Four-Dimensional Computed Tomography-Based Finite Element Modeling of the Behavior of the Right Coronary Artery

Yoshihisa Nakagawa, MD, PhD; Hidetaka Hayashi; Chisato Izumi, MD, PhD; Hirokazu Kondo, MD, PhD; Toshihiro Tamura, MD, PhD; Soichiro Enomoto, MD, PhD; Masashi Amano, MD; Shunsuke Nishimura, MD; Yuko Tanaka; Tomoharu Isshiki; Hiroshi Watanabe; Kanji Hanafusa; Yuichi Yamazaki; Tomohiro Nakamura; Kazunori Eguchi

Figure 1. (A) Segmented heart image obtained on 320-slice computed tomography. (B) Converted into a polygonal image. (C) Core element image of the aortic root and the right coronary artery (RCA). (D) Beam element model of the RCA.
In the balloon angioplasty era, percutaneous coronary intervention (PCI) for right coronary artery (RCA) ostial lesions achieved a suboptimal success rate in comparison with non-ostial lesions. Although bare-metal stent implantation reduced restenosis compared with balloon angioplasty, the rate of stent restenosis remained high in RCA ostial lesions. The advent of the drug-eluting stent (DES) has led to a marked decrease in the restenosis rate. Treatment of ostial lesions in the RCA, however, is still associated with a high restenosis rate even after DES implantation. The next challenge is to improve the performance of PCI for RCA ostial lesions, although the mechanisms responsible for restenosis in such abnormalities have not been fully determined. The RCA and left coronary arteries (LCA) run on the surface of the epicardium and move in step with cardiac motion, expanding, contracting, bending, and twisting. These motions collectively make up the entire movement of the coronary artery. A detailed analysis of coronary motion is therefore essential to improve the results of PCI for RCA ostial lesions. At present, 320-slice computed tomography (CT) provides 3-D coronary imaging during the cardiac cycle. In this study, we analyzed the motions of the RCA using finite element (FE) modeling of 4-D space-time data, a combination of 3-D space and 1-D time. The FE modeling was carried out by MSC Software (Shinjuku, Tokyo, Japan). The limitation of this study was that it did not cover the LCA, owing to a limited budget for the FE modeling.

The subject was a 44-year-old man who underwent 320-slice coronary CT for the evaluation of suspected ischemic heart disease. This involved an effective dose estimation of 20.8 mSv, or a dose-length product of 1,485 mGy-cm. No coronary narrowing was seen, and no abnormality in left ventricular wall motion was detected on transthoracic echocardiography. The CT imaging data obtained during a single cardiac cycle was divided into 20 datasets and stored in the Digital Imaging and Communications in Medicine (DICOM) format. The first DICOM dataset corresponds to the beginning of the systole. Using Simpleware technology (Synopsys, Mountain View, CA, USA), the heart image was segmented into regions (Figure 1A). The CT volume data were converted into a polygonal image and, based on anatomic knowledge, each cardiac chamber was extracted from the image (Figure 1B). The resulting image consisted of core elements only: the aortic root, including the sinus of Valsalva, and the RCA (Figure 1C). The structure of the RCA was modeled using beam elements, which have translational and rotational degrees of freedom. A shell element model was created based on the 15th DICOM dataset, corresponding to a time point between the early and atrial filling (Figure 1D). In this study, the aortic root, including the sinus of Valsalva, and the RCA (Figure 1C). The structure of the RCA was modeled using beam elements, which have translational and rotational degrees of freedom. A shell element model was created based on the 15th DICOM dataset, corresponding to a time point between the early and atrial filling (Figure 1D). In this study, Marc Software (MSC Software, Newport Beach, CA, USA), a non-linear finite element analysis software suite, was utilized. The beam element model was placed near the central axis of the shell element model to measure the motion of the RCA. In the body the origin of the RCA moves with the cardiac motion, and the trajectory of this point was analyzed (Figure 2A). As shown in the enlarged view (Figure 2B), the RCA origin moves dynamically forward and backward in an elliptical pattern. In the next analysis, the aortic root was fixed as an immovable point at the RCA origin, and the motion of the RCA was calculated (Figure 2C; Movie S1).
The proximal part of the RCA moves like a conical pendulum suspended from the RCA origin (Figure 2D; Movie S2). In addition, the coronary motion also affects the shape of the sinus of Valsalva (Movie S2). We estimated that this complicated movement would generate high mechanical stress on the stent placed in the ostial RCA.

Stent fracture after DES implantation has recently become a major concern because of its potential association with in-stent restenosis and stent thrombosis. Use of this novel analytical method might have the potential to clarify the mechanism of stent fracture. For in vivo motion analysis of the coronary arteries, an imaging device must be able to visualize the motion of the coronary arteries throughout the cardiac cycle and also locate their positions in a coordinate system. The present study has shown that FE modeling of 4-D CT data can be used to successfully visualize and evaluate the detailed motion of the coronary arteries, although the potentially high radiation dose delivered in 4-D CT is a major concern. Further studies with a larger number of patients are needed to establish a more detailed motion analysis of the coronary arteries, including the LCA, to improve the outcomes of PCI.

Acknowledgments

We would like to thank Mr. Takeshi Masumoto and Mr. Keisuke Suzuki for their sincere support of this study. This study received financial support from Japan Lifeline.

Disclosures

The authors declare no conflict of interest.

Funding

This study received financial support from Japan Lifeline.

References


Supplementary Files

Supplementary File 1

Movie S1. Movement of the right coronary artery during a cardiac cycle.

Supplementary File 2

Movie S2. Movement of the proximal part of the right coronary artery during a cardiac cycle.

Please find supplementary file(s);