

Dynamic Assessment of The Pulmonary Veins in The Cardiac Cycle of Adults Without Heart Disease by Cardiac CT

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Abstract

Purpose The purpose of this study was to explore the influence of cardiac cycle and the traditional risk factors on the four pulmonary veins (PVs) of adults and to determine the phase for measuring the maximum value of PVs.

Methods Cardiac CT was performed in 101 subjects. The diameter, area, cross-sectional angle, and coronal-section angle of four PVs in 10 phase were reconstructed and measured at 10% step from 5%-95% R-R interval. The differences in PVs size and spatial angles in cardiac cycles and the correlation between the indicators of four PVs and traditional risk factors were analyzed using two-level model.

Results All the maximum size values of the four PVs were found in 45%, while the minimum values were found in 5% or 95% of cardiac phases. Gender influenced the size of three PVs—right superior pulmonary vein (RSPV), right inferior pulmonary vein (RIPV), and left inferior pulmonary vein (LSPV). The diameter of the RSPV was small in hypertensive patients and smokers. In addition, the cross-sectional angles of the left superior pulmonary vein (LIPV) changed during cardiac cycles, and age affected these changes. We found no changes in the spatial angles of the RSPV, RIPV, and LSPV, as well as the coronal-section angle of the LIPV.

Conclusions PVs ostia size of normal person varies during cardiac phases. Compared with normal person, AF could affect the cardiac phase in which the maximum and minimum of PVs is, and it may lead to a reduction of the PVs' size slightly.

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Introduction

The pulmonary veins (PVs) are large blood vessels that transport blood from the lung to the left atrium (LA), and are the only veins rich in oxygen blood flows, including right superior pulmonary vein (RSPV), right inferior pulmonary vein (RIPV), left inferior pulmonary vein (LSPV) and left superior pulmonary vein (LIPV). In recent years, the involvement of the PVs in several pathogenetic processes has increasingly been recognized.[1] The primary PVs stenosis associated with normal PVs is a rare anomaly, its severity ranges from mild discrete stenosis at the venous atrial node and PVs stenosis to the venous atresia. And involving one or more PVs can lead to severe pulmonary arterial hypertension and right ventricular failure, which could lead to death though repaired.[2] In addition, hemodynamic evaluation shows that pulmonary arterial hypertension is proportional to the increase in PVs pressure, which ultimately leads to cor pulmonale.[3, 4] The PVs also play a role in the onset of atrial arrhythmias, such as atrial fibrillation (AF).[5]

In recent years, several studies have explored the PVs ostia size of AF patients in radiology.[6–16] However, the focus of PVs study is on patients with AF or other cardiac disease at present, and there is

very little study on the characteristics of normal population PVs. Only knowing the characteristics of PVs in the normal population, we can research the PVs disease better.

As we all know, PVs' size change significantly between end-systole and end-diastole,[10] but to date, no research has investigated the change of PVs size or spatial angles of normal person in detailed cardiac cycles. Hence, this study primarily aims to get more information about normal PVs—assess the dynamic changes of the size and spatial angles of normal person in 10 cardiac phases. And to the best of our knowledge, this is the first study about the dynamic changes of PVs' size and spatial angles of normal person, and it could be the basic of studying the PVs related disease better in the future.

Materials And Methods

Study population

In this study, we collected 110 imaging data of volunteers who underwent cardiac CT between June 2019 and August 2019. The inclusion criteria were as follows: (i) subjects who passed the image quality score (graded ≥ 3 points). [Of note, the image quality scoring criteria were as follows: 1 = the image has no diagnostic value; 2 = all or part of the cardiac cycle image has severe artifacts; 3 = the image has a few artifacts and exerts little effect on the display of the PVs; 4 = each phase image is clear, without artifacts.] (ii) subjects' 256-slice cardiac CT scans were negative, and all had sinus heart rate (heart rate, 58–96 bpm). The exclusion criteria were as follows: subjects with AF, pulmonary hypertension, or any other cardiovascular disease that causes left atrial changes such as congenital heart disease and heart valve disease, contrast agent allergy, respiratory dysfunction, and renal or cardiac insufficiency. Finally, we enrolled 101 subjects (51 males and 50 females) in this study.

In the final data statistical analysis, based on the prevention and control of adult overweight and obesity issue, grouping by the body mass index (BMI, kg/m^2) was as follows: group 1, underweight, BMI < 18.5 ; group 2, normal weight, BMI 18.5–23.9; group 3, overweight, BMI 24.0–27.9; and group 4, obesity, BMI ≥ 28.0 . Grouping by age was as follows: group 1, youth group, 18–45 years; group 2, middle-aged group, 46–69 years; and group 3, elderly group > 69 years.

In accordance with the 1964 Declaration of Helsinki and its later amendments, the institutional review board in our hospital reviewed our study. Because of the retrospective nature of the study, we were not required to get signed subjects informed consent.

Cardiac CT

All subjects underwent strict breathing training before the examination and were instructed to lie down during the examination; they were asked not to take β -blockers, such as metoprolol, before the examination. All subjects were scanned by a 256-slice scanner (Philips Brilliance iCT; Philips Medical Systems, Cleveland, OH) with retrospective ECG; the scanning range was precisely from the bifurcation of the pulmonary artery to the level of the diaphragm with a thickness of 0.5 cm. During scanning, a

contrast agent iodixanol (1.0–1.2 mL/kg; General Electric Pharmaceutical Co., Ltd., Shanghai, China) was injected using contrast agent monitoring technology, and the CT threshold of ROI was set at 110 HU. Of note, acquisitions were obtained during a single breath-hold after the injection. Scan parameters were as follows: to decrease the radiation dose of scan, the scan voltage was adjusted per the patients' weight and BMI, using automatic tube current technology. The tube voltage was 120 kV for subjects weighing ≥ 75 kg and 100 kV for subjects weighing < 75 kg; 1200 mas/slice for subjects with BMI ≥ 24 , and 900 mas/slice for subjects with BMI < 24 .

Image processing and measurement methods

The original images were reconstructed from 5–95% cardiac phases at 10% intervals. The reconstructed images were transferred to the post-processing software (IntelliSpace Portal Workspace; Philips) and loaded into the cardiac viewer application, which enabled three perpendicular axes to be adjusted simultaneously to attain perpendicular imaging planes for measurement. Two experienced radiologists (with 2- and 5-year experience in the interpretation of cardiac CT images), blinded to clinical data, independently reviewed the CT images on a dedicated post-processing workstation. They measured the diameter, area, cross-sectional angle, and coronal-section angle of the four PVs ostia. As shown in **Fig. 1**, we measured the diameter and area of the sinus ostium at the PVs ostia, followed by measuring the cross-sectional and coronal-section angles of the PVs ostia, respectively.

Statistical analysis

All statistical analyses in this study were performed using by MLwin software (version 2.36; University of Bristol, Bristol, The United Kingdom). We computed descriptive statistics, such as mean and standard deviation, for continuous variables. Based on the data characteristics, we built a two-level model. The dependent variables of each observation index included area, major axis, cross-sectional and coronal-section angle; $\alpha = 0.05$ was set as the inspection level. Cardiac phase was the first-level covariate, while gender, age, BMI, blood pressure, blood lipid, blood sugar, smoking, and drinking were second level covariates; only the statistically significant covariates were retained in the final model. Furthermore, considering interaction effects between various covariates and cardiac phases, we introduced interaction items in the final model; the interaction items that were not statistically significant after the introduction were eliminated.

Results

Baseline characteristics

In this study, we enrolled 101 subjects. **Table 1** shows the clinical characteristics of the study population. Of all, 24 subjects had hypertension, 35 had hyperlipemia, and 18 had hyperglycemia. In addition, the number of smokers and drinkers was 25 and 10, respectively.

Size of the four PVs

For the RSPV, the maximum and minimum values of diameter were observed in 45% ($19.91 \pm 3.26\text{mm}$) and 5% ($18.02 \pm 2.93\text{mm}$) of cardiac phases, respectively, while the maximum and minimum values of area were observed in 45% ($275.38 \pm 83.29\text{mm}^2$) and 95% ($196.33 \pm 64.18\text{mm}^2$). The maximum and minimum values of RIPV diameter were observed in 45% ($17.04 \pm 2.46\text{mm}$) and 95% ($15.30 \pm 2.48\text{mm}$), while the maximum and minimum values of area were observed in 45% ($210.74 \pm 58.80\text{mm}^2$) and 95% ($169.92 \pm 54.11\text{mm}^2$), respectively. The maximum and minimum values of LSPV diameter were observed in 45% ($18.93 \pm 2.78\text{mm}$) and 95% ($16.68 \pm 2.62\text{mm}$), while the maximum and minimum values of area were observed in 45% ($224.22 \pm 62.53\text{mm}^2$) and 5% ($169.21 \pm 48.55\text{mm}^2$), respectively. For the LIPV, the maximum and minimum values of diameter were observed in 45% ($16.52 \pm 2.55\text{mm}$) and 5% ($15.11 \pm 2.23\text{mm}$), while the maximum and minimum values of area were observed in 45% ($154.84 \pm 60.52\text{mm}^2$) and 5% ($126.93 \pm 41.23\text{mm}^2$), respectively (Tables 2 and 3). The diameter and area of the four PVs ostia in cardiac phases varies significant (Fig. 2).

We used the quadratic curve model to fit the changes of the four PVs ostia diameter and area with cardiac phases; the covariates were screened one by one, and only the statistically significant factors were included in the final model to determine the correlation between traditional cardiovascular risk factors and PVs ostia (Suppl. Tables 1–12). Gender influenced the size of three PVs, like RSPV, RIPV, and LSPV. For the RSPV, RIPV, and LSPV, at the initial cardiac phase, the average level of the PVs' size between individuals of different genders was different; changes in the PVs differed at different cardiac phases, and the rate of change was also different. In addition, blood pressure and smoking affected the RSPV size, and the RSPV diameter was small in patients with hypertension and smokers. We found no effect of age, blood fat, blood sugar, BMI, and drinking on the PVs' size. Moreover, factors affecting changes in the three PVs ostia size didn't be found entirely. For the LIPV, no statistically significant variables were found.

Spatial angles of PVs

For the RSPV, the maximum and minimum values of cross-sectional angles were observed in 5% ($18.30 \pm 8.29^\circ$) and 45% ($16.41 \pm 7.55^\circ$) of cardiac phases, respectively, while the maximum and minimum values of coronal-section angles were observed in 5% ($25.10 \pm 8.73^\circ$) and 35% ($23.39 \pm 8.37^\circ$). The maximum and minimum values of RIPV cross-sectional angles were observed in 45% ($30.28 \pm 11.19^\circ$) and 5% ($29.30 \pm 11.69^\circ$) respectively, while the maximum and minimum values of coronal-section angles were observed in 5% ($18.06 \pm 9.93^\circ$) and 65% ($17.34 \pm 9.38^\circ$). And the maximum and minimum values of LSPV cross-sectional angles were observed in 45% ($17.17 \pm 8.31^\circ$) and 85% ($15.75 \pm 8.21^\circ$) respectively, while the maximum and minimum values of coronal-section angles were observed in 45% ($33.09 \pm 12.30^\circ$) and 75% ($31.10 \pm 11.68^\circ$). The maximum and minimum values of LIPV cross-sectional angles were observed in 45% ($22.18 \pm 9.06^\circ$) and 5% ($20.18 \pm 8.76^\circ$), while the maximum and minimum values of coronal-section angles were observed in 55% ($20.59 \pm 10.01^\circ$) and 85% ($19.38 \pm 9.02^\circ$), respectively (Tables 2 and 3).

As the changing trend of the RSPV, RIPV, and LSPV spatial angles was a straight line, they were not included in the model fitting stage, neither did the LIPV coronal-section angle. Figure 2 shows the difference in the cross-sectional angle of the LIPV. We used a quadratic model to fit the trend of the LIPV cross-sectional angle with cardiac phases. The covariates were screened one by one; as the fixed effects of age were statistically significant, they were included in the final model. Suppl. Tables 13 and 14 show the final model. In the initial phase, the average value of LIPV's cross-sectional angle among different-age individuals was different. In different cardiac phases, different-age individuals exhibited different changes in LIPV's cross-sectional angle, and individuals with different ages had a different speed of the LIPV's cross-sectional angle change. Of note, factors affecting changes in LIPV's cross-sectional angles were not found entirely.

Discussion

Main findings

The statistical methods used in this study involved models that considered several factors, which makes it the most extensive study of normal PVs to date. This study reveals that the PVs ostia size is variable during cardiac cycles for normal person. All the maximum values of the four PVs' size were observed in 45% of cardiac phases, while the maximum values of the RSPV angles and RIPV coronal-section angles, were observed in 5%. In addition, the maximum values of the LSPV angles, LIPV cross-sectional angles, and RIPV cross-sectional angles were observed in 45%; however, the maximum values of the LIPV coronal-section angles were observed in 55%.

Size of PVs

In our study, the maximum PVs size was in 45% of cardiac phase, while the minimum PVs size was in the 5% or 95% phases. However, Choi et al.[9] argued that the maximum size of the RIPV was in 35%, while the minimum size of the RIPV was in 85% phase; thus, they measured the RSPV, LSPV, and LIPV in these two phases. The subject of Choi et al's study is AF and non-AF populations, while our study subject is only normal population. At the same time, Hauser et al.[17] find the timing of the PVs maximum size varied but generally occurred in ventricular diastole, and the timing of minimum PVs size also varied but generally occurred in ventricular systole, but they didn't provide specific cardiac timing points. Therefore, we believe that AF can affect the cardiac phase which the maximum and minimum of PVs is in. In normal population, Manghat NE et al.[10] directly measured the PVs size by MR cine in the end-systolic and end-diastolic stages of the ventricle, and found that the maximum size of the four PVs were all located in the ventricular end-systolic. Therefore, we can think that the ventricular end-systolic is equivalent to 45% phase of cardiac cycle in the CT reconstruction. According to Deng Wen et al's[18] physiological phases of the cardiac cycle, 40% phase corresponds to the ventricular isovolumic relaxation phase, while 50–90% corresponds to the filling phase, during which the atrial volume is larger in the early stage but later decreases. Some studies have demonstrated that during cardiac cycle, changes in the PVs ostia size are consistent with the changes in the atrial volume, and the atrial volume expansion could

lead to an increase in the PVs ostia.[8, 19] In addition, the minimum size of the four PVs ostia was observed in 5% or 95%, which is equivalent to the systolic period of the cardiac phases (the atrioventricular valve is closing); at this point, the blood flow in the atrium enters the ventricle totally, and the LA volume is the smallest. Thus, the change of the PVs ostia size corroborates the behavior of the atrial volume, and any disease that causes abnormalities in the LA, such as mitral valve disease, would change the PVs' size.

Dong et al.[20] measured the maximum diameter of the four PVs in AF patients. Compared with our study, RSPV (19.91 ± 3.26 mm) VS (17.79 ± 4.30 mm), RIPV (17.04 ± 2.46 mm) VS 15.92 ± 3.19 mm), LSPV (18.93 ± 2.78 mm) VS (18.54 ± 3.44 mm), and LIPV (16.52 ± 2.55 mm) VS (15.56 ± 3.25 mm), we can find that the diameter of the four PVs in normal person is higher than that in AF patients. Hence, it is obvious that AF could lead to a reduction of the PVs' size; however, Dong et al.[20] did not provide the phase of the maximum value of the PVs ostia.

The correlation between traditional risk factors and PVs

Regarding the correlation between gender and PV size, we found that the RSPV, RIPV, and LSPV differed between males and females. At the initial phase of the cardiac cycle, the average level of the three PVs size between individuals of different genders was different, and the size of these three PVs was larger in males than that in females. At different phases of the cardiac cycle, changes in the three PVs (RSPV, RIPV, and LSPV) were different, and the rate of change was also different. Notably, blood pressure and smoking affected the RSPV size. The diameter of the RSPV in hypertensive patients and smoker was small. We observed no effect of age, blood fat, blood sugar, BMI, and drinking on the PVs' size.

Spatial angle of PVs

The changing trend of the RSPV, RIPV, and LSPV cross-sectional and coronal-section angles was a straight line. For the LIPV, however, the maximum and minimum values of cross-sectional angles were observed in 45% and 5% of cardiac phases, while the maximum and minimum values on coronal-section angles were observed in 55% and 85%, respectively.

Wang et al.[12] measured the angle of the PVs at a certain phase and reported that the angle is a real and stable imaging anatomical feature, which has nothing to do with gender or image features (magnetic resonance or CT).[12] In our study, we measured the spatial angles (cross-sectional and coronal-section angles) of the four PVs in 10 cardiac phases and revealed that in the initial phase of the cardiac cycle, the average value of the LIPV cross-sectional angles among individuals with different ages was different; with increasing age, the angle also increases. In different cardiac phases, individuals with different ages revealed different changes in the LIPV cross-sectional angles, and individuals with different ages had a different speed of LIPV cross-sectional angle changes. However, the cross-sectional and coronal-section angles of the RSPV, RIPV, and LSPV, as well as coronal-section angle of the LIPV, did not change considerably with the cardiac cycle change. Moreover, we found no effect of gender, blood lipid, blood glucose, BMI, drinking, and smoking on the spatial angle of these PVs. Thus, if intervening on the RSPV,

RIPV, or LSPV, we concur with Wang et al.[12]; it is recommended to adjust the angle of the central X-ray based on the average value of the central X-ray angle. If intervening on the LIPV, we recommend that the pre- and postoperative image assessment should be performed at the same cardiac phase, and during the operation, the surgeon(s) must closely observe the changes in LIPV angles.

Conclusion

In conclusion, this study demonstrates that the PVs ostia size of normal person varies during cardiac phases, which is consistent with that in atria. Compared with normal person, AF could affect the cardiac phase in which the maximum and minimum of PVs is, and it may lead to a reduction of the PVs' size slightly. This study also find that the ventricular end-systolic is equivalent to 45% phase of cardiac cycle in the CT reconstruction. In addition, the degree of PV changes in the cardiac phases varies with gender. Thus, this study suggests that the measurement of the PVs should always be at the same cardiac phase to avoid misinterpretation of variations in the cycle as stenosis. Furthermore, the angles of the RSPV, RIPV, and LSPV, is a real and stable imaging anatomical feature.

This study has some limitations worth acknowledging. First, in this study, the radiation dose was generated using CT, but the radiation dose was generally lower than the international or domestic standard. Second, this study only measured the PVs size in the normal population, and did not measure the PVs size of AF patients in 10 cardiac phases. In future study, we will continue to research the characteristics of patients' PVs with heart disease or AF.

Abbreviations

PVs, pulmonary veins; AF, atrial fibrillation; RSPV, right superior pulmonary vein; RIPV, right inferior pulmonary vein; LSPV, left inferior pulmonary vein; LIPV, left superior pulmonary vein; LA, left atrium; BMI, body mass index.

Declarations

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The authors did not receive support from any organization for the submitted work.

Conflicts of interest/Competing interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Availability of data and material

All the data involved in this study are available.

Code availability

The model establishment is completed with MLwin2.36 software (version 2.36; University of Bristol, Bristol, The United Kingdom).

Authors' contributions

Jing Chen provided the ideas of this study, analyzed the data, and revised the article finally; Jing Dong collected and searched patient images, measured data, analyzed the image and data, and wrote articles; Hui Li statistics and analysis all the data; Yu-jiao Deng and Jin-rong Zhou analyze images.

Ethics approval

This study has been approved by our hospital ethics committee and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments (KY201907). Because of the retrospective nature of the study, we were not required to get signed subjects informed consent.

Consent to participate

Because of the retrospective nature of the study, we were not required to get signed subjects informed consent.

Consent for publication

All authors involved in this study agree to the publication of this article

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Tables

Table 1. Subject characteristic

	n=101
Male/Female	51/50
Age, mean \pm SD, years	50.79 \pm 10.10
BMI	23.61 \pm 3.28
hypertension	24
hyperlipemia	35
hypercemia	18
somking	25
drinking	10

BMI, body mass index; data are presented as mean \pm standard deviation or n.

Table 2. The comparisons of RSPV and RIPV's size between cardiac phases

	diameter	area	cross-sectional angle	coronal-sectional angle
RSPV				
5%	18.02±2.93	201.73±66.20	18.30±8.29	25.10±8.73
15%	18.57±3.06	211.80±65.00	18.08±8.14	24.32±8.16
25%	19.10±3.00	239.61±73.31	17.04±7.96	23.73±8.14
35%	19.59±3.35	268.66±82.35	16.74±7.71	23.39±8.37
45%	19.91±3.26	275.38±83.29	16.41±7.55	23.72±8.22
55%	19.61±3.10	255.14±77.59	17.08±7.75	23.96±8.28
65%	19.60±3.13	240.42±68.58	16.97±7.74	23.94±8.35
75%	19.73±3.12	244.71±69.45	16.81±7.86	23.78±8.48
85%	19.42±3.10	234.29±68.19	17.20±7.81	24.28±8.61
95%	17.28±2.82	196.33±64.18	17.79±24.9	24.91±8.68
RIPV				
5%	15.58±2.25	175.12±50.17	29.30±11.69	18.06±9.93
15%	15.93±2.33	183.01±51.47	29.46±11.42	17.63±9.42
25%	16.52±2.35	194.68±55.26	30.04±11.08	17.88±9.40
35%	16.86±2.48	206.67±59.32	30.08±11.20	17.53±9.45
45%	17.04±2.46	210.74±58.80	30.28±11.19	17.62±9.45
55%	16.79±2.43	201.53±56.20	29.77±11.14	17.82±9.39
65%	16.54±2.35	197.59±53.64	29.54±10.93	17.34±9.38
75%	16.58±2.45	198.80±56.64	29.91±11.20	17.72±9.52
85%	16.22±2.55	194.04±60.51	29.85±11.12	17.66±9.55
95%	15.30±2.48	169.92±54.11	29.56±11.22	17.77±9.93

Data are presented as mean ± standard deviation; RSPV, the right inferior pulmonary vein; RIPV, the right inferior pulmonary vein.

Table 3. The comparisons of LSPV and LIPV's size between cardiac phases

	diameter	area	cross-sectional angle	coronal-sectional angle
LSPV				
5%	16.79±2.79	169.21±48.55	16.02±8.60	34.23±11.96
15%	17.01±2.65	175.68±51.43	16.46±8.04	33.71±12.12
25%	17.80±2.73	199.10±56.80	16.95±8.12	33.09±12.31
35%	18.66±2.79	216.72±60.23	17.16±8.38	32.80±12.74
45%	18.93±2.78	224.22±62.53	17.17±8.31	33.09±12.30
55%	18.46±2.63	204.98±54.99	16.65±8.29	32.29±12.02
65%	18.34±2.85	191.91±50.66	15.87±8.10	31.13±11.80
75%	18.47±2.87	192.10±52.35	15.77±8.20	31.10±11.68
85%	18.23±2.86	191.69±52.96	15.75±8.21	31.47±12.17
95%	16.68±2.62	171.99±47.24	16.15±8.11	32.70±12.27
LIPV				
5%	15.11±2.23	126.93±41.23	20.18±8.76	20.24±10.14
15%	15.53±2.43	130.40±43.00	20.49±9.11	19.98±9.73
25%	16.00±2.58	144.32±53.97	21.23±9.04	20.38±9.63
35%	16.44±2.77	152.02±59.17	21.80±8.87	20.47±9.66
45%	16.52±2.55	154.84±60.52	22.18±9.06	20.44±9.49
55%	16.39±2.48	146.87±51.56	21.87±8.80	20.59±10.01
65%	16.27±2.51	142.93±48.04	21.48±8.31	20.11±9.37
75%	16.30±2.35	144.16±49.22	21.25±8.31	19.91±9.46
85%	16.12±2.47	141.82±48.44	20.72±7.94	19.38±9.02
95%	15.26±2.10	130.27±42.20	20.20±8.18	19.65±9.33

Data are presented as mean ± standard deviation; LSPV, the left inferior pulmonary vein; LIPV, the left inferior pulmonary vein.

Figures

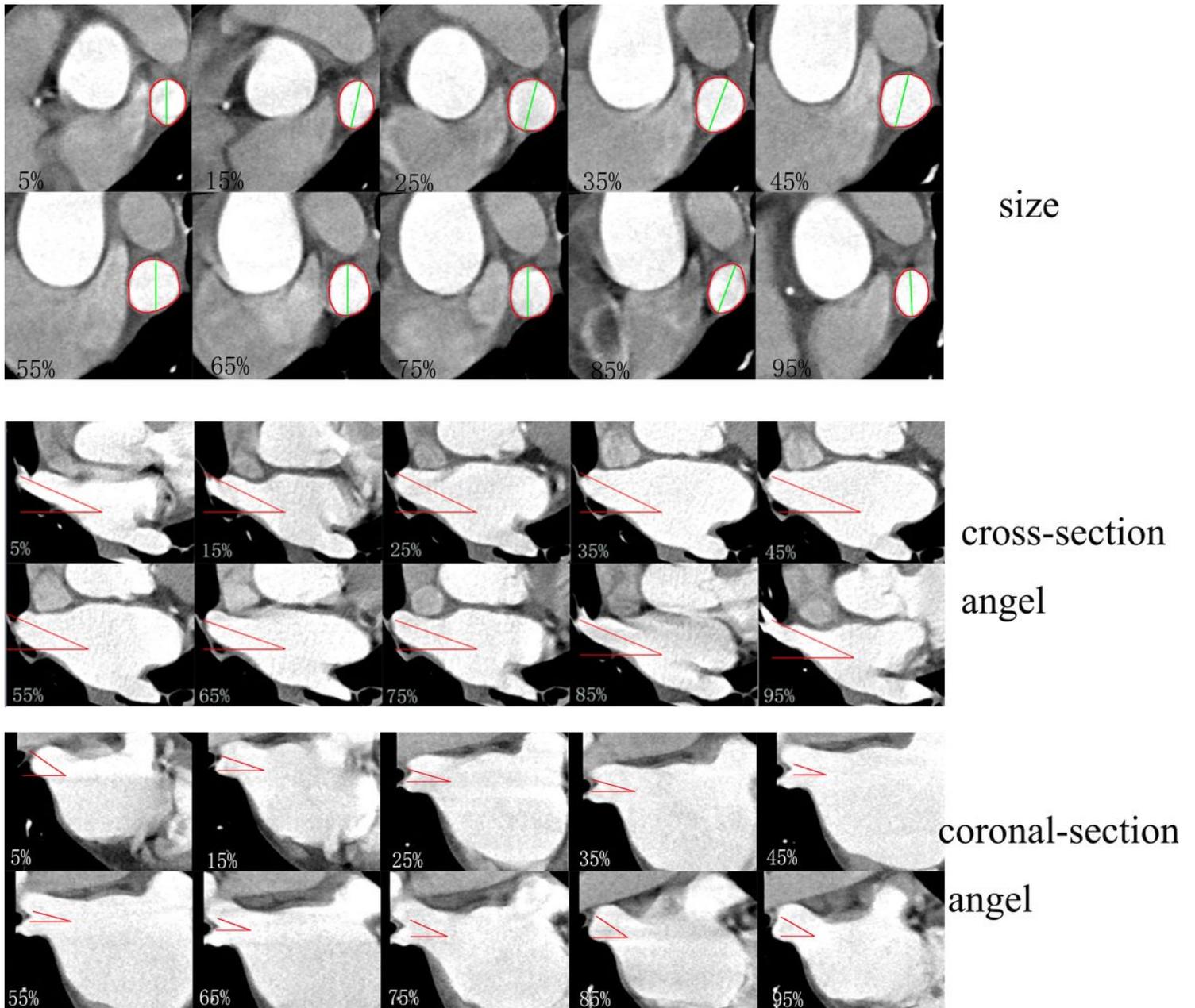


Figure 1

The original images were reconstructed from 5% to 95% cardiac phases at 10% intervals. The reconstructed images were transferred to the post-processing software (IntelliSpace Portal Workspace; Philips) and loaded into the cardiac viewer application, which enabled three perpendicular axes to be adjusted simultaneously to attain perpendicular imaging planes for measurement. Two experienced radiologists (with 2- and 5-year experience in the interpretation of cardiac CT images), blinded to clinical data, independently reviewed the CT images on a dedicated post-processing workstation. They measured the diameter, area, cross-sectional angle, and coronal-section angle of the four PVs ostia. As shown in Fig. 1, we measured the diameter and area of the sinus ostium at the PVs ostia, followed by measuring the cross-sectional and coronal-section angles of the PVs ostia, respectively.

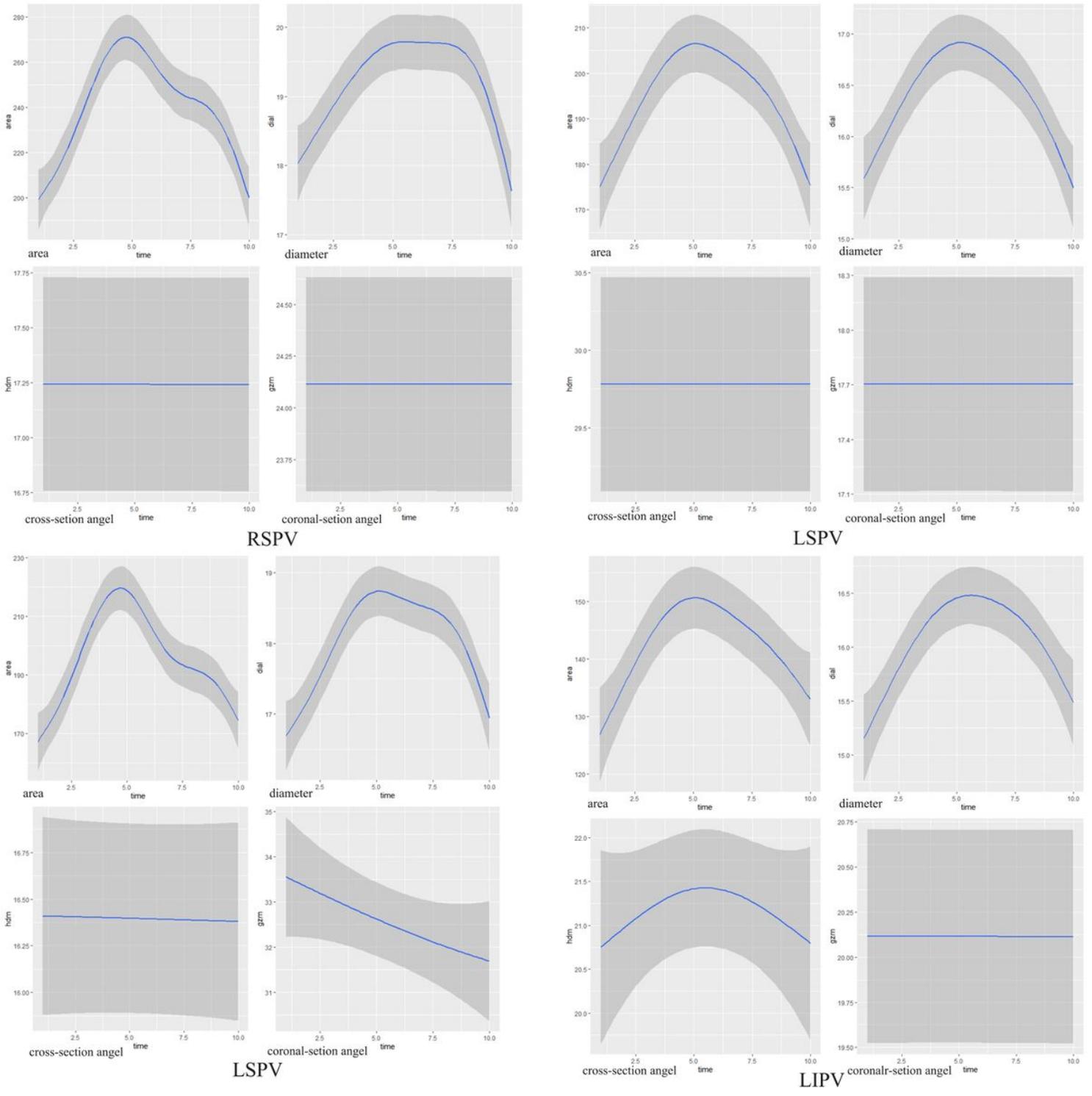


Figure 2

Figure 2 shows the difference in the cross-sectional angle of the LIPV. We used a quadratic model to fit the trend of the LIPV cross-sectional angle with cardiac phases.

Supplementary Files

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