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Vectors through a cross-sectional image (VCI): A visualization method for four-dimensional motion analysis for cardiac computed tomography

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Abstract

Background—Cardiac computed tomography (CT) has the potential for fully four-dimensional (4D for 3D plus time) motion analysis of the heart. We aimed at developing a method for assessment and presentation of the 4D motion for multi-phase, contrast-enhanced cardiac CT data sets and demonstrating its clinical applicability.

Methods—Four patients with normal cardiac function, old myocardial infarction (OMI), takotsubo cardiomyopathy, and hypertrophic cardiomyopathy (HCM) underwent contrast-enhanced cardiac CT for one heartbeat using a 320-row CT scanner with no tube current modulation. CT images for 10 cardiac phases (with a 10%-increment of the R-R interval) were reconstructed with the isotropic effective resolution of (0.5 mm)³. An image-based motion-estimation (iME) algorithm, developed previously, has been used to estimate a time series of 3D cardiac motion, from the end-systole to the other nine phases. The iME uses down-sampled

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images with a resolution of $(1.0 \text{ mm})^3$, deforms the end-systole images non-rigidly to match images at other phases. Once the agreement is maximized, iME outputs a 3D motion vector defined for each voxel for each phase, that smoothly changes over voxels and phases. The proposed visualization method, which is called “vectors through a cross-sectional image (VCI),” presents 3D vectors from the end-diastole to the end-systole as arrows with an end-diastole CT slice. We performed visual assessment of the VCI with calculated the mean vector lengths to evaluate regional left ventricular (LV) contraction.

Results—The VCI images showed the magnitude and direction of systolic 3D vectors, including the through-plane motion, and successfully visualized the relations of LV wall segments and abnormal regional wall motion. Decreased regional motion and asymmetric motion due to hypokinetic infarct segment, takotsubo cardiomyopathy, and hyper trophic cardiomyopathy was clearly observed. It was easy to appreciate the relation of the abnormal regional wall motion to the affected LV wall segments. The mean vector lengths of the affected segments with pathologies were clearly smaller than the other unaffected segments (1.2–1.7 mm versus 2.5–4.7 mm).

Conclusions—VCI images could capture the magnitude and direction of through-plane motion and show the relations of LV wall segments and abnormal wall motion.

Keywords

cardiac computed tomography; cardiac wall motion; image-based motion estimation; myocardial infarction; cardiomyopathy

1. Introduction

Image-based cardiac functional motion analysis can provide an important indicator of the severity and prognosis of heart failure.^{1–3} However, problems will result if a complex three-dimensional (3D) heart deformation is analyzed using a series of a two-dimensional (2D) slice-of-interest. The heart moves forward and backward through the slice-of-interest—a phenomenon called through-plane motion—constantly during one heartbeat, which may increase or decrease the heart motion observed in the 2D image. Previous studies have shown substantial errors in measured cardiac function when through-plane motion was not taken into account.^{4,5} Thus, it is critical to take into account the effect of through-plane motion in addition to the in-plane motion for accurate evaluation of cardiac function. The problem of through-plane motion can be solved by using 3D images. Although some 3D tissue tracking solutions are currently available for echocardiography and magnetic resonance imaging (MRI), experience is still limited with computed tomography (CT).⁶

Recently, to evaluate the cardiac wall motion, a new image-based motion-estimation (iME) algorithm has been developed for use with CT.^{7,8} Similar to speckle-tracking for 3D echocardiography, iME estimates the regional four-dimensional (4D=3D plus time) motion of the heart from a time series of 3D CT images and outputs motion vector fields.^{9,10} One of the challenges in 4D motion analysis is how to display the motion vector field and CT images together in order to capture through-plane motion better. The aims of this study were to develop a method to analyze and present cardiac 4D motion in multi-phase, contrast-

enhanced CT data sets and demonstrate its clinical applicability with four patients with different pathologies.

2. Methods

This retrospective study received institutional review board approval, with informed consent waived. The following four patients with different pathologies were enrolled: A 61-year-old male with normal cardiac function (we call this case “normal case” in this report), a 65-year-old male with old myocardial infarction (“OMI case”), a 79-year-old female with takotsubo cardiomyopathy (“Takotsubo case”), and a 54-year-old male with hypertrophic cardiomyopathy (“HCM case”). Diagnoses were made based on clinical findings and examinations such as echocardiography, MRI, and nuclear medicine.

2.1. CT scanning and contrast injection protocols

The four patients underwent an axial scan with a third-generation, 320×0.5 mm detector-row CT unit (Aquilion One Genesis edition; Toshiba Medical Systems, Otawara, Japan). A cardiac CT scan was performed with 120 kVp for one full cardiac cycle (0–100% of R-R intervals). No tube current modulation was used; a tube current value was determined by automatic exposure control (SURE Exposure3D, Toshiba Medical Systems) using x-ray attenuations on anteroposterior and lateral scout images, targeting at an image noise level of 22 Hounsfield units (HU). Heart rates during the scan were 59 ± 11 beats per minute. High-concentration iodinated contrast agent (iopamidol 370 mgI/ml) was used for all examinations. The total contrast material volume was adjusted for each patient based on the body weight (450 mgI/kg) with a constant injection time duration of over 15 s, resulting in injection rates of 4.8 ± 1.2 ml/s, followed by 30 ml saline solution at the same rate. We recorded the scanner-generated volume CT dose index (mGy) and the dose–length product (DLP) for each examination. The effective radiation dose to the chest was estimated by $DLP \times 0.014^{11}$ and was 4.7 ± 1.5 mSv.

2.2. Image reconstruction and image post-processing

We reconstructed CT images for 10 cardiac phases (for 0%–90% R-R interval with a 10%-increment) using an iterative reconstruction algorithm (the adaptive iterative dose reduction 3D or AIDR3D) with the noise reduction strength of “weak” and a soft tissue kernel (FC43).¹² Image reconstruction was performed for a 20.0-cm display field-of-view for a 16-cm longitudinal coverage with the isotropic effective resolution of (0.5 mm)³.

Details of the iME algorithm have been reported elsewhere^{7,8} and we provide a brief description as follows. First, 3D images at 10 phases were down-sampled from $\sim 512^3$ voxels to $\sim 256^3$ voxels and one phase (it was the end-diastole at 0% of the R-R interval in this study) was chosen as the reference phase. Then the motion between the end-diastole to the other nine cardiac phases was estimated jointly and iteratively, by deforming the end-diastole images non-rigidly (flexibly) and matching the deformed images to each of the other nine phase images. During the process, the deformation was encouraged to be smooth at each phase and gradually changing over phases. Once the process is completed, iME outputs a 3D motion vector defined for each voxel for each phase. The entire heart and

pericardial regions were included in the process in order to fully describe a 4D deformation such that there are neither sudden appearances nor disappearances of anatomies over cardiac phases. It took 2–3 hours for iME to process one case using a graphical processing unit (GPU) and a multi-core central processing unit (CPU) (5 GB NVIDIA Tesla K20C for GPGPU, 1.9 GHz Intel Xeon, 32 GB RAM, 2.0 TB hard drive).

The end-systolic phase and end-diastolic phase were determined for each case using cardiac-phase search software (PhaseNavi; Toshiba Medical Systems), and they were 40% and 0%, respectively, of the R-R interval for all the cases. Then the proposed visualization method, which is called “vectors through a cross-sectional image (VCI)”, created fusion images to evaluate systolic function of left ventricle (LV) as follows. First, we specified a desirable slice-of-interest (typically either a short-axis or a horizontal long-axis plane) at the end-diastolic phase. Then, from the output of iME, VCI extracted motion vectors from the end-diastolic phase at the slice-of-interest to the end-systolic phase. VCI then displayed the vectors as arrows with no scaling with the end-diastolic CT image. The fusion images were created using Matlab (The MathWorks, Inc., Natick, MA) and could be observed from any desirable direction, which could be changed interactively on the workstation. Vectors are shown every eight pixels in each direction and the vector length represents the length of pixel movement (with no scaling) during the systolic motion.

We have performed both quantitative and qualitative assessment of the regional systolic motion. The visibility of the regional systolic motion with the proposed VCI was assessed descriptively. The regional wall motion was assessed using the mean vector lengths per myocardial segment on short-axis images at the apical level using the American Heart Association 17-segment model with “normal case,” “OMI case,” and “HCM case”; and at the apex (segment 17) and basal walls/segments on the horizontal long-axis image with “Takotsubo case.”

3. Results

Figure 1 shows the VCI image of the normal case. Vectors demonstrated that the LV myocardial contraction was relatively symmetric, indicating the effective cardiac output. Calculated regional wall motion index values agreed with the visual interpretation: The mean vector lengths were 4.5 mm at the septal wall, 3.7 mm at the inferior wall, 3.4 mm at the lateral wall, and 3.1 mm at the anterior wall. Inter-segment vector length variability (standard deviation) was as small as 0.6 mm.

The result of the OMI case is shown in Fig. 2. A severe perfusion defect was clearly observed at the apical lateral wall on nuclear stress myocardial perfusion image (Fig. 2A). Cardiac CT at 0% phase revealed myocardial fat deposition after LV myocardial infarction at the correlated region in the apical lateral wall (Fig. 2B). The VCI image shows that the wall motion was not symmetric and that the motion of the apical lateral wall was hypokinetic (Fig. 2C). The observation was reasonable because necrotic segments lose their contractibility. The quantitative analysis supported the findings: The mean vector lengths were 2.5 mm at the septal wall, 4.7 mm at the inferior wall, 1.2 mm at the lateral wall

(infarcted segment), and 3.9 mm at the anterior wall. The reduced motion at the lateral wall was apparent.

The result of Takotsubo case is shown in Fig. 3. Fig. 3A is the 0%-phase horizontal long-axis image. The patient had no obstructive coronary artery disease but exhibited LV systolic dysfunction with hypokinesis of the apex (Fig. 3B, C). Wall motion in the apex was apparently weak compared with that in the base (Fig. 3B); the VCI image from a different angle showed that the apex moved in the opposite direction (Fig. 3C). Decreased motion at the apex, which is typical of takotsubo cardiomyopathy, was confirmed with the quantitative analysis: The mean vector lengths were as small as 1.3 mm at the apex and while it was 4.3 mm at the base, which is the normal range.

The result of the HCM case is shown in Fig. 4. The hypertrophy of the myocardium was clearly observed on the 0% phase short-axis image (Fig. 4A). There was relatively asymmetric myocardial motion, including an area of asymmetric septal hypertrophy (Fig. 4B). The mean vector lengths were 1.4 mm at the septal wall, 3.3 mm at the inferior wall, 3.4 mm at the lateral wall, and 1.7 mm at the anterior wall. The two wall segments with an increased wall thickness had decreased wall motion (i.e., a decreased vector length), which agreed with the asymmetric hypertrophy.

4. Discussion

We have developed VCI to present 4D motion analysis results for multi-phase, contrast-enhanced cardiac CT data sets. The VCI image showed the magnitude and direction of the estimated 4D motion, including through-plane motion, which visualized the relations of LV wall segments and abnormal regional wall motion. In this study, we demonstrated its clinical utility in four patients with different pathologies: VCI images successfully presented the key findings on regional LV wall motion unique to each pathology, and agreed with the quantitative analysis results. The magnitude and direction of vectors may be a good index to assess the treatment response of patients (e.g., with Takotsubo cardiomyopathy). Relatively asymmetric myocardial motion indicated the area with asymmetric hypertrophy, which suggested heterogeneity of the degree and extent of myocardial fibrosis in HCM.

Through-plane motion has a potential impact on LV functional analysis. The myocardium is a 3D thick shell, with its internal arrangement of fibers following a counter-directional helical pattern. Because of this complex fiber orientation, fiber contraction leads to intricate myocardial and ventricular deformation, consisting in a combination of radial thickening, circumferential and longitudinal shortening, and rotational motion. Theoretically, therefore, 2D image-based motion analysis produces errors in interpretation of the deformation, such as those that may result from through-plane displacements of 3D structures. A previous MRI study showed that accounting for through-plane motion is critical for accurate LV motion quantification because there is an inherent base-to-apex gradient in LV rotation.⁵ A previous echocardiography study reported that through-plane motion produced discrepancies in strain measurements between 2D and 3D echocardiography, especially at the LV basal level.⁴ To our knowledge, in CT, the effect of through-plane motion on cardiac functional CT analysis has not been systematically investigated, and a CT imaging method to visualize through-

plane motion has not been developed. The proposed VCI enabled visualizing the 3D motion (including the out-of-plane motion) with the relations to the high resolution LV wall images very clearly.

Multiple noninvasive imaging modalities can perform cardiac motion analysis. Echocardiography provides the highest temporal resolution (at least 33 ms), but the spatial resolution is poor. Also, its quality is operator dependent and subjective to interpretive error. It has limited-view windows, especially for patients with cardiomegaly, as the epicardium may be outside the field-of-view. Cardiac MRI is estimated to offer temporal resolution of 25–45 ms,¹³ although it requires a 10-min acquisition time, has poor spatial resolution (5–10 mm), and usually scans only 1–5 slices, thereby not capturing through-plane motion. Cardiac CT is widely performed to assess various types of heart disease.¹⁴ Although insufficient temporal resolution—the temporal resolution of 320-row CT is 138 ms (=gantry rotation time/2=275 ms/2)—and the radiation dose to the patient remain the major disadvantage, cardiac CT has some advantages. It requires only one heartbeat, covers the entire heart, and provides uniform, high isotropic spatial resolution (0.5 mm)^{3,15} Compared with other modalities, VCI may be useful for detecting small abnormal lesions.

This study had some limitations. First was the small number of patients. While this pilot study was successful in demonstrating the promise of the proposed VCI, we will need to conduct a systematic evaluation study with a larger number of patients. Second, we included the LV cavity in the analysis and display. The blood pool appeared flat in CT images and did not provide sufficient information for motion estimation. As a result, the flow direction of the LV blood was not accurate, as it was always affected by the surrounding myocardium. Whether or not to display vectors for the LV cavity in the VCI images, can be a topic of a future study. Third, the phases for the end-systole and end-diastole were fixed for the entire pixels in this study. The phase may vary regionally at the presence of dyssynchrony, and thus, using different phases for different pixels may lead to more clinically valuable analyses. In fact, calculating and displaying maximum displacement for each pixel or assessing the spatial variation of phases (e.g., time-to-peak displacement) may be good ways to evaluate cardiac functions. We have another study underway to display maximum displacement of each pixel.

In conclusion, VCI visualized the magnitude and direction of through-plane motion and presented the relation of LV wall segments and abnormal wall motion clearly, which seems to improve both the evaluation and presentation of regional cardiac function with various cardiac diseases.

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List of Abbreviations

VCI	vectors though a cross-sectional image
AIDR 3D	adaptive iterative dose reduction 3D
CT	computed tomography
4D	four-dimensional
DLP	dose-length product
ECG	electrocardiogram
HCM	hypertrophic cardiomyopathy
HU	Hounsfield unit
iME	image-based motion-estimation
LV	left ventricular
MDCT	multidetector-row computed tomography
MRI	magnetic resonance imaging
OMI	old myocardial infarction

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Fig. 1.

A 61-year-old male with no coronary artery disease and normal cardiac function on echocardiography. Motion vectors (pink arrows) are shown every eight pixels in each direction. The vector length indicates the length of pixel movement from end-diastole to end-systole. The units of the labels were pixels, and 1 pixel was 0.39 mm in the x and y axes; the unit of the label was millimeters in the z-axis. The relatively symmetric LV contraction is demonstrated by the VCI image. The mean vector lengths were 4.5 mm at the septal wall, 3.7 mm at the inferior wall, 3.4 mm at the lateral wall, and 3.1 mm at the anterior wall.

Fig. 2.

A 65-year-old male with an old myocardial infarction involving the left circumflex artery. The perfusion defect in the apical lateral wall was severe, as shown on nuclear myocardial perfusion imaging (**A**, arrow). Cardiac CT at end-diastole (0% phase of the R-R interval) revealed myocardial fat deposition after LV myocardial infarction in the apical lateral wall (**B**, arrow). The VCI image shows that the wall motion of the apical lateral wall was hypokinetic (**C**, asterisk). The mean vector lengths were 2.5 mm at the septal wall, 4.7 at the inferior wall, 1.2 mm at the lateral wall (infarcted segment), and 3.9 mm at the anterior wall.

Fig. 3.

A-79-year-old female with takotsubo cardiomyopathy and hypokinesis of the apex on echocardiography. **A:** A horizontal long-axis image at the end-diastole (0% phase of the R-R interval). There was no obstructive coronary artery disease. **B, C:** The VCI images show LV systolic dysfunction with hypokinesis of the apex. We detected weak wall motion in the opposite direction in the apex compared with normal wall motion in the mid-ventricle (**C**, arrowhead). The mean vector lengths were 1.3 mm at the apex and 4.3 mm at the base.

Fig. 4.

A 54-year-old male with hypertrophic cardiomyopathy. **A:** LV asymmetric septal hypertrophy (asterisk). **B:** The VCI image shows asymmetric LV wall motion. The mean vector lengths were 1.4 mm at the septal wall, 3.3 mm at the inferior wall, 3.4 mm at the lateral wall, and 1.7 mm at the anterior wall.