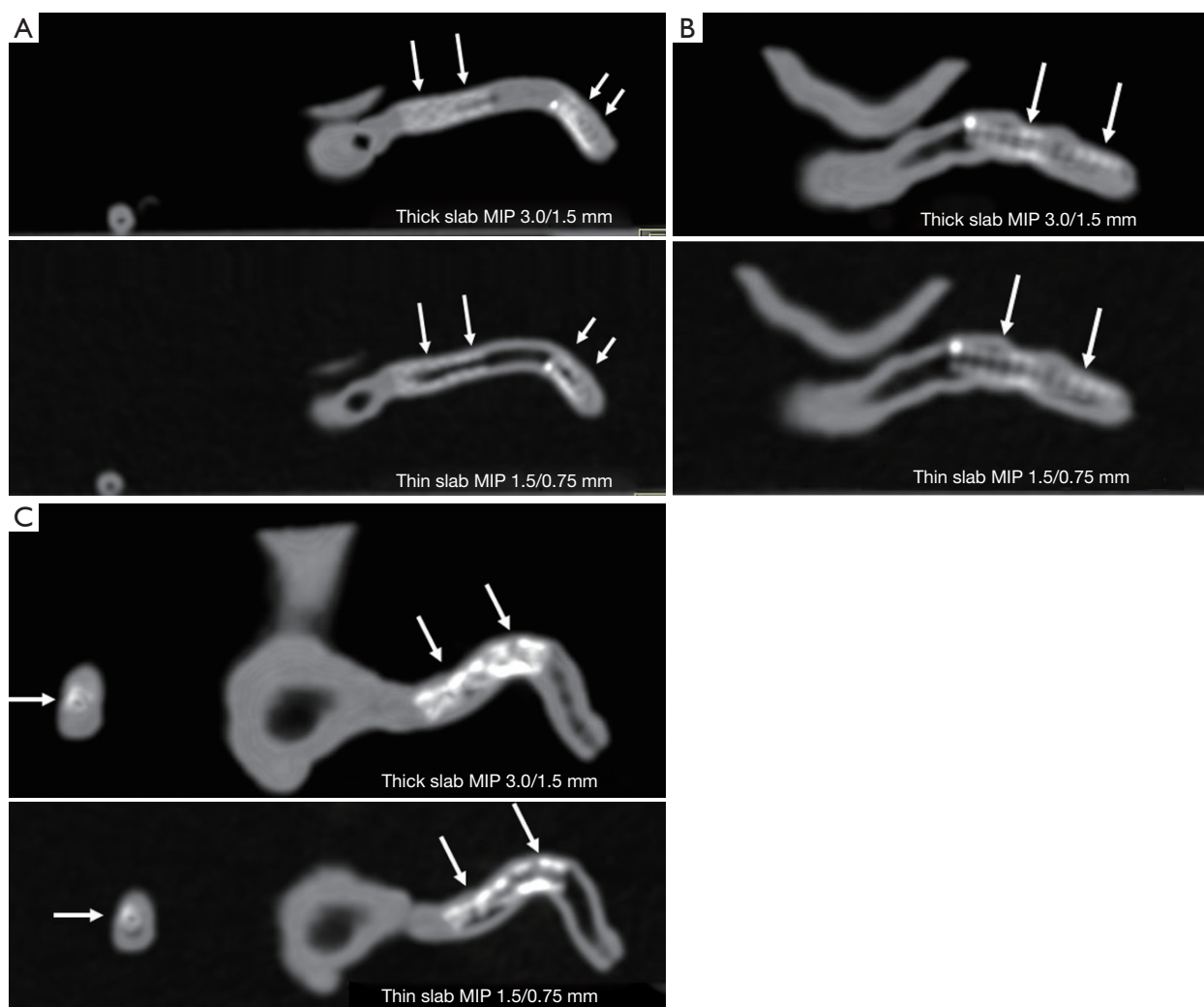


Figure 4 Comparison of measurement of stent lumen diameter between thick and thin slab maximum-intensity projection (MIP) images. (A) MIP images of RCA stents in model 1; (B) MIP images of RCA stent in model 2; and (C) MIP images of RCA and LCx stents in model 3. Arrows refer to the stents placed in these coronary arteries. LCx, left circumflex; RCA, right coronary artery.

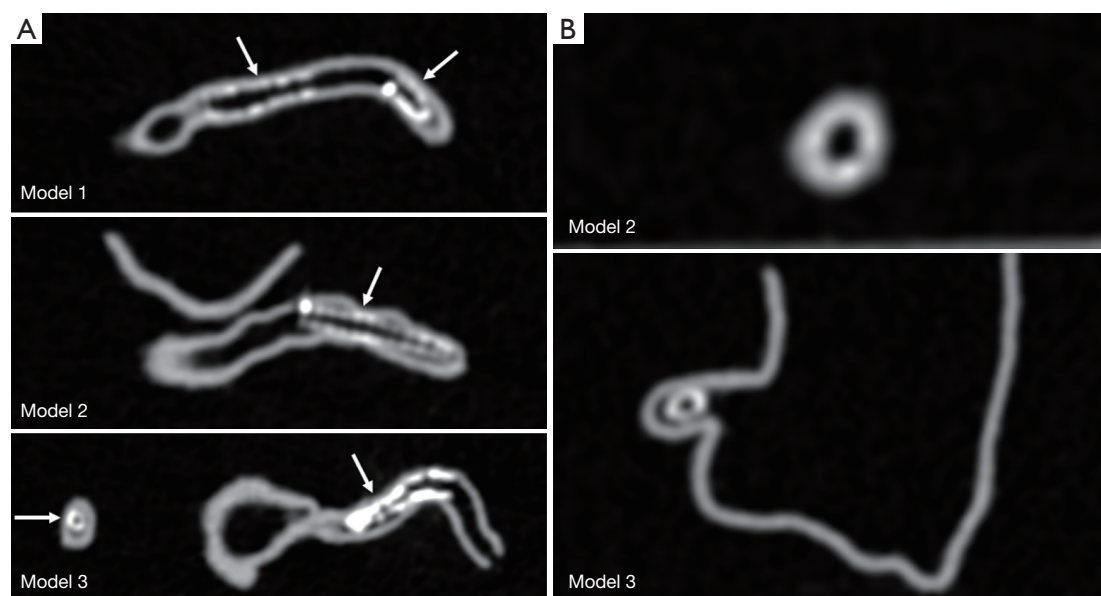


Figure 5 Coronary CT images reconstructed with smooth kernel Bv36. (A,B) 2D axial images showing the RCA stents (arrows) and LAD/LCx stents in these 3D printed models. LAD, left anterior descending; LCx, left circumflex; RCA, right coronary artery.

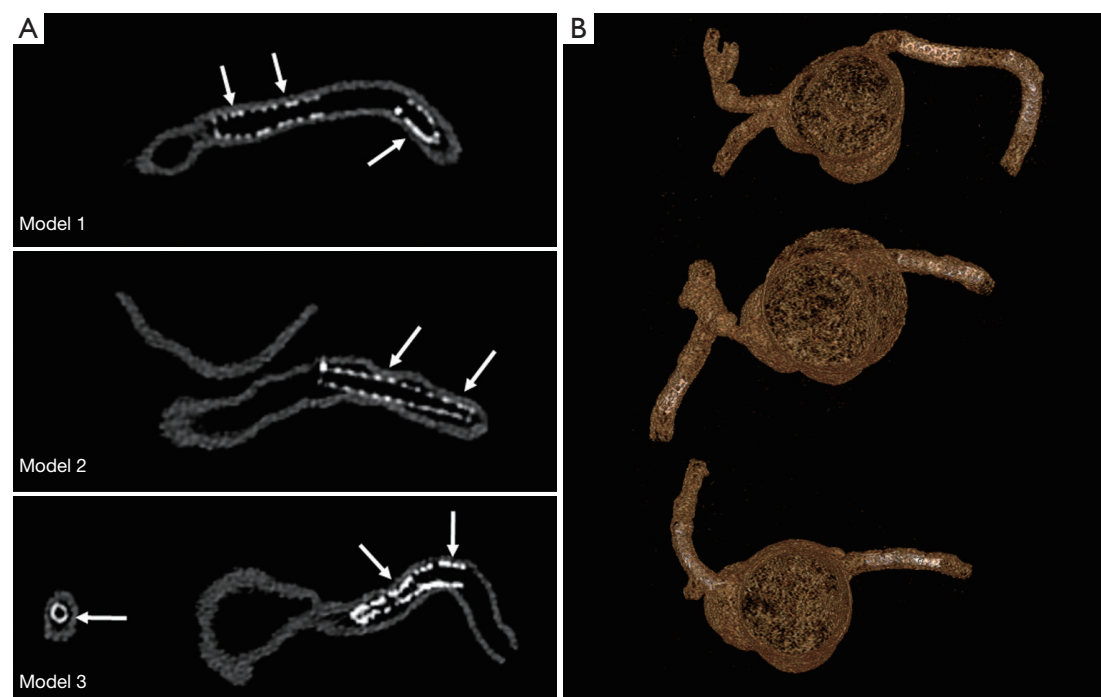


Figure 6 Coronary CT images reconstructed with sharp kernel Bv59. (A) 2D axial images showing the RCA and LCx stents (arrows) in these 3D printed models with clear visibility of the stent lumen when compared to *Figure 5*; (B) 3D volume rendering demonstrating the stent metal components clearly, but not for the visualization of coronary wall or soft tissue information. LCx, left circumflex; RCA, right coronary artery.

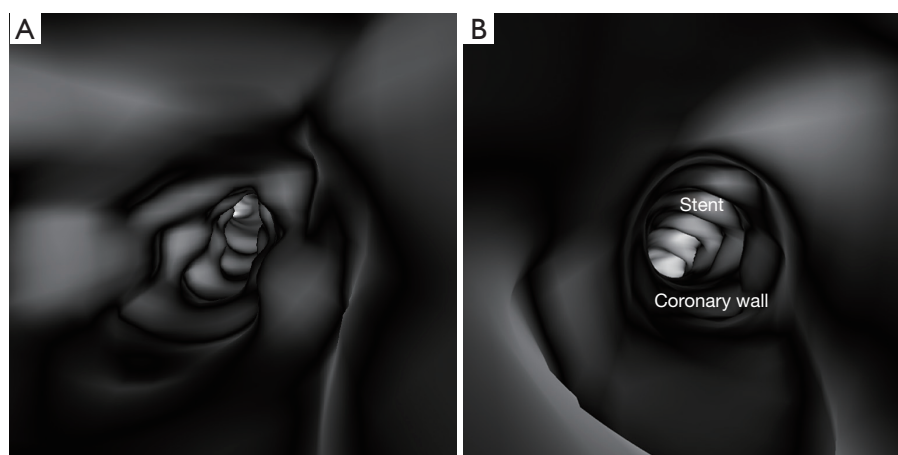


Figure 7 Virtual intravascular endoscopy (VIE) views of intraluminal appearances of coronary wall and stent. (A) Distal VIE view of the right coronary stents; (B) close VIE view of these two stents with patent lumen and smooth coronary wall.

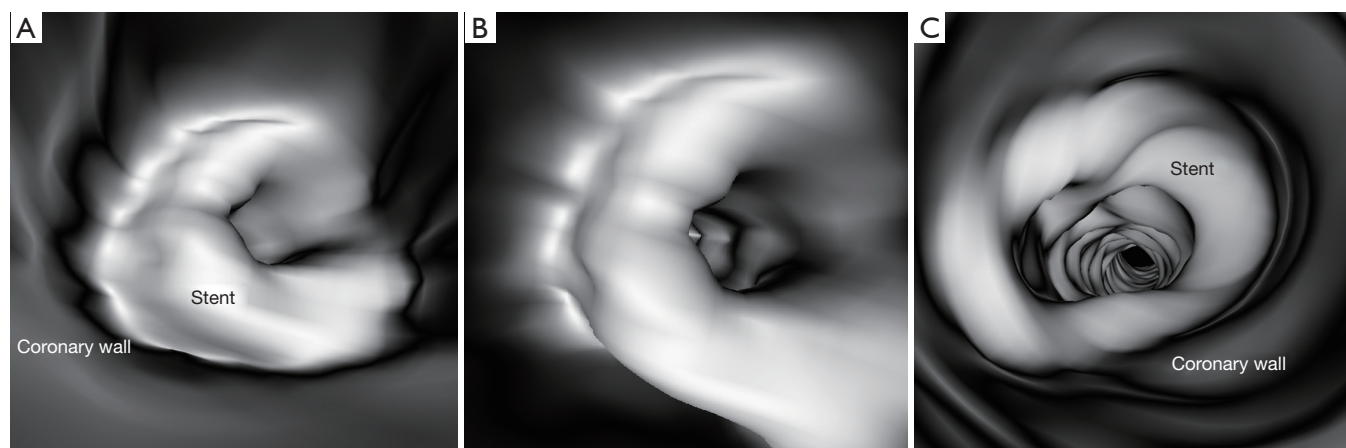


Figure 8 Virtual intravascular endoscopy (VIE) views of coronary wall and stent position. (A) Distal VIE view of the RCA stent which was not fully expanded, resulting in the no stent apposition along the coronary wall; (B) close VIE of the stent; (C) VIE view of the LAD stent with fully expanded showing circular appearance and good apposition along the coronary wall. LAD, left anterior descending; RCA, right coronary artery.

kernel algorithm with improved stent lumen visibility. Use of sharp kernel algorithm resulted in stent lumen visibility ranging from 68% to 98%.

3D VIE views were successfully generated in all images with clear demonstration of the intravascular appearances of coronary wall, stent lumen and stent position inside the coronary arteries. *Figure 7* demonstrates the VIE images of the stents at the RCA in the model 1 with stent patent and smooth coronary wall, while *Figure 8A,B* shows the lack of wall apposition between the coronary wall and the RCA stent in the model 2 because of insufficient expansion of the stent. The LCx stent was shown patent with circular

appearance (*Figure 8C*). The LAD stent in the model 3 was revealed as circular and smooth appearance, while the RCA stent was shown to be irregularly placed inside the coronary artery with lack of wall apposition between the stent and the coronary wall due to insufficient expansion (*Figure 9*).

Discussion

In this preliminary study, we have demonstrated the feasibility of simulating coronary stenting in 3D printed coronary artery models with good stent lumen visibility based on images acquired with the latest third generation

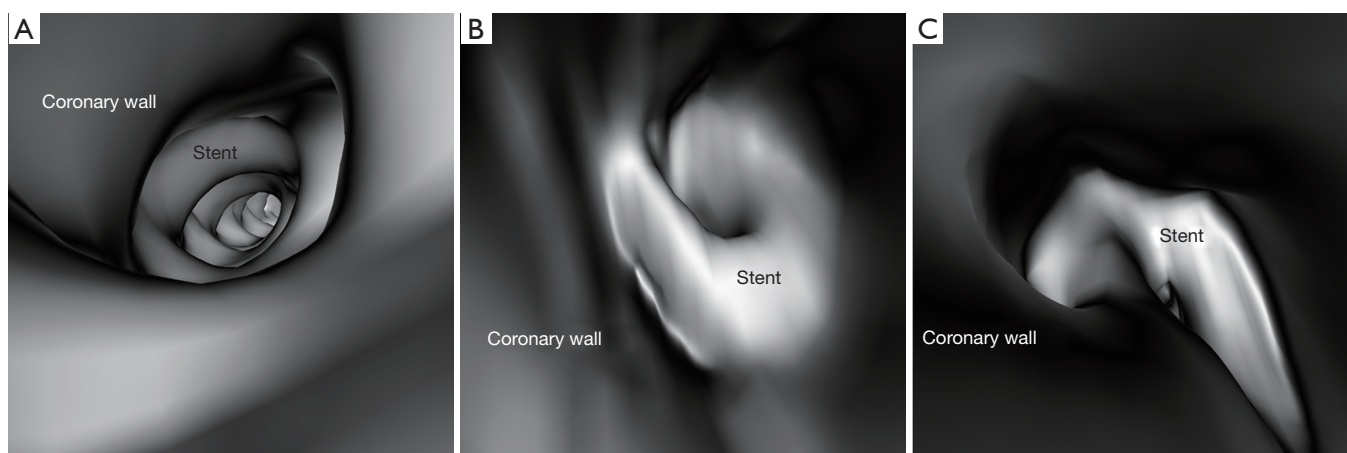


Figure 9 Virtual intravascular endoscopy (VIE) views of coronary wall and stent position. (A) VIE close view of the LCx stent with circular appearance; (B,C) VIE views of the RCA stent which was not fully expanded, with irregular appearance and lack of apposition between the stent and coronary wall. LCx, left circumflex; RCA, right coronary artery.

DSCT. With use of different image postprocessing kernels, visualization of coronary stents has been significantly improved when sharp kernel is applied, especially in the stenting areas with high degree of stent wire overlapping or presence of multiple stent wires. Findings of this study can be used to develop optimal CCTA protocols in coronary stenting.

Invasive coronary angiography still remains the gold standard for assessment of coronary lumen and detection of in-stent restenosis, however, given its invasive nature and potential risk of procedure-related morbidity and mortality, CCTA is a promising less-invasive modality in the follow-up of coronary stenting with improved scanning techniques available with latest scanners. Recent studies using advanced CT scanners such as high definition CT or third generation DSCT have reported the improved diagnostic value of coronary restenosis following coronary stenting (16–18). Results of our study are consistent with these findings, as we have shown the improved stent lumen visibility using the third generation DSCT. The stent lumen visibility in this study was higher than a recent report with *in vitro* evaluation of 24 stents (45–55% visibility for more than 50% of the stents evaluated), and this is most likely because of their study being conducted on a 128-slice CT (14). Given only a small number of stents placed in these coronary arteries in the 3D printed models, further research with assessment of more stents is needed to confirm our findings.

Another approach to reduce the effect of beam hardening or blooming artifacts resulting from stents is to apply reconstruction techniques or postprocessing algorithms

which has been shown to greatly enhance the diagnostic performance of CCTA in coronary stent assessment (21). When compared to the smooth kernel Bv36, the sharp kernel Bv59 showed significant improvements in stent lumen visibility, which is clearly demonstrated by assessing the RCA stent in the model 3 (Figure 6). The mean stent lumen measured with Bv59 was superior to the other image reconstructions (Table 2), with measured lumen diameter close to the actual size of 3.0 mm. Despite improved lumen visibility, the sharp kernel algorithm affects the visualization of soft tissue details such as coronary wall as shown in Figure 6B, thus, it is recommended for only assessing the stent lumen visibility.

3D printing has shown great promise in medical applications with increasing reports in cardiovascular disease, primarily in assisting pre-operative planning and simulation of surgical procedures, improving medical education and enhancing doctor-patient communication (23–30). Another emerging area of utilizing personalized 3D printed models in cardiovascular imaging is to develop optimal CT scanning protocols. Only a few studies are available in the literature with regard to testing different imaging parameters on 3D printed heart and pulmonary artery models (36–38). To our knowledge, this is the first study reporting the use of 3D printed coronary models for investigation of CCTA in coronary stenting. Although this study represents a preliminary report with simulation of only a few stents in the 3D printed coronary arteries, results are promising as it is feasible to place these stents in the 3D printed realistic models, therefore, encouraging further experiments to

identify optimal protocols in coronary CT stenting.

There are some limitations in this study. First, only 6 stents were tested in this study, and more stents with different diameters such as inclusion of 2.25 and 2.75 mm stents and various stent materials are needed. Second, despite using a patient-specific 3D printed coronary model, no simulation of contrast enhancement or electrocardiographic gating was performed. This could contribute to the high stent lumen visibility achieved with this study. Hence, results need to be interpreted with caution. Further, for simulation of the realistic anatomical environment, the coronary models should be placed in the thorax with inclusion of other anatomical structures such as lungs, ribs and heart. This could be addressed in future experimental design. Finally, in-stent restenosis was not simulated in this study. The main application of CCTA in coronary stenting is to detect in-stent restenosis so that early treatment can be offered to patients to reduce the risk of cardiac events. This is currently being investigated in our ongoing study by simulation of in-stent restenosis in 3D printed coronary models.

In conclusion, we have presented our preliminary experience of utilizing personalized 3D coronary artery models for placement of a number of stents in the coronary arteries by demonstrating the feasibility of visualizing the stent lumen using images reconstructed with different parameters. Visibility of the stent lumen overall is good, regardless of the stent diameter. Application of a sharp kernel algorithm improves stent lumen visibility, especially in areas with multiple stent wires. This study provides guidance for future experimental design with the aim of developing optimal coronary CT angiography protocols after coronary stenting.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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