Evaluation of Pulse Wave Velocity using 4D CT Cardiogram

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Abstract

The total arterial compliance (TAC) is defined as the sum of systemic arterial compliance which could be calculated at the root of aorta. It is an index to assess the status of arterial stiffness. Pulse wave velocity (PWV) is becoming a clinical index to assess the level of arterial stiffness. This abstract will be discussed the methodology of evaluation of PWV that will be correlating with TAC using 4D CT Cardiogram. Fifteen subjects' 4D CT cardiograms were using in this study. The aortic volume calculated at the aortic root from 4D cardiac images were ranging from 68.9 ml to 97 ml. The data was checked against the cardio outputs from the Left Ventricular (LV) images with excellent correlation (R = 0.970, P <0.01). The PWV was calculated from difference of distance that divided to the time difference (Δd/Δs). The PWVs were ranging from 7.8 to 15.6 m/s. The data was positively correlated to the total compliance calculated at the aortic root (R = 0.672, p < 0.01). And, the PWV was negatively correlated to the distention of aorta (R=-0.855, P<0.01). The derived methodology to calculate PWV from 4D CT cardiac images could be used as an index in evaluation of arterial stiffness.

1. Introduction

Recent studies have shown that patients who have atherosclerosis would increase the risk of cardiovascular disease directly or indirectly. The severity of atherosclerosis will be deteriorating as the arterial stiffness worsens. The arterial stiffness will be directly contributing to the after load of left ventricle. It is the factor of rising the systolic pressure as well as diastolic pressure. Arterial stiffness is affected by various risk factors and biologic processes. In the vascular tree, it is affecting the propagation speed of pulse waveform in the arterial tree and shifting the shape of pressure waveform. This affect is not only penetrating the micro-vascular of artery but only have sever affect to several target organs such as the brain and kidney. Many risk factors may also be exacerbating the arterial stiffness and lead to cardiovascular disease. The arterial stiffness worsens with aging and various disease states, including hypertension, diabetes mellitus, obesity and kidney disease. Therefore, measurement or estimation of arterial stiffness became important in evaluating the wellness of cardiovascular system.

Clinically, the Pulse Wave Velocity (PWV) was used as an index of assessing the level of arterial stiffness. From the physical view, in a closed system, the higher number of propagation speed, the stiffer of the material in wall of the tubing. The pulse wave velocity is calculated from the time difference of blood pressure pulsatility between the carotid artery and femoral artery. It is an indicator that wildly used to index the arterial stiffness. The estimation the stiffness of large artery is becoming significant and easier. However, the index that provided from these PWV devices does not represent the stiffness of aorta.

This report was taking another approach to evaluate the pulse wave velocity. The methodology was direct measurement the distention with time of ascending aorta from the 4D CT cardiogram. It is non-invasive evaluation PWV and it is directly look into the arterial stiffness at the aortic root.

2. Methods

A self-developed program with a user friendly interface was integrated as an image processing tool for analyzing 4D cardio CT image data set. The program was developed in visual C++ 6.0 that runs on Window XP and Window 7 operating system. The 3D reconstruction of cardiac model and the cardio function analysis were able to use a minimal user interface in extracting the contour information.

The protocol of our CT study was evaluated with an ECG gated (Figure 1), 64-slice multi-detector CT scanner (Aquilion 64 CFX, Toshiba Medical System, Tokyo, Japan). The patients were instructed to hold their breath to acquire the images, which covered from the superior margin of the pulmonary hilum to the cardiac apex (64 X 0.5 mm collimation, gantry rotation time 350 ms, table speed 6.3 mm/rotation, tube voltage 120 kV, effective tube current 545 mA). The acquisition time was 8–12 s depending on the heart rate. The fifteen sets of cardio 4D images were used in this study with patients' consent.

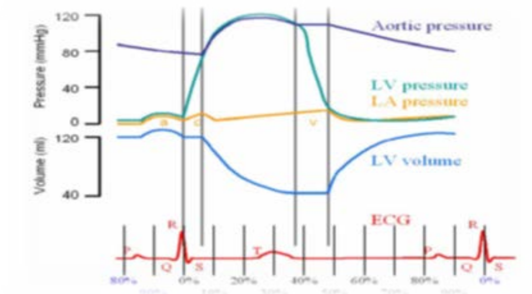

Figure 1. The R-R interval in relation to the percentage of cardiac cycle.

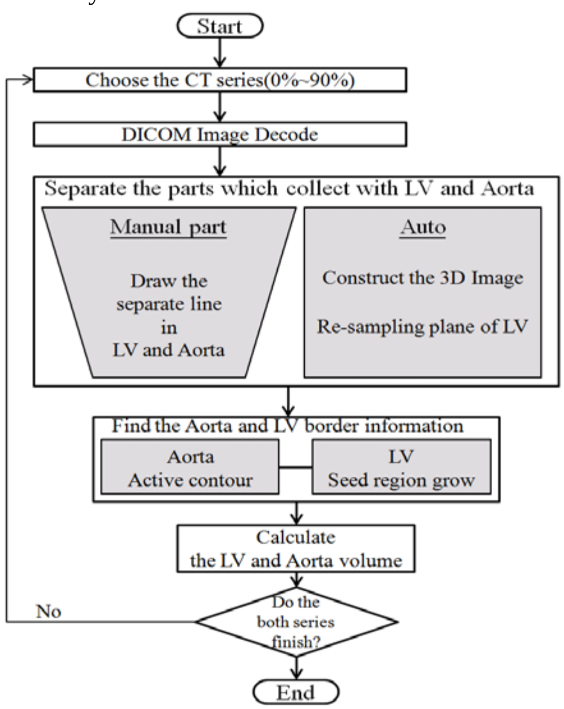

Figure 2. The flow chart of processing procedure for proposed methodology.

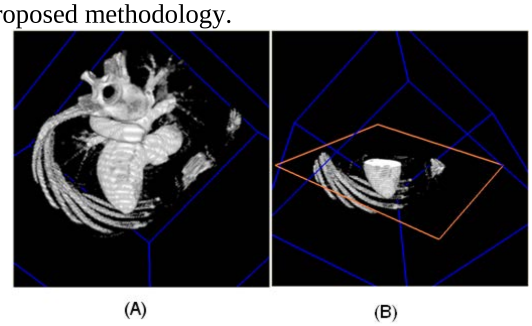

Figure 3. 3D reconstructed cardio model. (A) raw data 3D reconstructed cardio view. (B) long axis re-alignment for short axis re-sampling.

The CT images were recorded in DICOM format. The flow chart of image and reconstruction process was illustrated in Figure 2. The cardio images data set at 10 distinctive times frame will be reading into the self developed image processing system. Then, a 3D cardio image will be reconstructed and displayed for inspection and further process shown in Figure 3(A). Ten sets of 3D cardio image (with ECG gating, see Figure 1) will be registered using the rib bone as reference. The images were aligned with the minimum difference of rib bone images shown in Figure 3(B). After the registration process, the cardio images were ready for image re-sampling to extract the contour. The contour information will be used in various purpose such finding the center of the interested object area, the reconstruction of 3D wire mesh view display, volume calculation and wall motion. The self developed image processing program will be reconstructing cardiac DICOM images into 10 frames of 3D heart models for data inspection. The region of interest (ROI) will be aligned to delineate the normal direction of area. The volume at ROI was calculated using data specified in the DICOM data set. The processing steps were as shown in Figure 4.

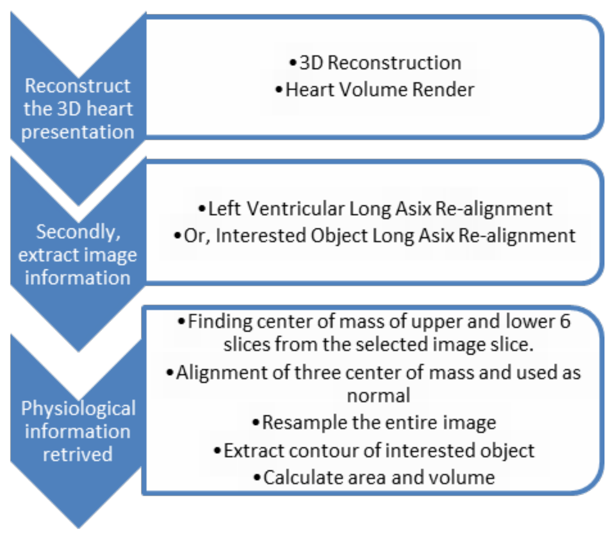

Figure 4. The summary of processing steps.

The contour of interested object area was extracted using guided active contour method [1, 2]. In this study, the volume of each time frame in a heart cycle was evaluated. The self-developed image analysis program will be reading in the data set, for example, the data set at each ECG gated frame of heart cycle. And, the program will be reconstructing into 3D volume of heart. Then, using a cutting plane as reference, one may re-sample images for accurately cutting at the root of aorta and base of LV from the atrium and set the boundary (as shown in Figure 3). Then, the user may select few slices of CT image as the seed to make a starting delineation. The self-developed heart function evaluation program will be starting to delineate the completed data set using given active contour method and seeded regional growth to delineate the atrial contour. A cubic spline procedure was performed to better fitting the atrial contour, as shown in Figure 5. In this way, the contour of ROI can be delineated in the normal plane and the short axis of area can be calculated with minimal partial fraction. With 10 frames recording for a heart cycle, the wall motion, volume of the ROI or object will be calculated from the normal vector, as shown in Figure 5 indicated by the red arrow. The calculated results will be reconstructed into 3D volume representations for inspection, as shown in Figure 3.

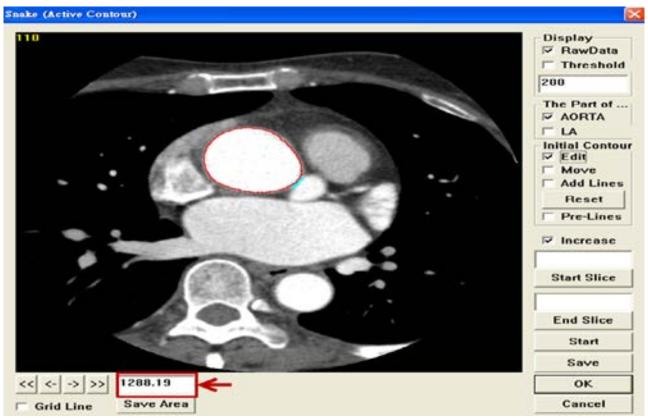

Figure 5. The result of cubic spline procedure of the contour delineation and area calculation.

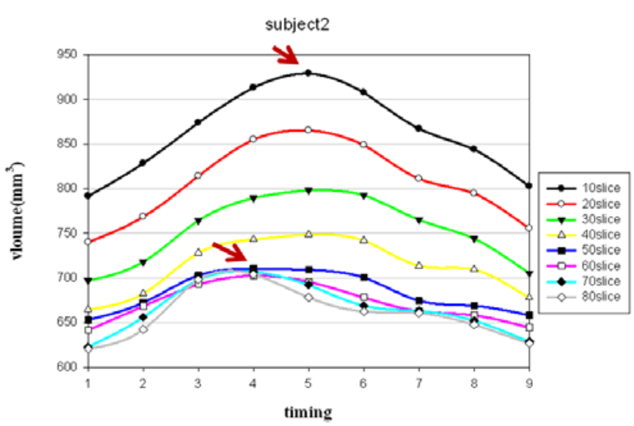

Figure 6. The result of aortic area calculation plotted with time and slices.

3. Result

The image slices at aortic area were first aligned with normal vector. Then, the area and volume will be calculated. The total of 80 slices was evaluated for in each subject. The example of calculated results was shown as Figure 6. The calculation of Pulse Wave Velocity is the selection of 2 maximal distention of aortic slice with at least one timing difference. For example, for the slice 80, it has maximal distension at timing 4 which was pointed by red arrow. For the slice 10, it has maximal distension at timing 5. The calculation formula for PWV is listed at below. Pulse wave velocity is the ratio between the difference of distention and time.

$$\mathrm{PWV} = \frac{\Delta d}{\Delta s} = \frac{80\mathrm{slice} - 10\mathrm{slice}}{0.1\mathrm{s}} = 14.0\,\mathrm{m/s}$$

Prior to the CT acquisition, the blood pressure (systolic and diastolic pressure) was recording along with heart rate. Therefore, with the volume calculation illustrated above, many features of cardiovascular parameters can be obtained. For example, The compliance and Distensibility of aortic root can be calculated with the pulse pressure. The results were listed in Table 1.

The aortic volume calculated from 4D cardiac images were ranging from 68.91 ml to 97.54. The data was correlated with the cardio outputs from the Left Ventricular (LV) images with excellent correlation (Aortic Volume = 0.88 * Cardio Output+8.63 ml, R^2=0.940, R = 0.970, P <0.01). The Bland–Altman analysis of aortic volume and cardio output is within 2 standard deviations, as shown in Figure 8. The PWV was calculated from difference of distance that divided to the time difference (Δd/Δs). That was to select the max distention from aortic slices and the distance between the slice with the time difference were calculated. The PWVs were ranging from 7.8 to 15.6 m/s, as listed in Table 1. The data was positively correlated to the Total compliance calculated at the aortic root (R = 0.672, p < 0.01) And, the PWV was negatively correlated to the distention of aorta (R=-0.855，P<0.01), as shown in Figure 7. This result shows that the higher number of PWV has lower distensibility. The lower value of PWV has higher distensibility.

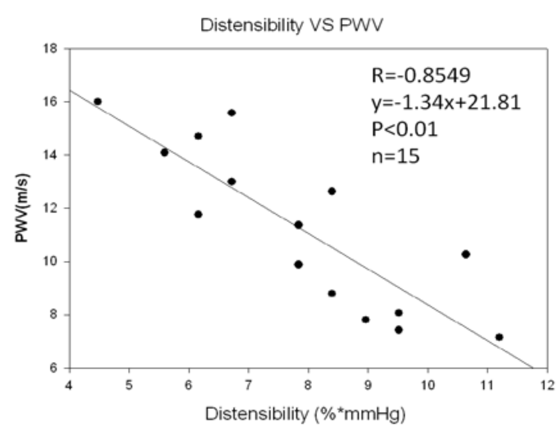

Figure 7. The Pulse wave velocity is negative correlated to Distensiblity

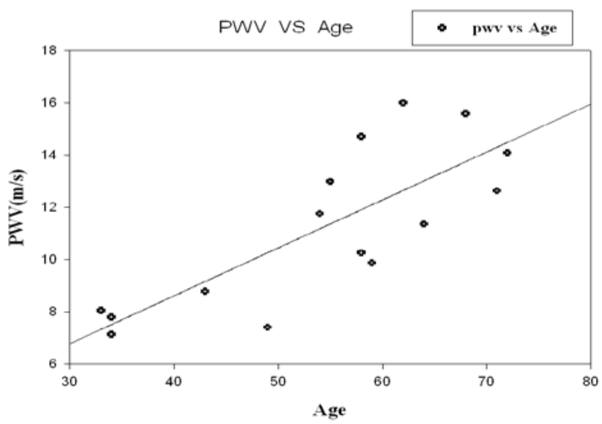

Figure 8. The correlation of PWV with the Age.

4. Conclusion

In this study, we have reported the methodology of PWV calculation from the 4D cardio image. The cardio images were acquired from multiple detectors CT with 10 timing using gated ECG. The calculated data was validated with the input (aortic volume) and output (cardio output) volume with excellent correlation. The result of PWV was listed in the Table 1. The calculated result of PWV was checked against to Distensibility of aortic image. The faster velocity is correlated to lower distensibility. Our results were in accordance to previous studies that was showing the PWV is positive correlated to the age of subject [4], as shown in Figure 8. With these result, therefore, the derived methodology to calculate PWV from 4D CT cardiac images could be used as an index in evaluation of arterial stiffness.

Acknowledgements

The research was support by grant from National Science Council, NSC- 101-2221-E-033-003.

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Table 1. The list of recordings and results for study subject

C: compliance D: Distensibility ΔP: pulse pressure ΔV: Volume Change

Subjects	Age	HR	Systolic	Diastolic	PWV(m/s)	ΔP(mm-Hg)	ΔV(ml)	C	D
1	72	84	120	73	14.1	47	94.4	3.54	5.6
2	62	60	115	58	16.0	57	69.9	4.02	4.48
3	34	71	115	77	7.1	38	92.1	1.80	11.2
4	54	71	129	77	11.8	52	87.5	2.96	6.16
5	34	77	109	69	7.8	40	90.4	1.96	8.96
6	59	74	130	84	9.9	46	97.5	2.48	7.84
7	49	66	109	74	8.9	35	80.5	2.23	9.52
8	58	88	122	93	14.7	29	78.8	3.69	6.16
9	55	78	121	64	13.0	57	70.4	3.26	6.72
10	71	63	162	82	12.6	80	72.8	3.17	8.4
11	68	77	141	91	15.6	50	80.3	3.92	6.72
12	58	77	157	104	10.3	53	75.6	2.58	10.64
13	33	97	113	65	7.8	48	68.9	1.96	9.52
14	43	64	120	70	8.8	50	80.5	2.21	8.4
15	64	68	90	58	11.4	32	80.5	2.86	7.84