Ex-vivo aortic root and coronary artery cast measurement to validate the accuracy of virtual imaging.

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Running title: Validation of 3D-VR measurement accuracy

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Abstract

Background and aim of the study: To investigate the accuracy of two methods of measuring features in cardiac anatomy, using an objective standard cast model.

Methods: We made a silicone cast using a swine heart. CT data of the solidified cast were processed through virtual-reality (VR) software and through two-dimensional multiplanar-reconstruction (2D-MPR), and all measurements were compared against physical measurements of the cast.

Results: The cast perfectly demonstrated the fine detail of the aortic valve and the proximal parts of coronary arteries. Anatomical features were measured by 3D-VR, 2D-MPR, and directly on the cast. Measurement differences between 2D-MPR and the cast were on average at least 3.6 times larger than those between 3D-VR and the cast.

Conclusions: Based on the observed accuracy, 3D-VR measurements seem considerably more accurate than the current standard 2D-MPR, and 3D-VR may be considered as the next gold standard for 3D measurement of cardiac anatomy in-vivo.

Introduction

Virtual reality (VR) has emerged as a novel technology permitting three-dimensional (3D) visualization of medical and other images, and it has been increasingly applied as an effective tool for anatomical understanding in diagnosis and preoperative planning. The Vesalius 3D suite combines virtual imaging software with optic-tracking navigation, allowing fast, intuitive, and efficient interactions for exploration and measurement of reconstructed 3D images[1]. However, there is still little information on relative accuracy of 3D measurements[2], which would be needed before a decision on clinical application. In this study, we cast a model and used it as a standard to which to compare 3D-VR and two-dimensional (2D) measurements.

Materials and Methods

An explanted porcine heart specimen was received from a local supplier. Institutional review board approval was not applicable in this study. A casting apparatus using an explanted porcine heart was designed for filling silicone compound into the aortic root and the proximal region of the coronary arteries (Fig 1). A fiberoptic scope was inserted to monitor the aortic valve and the filling process of silicone rubber. Immediately before use, a two-component liquid silicone suspension (ELASTOSIL®P-7684/60A/B, Wacker-Chemie-AG, Munich, Germany) of very low viscosity was thoroughly mixed with solidifier. Without delay, the liquid mixture was loaded in a syringe and injected into the aortic root, with care taken to ensure that the silicone liquid filled all parts without stretching or distorting any soft tissues (Fig 2A). The whole apparatus was left to stand overnight at room temperature for the silicone to solidify completely. CT scanning was performed with 320 x 0.5mm slice collimation (Fig 2B). The CT datasets in DICOM format were transferred to 3D-VR software, the Vesalius 3D suite (PS Medtech, Amsterdam, Netherlands), and a virtual image was reconstructed for 3D measurement. After the CT scan, the native tissue was carefully dissected away, and the epicardial coronary arteries were opened longitudinally with surgical scissors. The extracted solidified cast was then measured for anatomical parameters of the coronary arteries and the aortic valve that might be important for coronary artery bypass grafting or aortic valve-sparing surgery (Table 1). We compared the lengths and the diameters of precisely the same features that were marked on the VR images, and which were also measured in the conventional way in 2D multi-planar reconstruction (MPR) of the CT data, performed using Ziostation 2 software (Ziosoft, Tokyo, Japan). The experimental sequence can be seen in the supplemental video.

Results

Reconstructed VR images of the cast showed clear enhancement, displaying the aortic root anatomy and the coronary arteries (Fig 2C). During the removal of the native tissue surrounding the set silicone, there were no significant adhesions, noticeable looseness, or apparent stretching identified between native tissue and silicone cast. The timing between CT scanning and tissue removal was within an hour. The extracted silicone cast perfectly preserved the details of the coronary arteries, arterioles, and small branches such as the septal perforators (Fig 2D). The physical measurements were performed by a resident (Y.M.) who was blinded to the CT measurements. Extreme care was taken to avoid stretching the silicone rubber when straightening coronary arteries for a caliper measurement (Fig 3A, 4A). Anatomical landmarks were three-dimensionally evaluated by a surgeon (K.K.) (Fig 3B, 4B), while 2D-MPR measurements were conducted by an experienced radiologist (Y.N.) (Fig 4C, 4D). Both CT observers were blinded to each other's measurement data. The raw data of measurements in each method are shown in Table 1. The mean error of MPR versus direct measurement (1.74mm, 5.65%) was 3.63 times larger than the mean error for VR compared with direct measurement (0.48mm, 1.55%), excluding the diameter measurements, which showed from 9 to 26 times larger errors in MPR.

Conclusions

Modern imaging technology is developing toward patient-specific surgical planning and precise guidance for procedures. Accordingly, CT angiography is increasingly applied as a standard imaging modality. However, information in volume-rendered images supplied by CT angiography is conventionally evaluated through MPR on a two-dimensional screen[3], which limits the ability to encompass true depth. Moreover, the reliance on 2D images with numerous measurements requires a cumbersome, time-consuming process with large CT datasets, and expert interpretation[4]. Virtual reality has emerged as a novel method to overcome these barriers. Our previous report found that 3D analysis using Vesalius 3D may promote understanding of aortic root anatomy, allowing more accessible patient-specific preparation and facilitating valve-sparing surgery[1]. There were no published data on the measurement accuracy of this VR system. Preoperative planning in cardiac surgery is often based on measurements in the order of millimeters[5], and precision may be essential for optimizing outcomes. In this initial study, VR measurements and direct cast measurements (i.e., the reference standard) showed only small differences, with a mean error of 0.37 mm overall, which might be within the clinically acceptable range. In contrast, we found larger errors in 2D-MPR, showing on the average 5% under-measurement of coronary artery lengths and 9% under-measurement of coronary luminal diameters at orifices. Such errors associated with 2D measurement may be due to the fact that MPR was taken in a plane perpendicular to the manually-corrected centerline of the vessel, whereas the luminal diameters were calculated as the mean of maximum and minimum diameters in the cross-sectional images. Also, there are some regions where 2D-MPR is inadequate, such as the hinge-lines of aortic valve cusps, where not all parts are aligned in a single plane. In such locations of complex shapes, axial measurements using bisecting planes may be under- or over-estimated, with significant variability of lengths in MPR. A possible limitation of our experiment is the behavior of the silicone material. Post-mortem cast angiography was a relatively classical method for detection of coronary artery stenosis[6]. However, technical failures might occur, including incomplete filling of contrast medium resulting from trapped air or residual saline solution, or from inadequate infusion pressure, which could make the interpretation unreliable. In our case, small air bubbles were noticed on the VR image of the aorta, presumably included during the mixing procedure. Therefore, we focused on the coronary arteries that gave a clear view, where any air was displaced toward the capillaries by the silicone mass. Our method seemed to be well suited to demonstrate the reference model ex vivo. Further work, including studies of intra- and inter-observer reliability, is needed to confirm the apparently more than three times better accuracy offered by VR over MPR. Measuring larger features, we found 3.63 times greater mean errors in MPR measurements than in VR, but the errors in artery diameter measurements by MPR were so large and so varied that far more data will be needed to fairly assess relative accuracy of MPR versus VR. Different surgical teams will presumably have differing approaches and priorities, and which CT interpretation system is preferable, for what reasons, and in which contexts, has yet to be decided.

Conflict of Interests

The authors received a complimentary user license for Vesalius 3D suite supported by PS Medtech and used in this study.

Author Contributions

Conceptualization: Kenichi Kamiya, Yukihiro Nagatani. Data collection, analysis, and interpretation: Kenichi Kamiya, Yuji Matsubayashi, Shinya Terada, Yukihiro Nagatani. Drafting article: Kenichi Kamiya. Critical revision: Taihei Fujii, Susumu Nakata. Approval of article: Tomoaki Suzuki.

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Table 1. Modality comparison data of all measurements for the silicone cast model

		VR	MPR	Direct measurement	Direct-VR *	Direct-MPR **
Coronary length (mm)	LAD	31.9	31.2	32.37	0.47	1.17
	LCX	21	21.3	21.59	0.59	0.29
	RCA	31.1	28.4	31.56	0.46	3.16
Coronary diameter (mm)	LMT	6.4	6.7	6.43	0.03	0.27
	RCA	3.8	4.35	3.82	0.02	0.53
Cusp length (mm)	RCC	36.2	35	35.73	0.47	0.73
	LCC	31.2	34	31.64	0.44	2.36
	NCC	32.6	29.4	32.15	0.45	2.75
Average (mm)				24.41	0.37	1.41

LAD = left anterior descending artery; LCC = left coronary cusp; LMT = left main trunk; LCX = left circumflex artery; MPR = multi-planar reconstruction; NCC = non-coronary cusp; RCC = right coronary cusp; RCA = right coronary artery; VR = virtual reality; * and ** = difference between direct measurement and VR or MPR (given as absolute values).

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Figure legends

Figure 1. The casting apparatus using a porcine heart that includes an endoscope for viewing the aortic valve and an injection route for the silicone compound into the aortic root.

Figure 2. Cast angiography technique: The silicone gradually filled the aortic root (A). The solidified cast was taken to the CT scanner (B). The extracted solidified silicone cast (C) and the reconstructed virtual image of the cast (D). Note that the cast demonstrated the precise anatomy of the coronary vessels.

Figure 3. Three different ways of measuring the length of the left anterior descending coronary artery between the bifurcation and the first branch. Each feature was evaluated by the direct cast measurement (A) as the standard, by virtual 3D image (the purple dots in B), and by 2D multiplanar reconstruction (the green dots in C).

Figure 4. The length of the aortic valve cusp (right coronary cusp) was measured in three different ways. Note that the green string was anchored to the cast and directly measured (A). The 3D-VR image shows the plotted points (purple dots) on the iso-surface at the same location on the cast (B). In 2D-MPR measurement, the curved length (the green dots in C, D) was calculated on the multiple planes bisecting the sinus of Valsalva.