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Association of epicardial adipose tissue density with postoperative atrial fibrillation after isolated aortic valve replacement

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ABSTRACT

Backgrounds: It is well known that epicardial adipose tissue (EAT) is associated with the development of atrial fibrillation (AF). The aim of this study was to investigate whether EAT density (EAT-d) is associated with the development of new-onset atrial fibrillation (POAF) after aortic valve replacement (AVR).
Methods: We retrospectively studied 143 patients who underwent simple AVR at Department of Cardiovascular Surgery of the General Hospital of Northern Theater Command between June 2020 to August 2023. All patients received cardiac coronary artery computed tomography (CT) before surgery. EAT-d, EAT volume and EAT volume index (EATVI) were quantitatively measured and analysed using EAT analysis software (TIMESlicePro). POAF was detected by 7-day Holter monitoring.
Results: Of 143 patients undergoing AVR, 55 patients (38.46 %) developed POAF after surgery. Male patients and patients who had elder age or smoking history were more likely to develop POAF. On univariable analysis, patients developed POAF had significantly more EAT-d (−79.19(−83.91, −74.69) vs. −81.54(−87.16, −76.76); P = 0.043) and EATVI (4.14(3.32,5.03) vs. 3.90(2.70,4.51); P = 0.043) than patients without POAF. On multivariable analysis, EAT-d and age were independent risk factors for POAF (odds ratio (OR): 1.186, 95 % confidence interval (CI): 1.062–1.324, P = 0.002; OR: 1.119, 95 %CI: 1.055–1.187, P < 0.001). Furthermore, EAT-d was significantly associated with age. Furthermore, EAT-d was associated with cardiac structure changes, such as cardiac left ventricular end-diastolic, left ventricular end-systolic volumes and NT-proBNP before surgery.
Conclusion: EAT-d and age are independent predictors of POAF after simple AVR. EAT-d was related with age.

1. Introduction

Atrial fibrillation (AF) is one of the most common complications after cardiac surgery with an incidence of 10 %-60 % [1–3]. Postoperative atrial fibrillation (POAF) occurs in 30 %-60 % of patients who underwent aortic valve replacement (AVR) [4–6]. POAF leads to the risk of stroke, heart failure, and a significant increase in hospitalization costs, intensive care unit time, and length of hospital stay [7]. The mechanisms of POAF has been an unanswered question. It has been well documented that POAF may be related to inflammation, fibrosis and adipose tissue infiltration [8].Furthermore, the pre-existing substrate increased the atria vulnerable to atrial fibrillation induction and maintenance [9–11].

Epicardial adipose tissue (EAT) is anatomical and functional contiguity to the myocardium. It can affect the myocardium and coronary arteries through vasocrine or paracrine secretion of proinflammatory cytokines, which is one of the main triggers in POAF [12,13]. Many studies suggested that EAT played an important role in the development of AF [14–19]. EAT can be noninvasively quantified with computed tomography (CT). Additionally, CT scans provided three-dimensional estimates of the overall EAT volume (EATV) and the calculation of EAT density (EAT-d) (measured in Hounsfield Units, HU) [20]. As the coronary artery CT is the routine examination before valvar surgery, we

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can assess the volume and density of EAT without extra cost. Therefore, we sought to determine whether EAT by coronary artery CT might be used as a biomarker of POAF in patients underwent AVR.

2. Materials and methods

2.1. Study population

We retrospectively studied consecutive patients who underwent AVR at the Department of cardiovascular surgery between June 2020 and August 2023. Total 143 patients who underwent isolated AVR were included. Patients were excluded from the study if they had 1. history of atrial fibrillation or other arrhythmias; 2. implantation of a pacemaker or defibrillator; 3. need for mitral valve surgery or coronary artery bypass grafting during the same period; 4. incomplete or poor-quality coronary CT arteriography images for analysis. All procedures in this study were carried out in accordance with the Declaration of Helsinki.

2.2. Diagnosis and definitions

All patients were monitored continuously using an ambulatory electrocardiogram preoperatively and for 7 days before and post operation. AF was defined as an irregular rhythm without significant P waves lasting at least 30 s [21,22].

2.3. Data collection

Data were collected from the medical record system by 2 trained physicians who were blind to the purpose of the study. The investigators classified patients after AVR into a POAF group and a no-POAF group based on the presence of new-onset POAF within 7 days postoperatively and collected baseline characteristics and clinical data, including demographic characteristics, preoperative cardiac ultrasound parameters, and preoperative laboratory indices.

2.4. CT scanning

Coronary CT arteriography was performed on 143 patients by a Toshiba Aquilion ONE Vision Edition 2nd generation 320-row spiral CT scanner. The scanning technician trained the patients to hold their breath before scanning and instructed the patients to lie in the supine position, selecting the head-to-foot position as the scan direction, the tracheal crest to 2 cm below the diaphragm as the total scan area, and the area of interest during the scanning process. Scanning was completed by holding the breath after a single inspiration. Metoprolol was administered at least 1 h previously to control the heart rate in patients with an unstable heart rate or a heart rate greater than 80 beats per minute. Prospective cardiac gating was used with a tube voltage of 120 kV, automatic tube current, slice thickness of 0.5 mm and slice spacing of 0.5 mm; all exposure times were 75 % of the R-R interval. The detector width was 160 mm, spiral scan, rotation time 0.275 s. Iohexol was injected via the dorsal foot vein or the right elbow vein in a dose of 30–60 ml at a rate of 3.5–5.0 ml/sec. A monitoring target was set in the descending aorta with a trigger threshold of 180 HU, and continuous breath holding was used during the scanning period, with a saline washout of 5–20 ml of static saline injected at the same rate [23].

2.5. EAT and PCAT measurements

The CT value of epicardial adipose tissue was set at −190–30 HU. Using TIMESlicePro [24], a fully automated EAT recognition software developed by the General Hospital of the Northern Theatre of Operations and Northeastern University, the original CTA images of 55 %–75 % diastolic phase of all patients were transferred to the software by two uninformed personnel according to the method used in the software literature. The area of EAT was automatically identified by an artificial intelligence algorithm. EAT was reconstructed into a 3D region, and EATV and EAT-d were calculated (Supplementary Fig. S1). And EAT volume index (EATVI) was further calculated according to the EAT volume index formula.

The software was used to manually trace the 40 mm segment proximal to the left anterior descending (LAD) and left circumflex (LCX) and the 10–50 mm segment proximal to the right coronary artery (RCA). The software reconstructed the pericoronary fat in three dimensions and provided fully automated quantitative measurements of EATV and EAT-d (fat attenuation) in the three main coronary arteries (LAD, LCX and RCA) (Supplementary Fig. S2).

Table 1
Demographic and clinical characteristics by presence of Postoperative Atrial Fibrillation (PoAF).

Characteristics	POAF (n = 55)	NO-POAF (n = 88)	P
Age(y)	63.00(58.00,69.00)	55.00(50.25,64.00)	<0.001
Women , %	14 (25 %)	40 (45 %)	0.016
Heart rate	69.00(63.00,78.00)	71.50(61.00,79.00)	0.751
NYHA			0.225
II	3 (5%)	2 (2%)	
III	33 (60 %)	44 (50 %)	
IV	19 (35 %)	42 (48 %)	
BMI(kg/m^2)	24.00 ± 3.30	24.44 ± 3.47	0.460
Drinking , %	20 (36 %)	19 (22 %)	0.054
Smoking , %	27 (49 %)	24 (27 %)	0.008
COPD , %	8 (14.5 %)	6 (6.8 %)	0.130
Hypertension , %	21 (38 %)	34 (39 %)	0.957
Diabetes mellitus , %	1 (1.8 %)	5 (5.7 %)	0.489
AS , %	29 (52.7 %)	42 (47.7 %)	0.561
Preoperative ultrasonic parameters			
LAD(mm)	39.00(36.00,43.00)	39.00(35.00,42.00)	0.177
IVST(mm)	13.00(12.00,14.00)	12.00(11.00,14.00)	0.321
PWT(mm)	12.00(11.00,13.00)	12.00(11.00,13.00)	0.329
LVEDD(mm)	51.00(45.00,62.00)	52.00(45.00,58.00)	0.741
LVMI (g/m^2)	151.19 (126.15,179.50)	141.01 (112.76,176.68)	0.215
LVEDV(ml)	123.00 (96.00,194.00)	134.00 (92.00,168.00)	0.745
LVESV(ml)	53.00(39.00,92.00)	59.00(38.00,77.00)	0.773
SV(ml)	72.00(53.00,99.00)	74.50(53.00,91.00)	0.605
LVEF	0.57(0.52,0.59)	0.57(0.52,0.60)	0.616
Preoperative laboratory parameters			
White blood cell(*10^9/L)	5.40(4.60,6.60)	5.90(4.90,6.98)	0.112
Neutrophil(*10^9/L)	3.45(2.47,4.07)	3.64(2.71,4.16)	0.226
Monocyte(*10^9/L)	0.37(0.29,0.48)	0.36(0.29,0.47)	0.99
Lymphocyte(*10^9/L)	1.67(1.35,1.93)	1.80(1.4325,2.15)	0.101
PCT , ‰	17.70(14.10,20.90)	18.75(15.73,22.18)	0.037
Blood Urea(mmol/L)	6.30(5.58,7.95)	6.05(5.03,7.24)	0.057
serum creatinine(mg/dL)	78.83(67.65,85.80)	66.20(57.06,74.21)	<0.001
CYCS(mg/L)	0.97(0.84,1.10)	0.89(0.81,1.01)	0.033
NT-proBNP(pg/mL)	747.00 (378.70,1745.00)	420.60 (128.70,1133.00)	0.013
HsTnT(ng/mL)	13.00(8.00,21.00)	10.00(7.00,15.00)	0.020
Intraoperative parameter			
CPB	91.00 (80.00,106.00)	93.00 (74.50,110.00)	0.807
ACC	59.00(48.00,69.00)	57.50(49.00,68.75)	0.921

Values are media(first,third quartile) or n(%) or $\bar{x}$±s. COPD: chronic obstructive pulmonary disease; AS: aortic stenosis; LAD: left atrial diameter; IVST: interventricular septal thickness; PWT: posterior wall thickness; LVEDD: left ventricular end diastolic diameter; LVEDV: left ventricular end diastolic volume; LVESV: left ventricular end systolic volume; SV: stroke volume; LVEF: left ventricular ejection fraction; PCT: platelet Compression Cubic Tract; CYCS: Cystatin C; CPB: extracorporeal circulation time; ACC: aortic block time.

Table 2
Univariable and multivariable Logistic regression analysis of risk factors of PoAF.

Variables	Univariate			Multivariate		
	OR	95 %CI	P value	OR	95 %CI	P value
Age(y)	1.093	1.046–1.142	<0.001	1.119	1.055, 1.187	<0.001
Women，%	0.410	0.196–0.857	0.018			
Smoking，%	2.075	0.982–4.385	0.056			
Drinking，%	2.571	1.268–5.214	0.009			
Blood Urea(mmol/L)	1.205	0.978–1.483	0.079			
serum creatinine(mg/dL)	1.019	1.001–1.019	0.035			
CYCS(mg/L)	3.855	0.961–15.462	0.057			
PCT，‱	0.900	0.830–0.975	0.01			
HsTNT(ng/mL)	1.021	0.994–1.049	0.122			
NT-proBNP(pg/mL)	1.000	1000–1.000	0.231			
LCX-d (HU)	1.030	0.995–1.067	0.094			
EATVI(ml*m^3/kg)	1.323	1.017–1.720	0.037			
EAT-d (HU)	1.061	1.011–1.114	0.017	1.186	1.062, 1.324	0.002

CI=confidence interval; OR=odds ratio. CYCS: Cystatin C; PCT: platelet Compression Cubic Tract; LCX-d: left circumflex volume density; EATVI: epicardial adipose tissue volume index; EAT-d: epicardial adipose tissue density.

EATV was defined as the volume of all cardiac surface adipose tissue within the pericardial sac. EATVI was calculated using the formula: EATVI=EATV/BMI. EAT-d was the mean CT value of all EAT within the pericardial sac. Coronary periarterial adipose tissue (PCAT) volume (PCATV) is the volume of adipose tissue in the proximal 40 mm segments of LAD and LCX arteries and the proximal 10–50 mm segment of RCA. PCAT density (PCAT-d) was the mean CT value of PCAT of *peri*-coronary artery fat.

2.6. Statistical analysis

All data analyses were performed using SPSS software version 27.0, with categorical variables expressed as counts and percentages (%), and continuous variables expressed as mean standard deviation or median and interquartile range. Comparison of parameter values between the two groups was performed using the independent samples *t*-test, non-parametric values were compared using the Mann-Whitney *u* test, and comparison of categorical variables was performed using the chi-squared test. Spearman correlation analyses were used to test the correlations between EAT-d and cardiometabolic risk markers and ultrasound parameters, respectively. One-way logistic regression analysis was used for univariable analysis. Potential risk factors for postoperative AF were investigated by one-way logistic regression analysis, and potential risk factors with $P < 0.1$ were included in multifactorial logistic regression to investigate independent risk factors for POAF. Receiver Operating Characteristic (ROC) curve analysis was employed to determine the sensitivity and specificity of EAT-d. All tests were two-tailed and $P < 0.05$ was considered statistically significant. Graphs were generated using GraphPad Prism version 9.0.

3. Results

3.1. Baseline characteristics of patients

From June 2020 to August 2023, a total of 143 consecutive patients who performed coronary CT and successfully underwent isolated AVR were included in this study. All patients were recorded by continuous 7 days Holter electrocardiography before and post operation. The characteristics included in this study are summarized in Table 1. Fifty-five (38.4 %) patients developed POAF. Patients who were elder, male and smoking were likely to have POAF ($P < 0.001$, $P = 0.016$ and $P = 0.008$, Table 1). Furthermore, patients who had elevated serum creatinine, NT-proBNP and HsTnT were more likely to develop POAF ($P < 0.001$, $P = 0.013$ and $P = 0.020$, Table 1). Meanwhile, other factors such as left atrial diameter, cardiopulmonary bypass time and aortic clamp time had no significant impact on the incidence of POAF.

3.2. EAT and PCAT characteristics

The distribution of preoperative EAT-d and EATVI values for AVR is shown in Supplementary Fig. S3, with a median EAT-d value of −80.5 HU; and a median EATVI value of 3.9788 ml*m^3/kg. Patients in the POAF group had significantly higher EAT-d (−79.19(−83.91,−74.69) vs. −81.54(−87.16,−76.76); $P = 0.043$, Supplementary Fig. S4) and higher EATVI ((4.14(3.32,5.03) vs. 3.90(2.70,4.51); $P = 0.043$, Supplementary Fig. S4). Although EATV was higher in the POAF group, there was no statistically significant difference between the two groups (100.73(74.58,126.30) vs. 93.67(61.39,121.14), $P = 0.133$). As shown in Supplementary Table S1, there was no statistically significant difference in PCAT indices (LAD, LCX, RCA) between two groups.

3.3. Univariable and multivariable analysis of POAF

Risk factors (age, sex, history of alcohol consumption, history of smoking, blood urea, blood creatinine, CYCS, platelet distributing width, HsTNT, NT-proBNP, LCX-d, EATVI and EAT-d) that reached $P < 0.1$ in the comparison between two groups were included in the multivariable logistic regression model. On multivariable logistic regression analysis, age and EAT-d were strong independent predictors of POAF in patients underwent isolated AVR (1.119, 95 %CI: 1.055–1.187, $P < 0.001$ and 1.186, 95 %CI (1.062–1.324), $P = 0.002$, Table 2). EATd was subjected to receiver operating characteristic (ROC) analysis, yielding an area under the curve (AUC) of 0.601 (95 % CI 0.508–0.634) (Supplementary Fig. S5, $P = 0.042$).

3.4. EAT-d and characteristics

Next, we divided EAT-d into high and low groups by median. The clinical characteristics and EAT-d were listed in Table 3. We observed that the EAT-d was significantly increased in patients who were younger ($P = 0.027$, Table 3). Interestingly, the EAT-d was significantly increased in patients who had larger left ventricular end diastolic volume (LVEDV), left ventricular end systolic volume (LVESV) and lower left ventricular ejection fraction (all $P < 0.001$, Table 3). Moreover, patients who have high EAT-d were also elevated in NT-proBNP and HsTnT (all $P < 0.001$, Table 3). Furthermore, EAT-d exhibited significant linear correlations with LVEDV ($r = 0.417$, $P < 0.001$), LVESV ($r = 0.449$, $P < 0.001$), NT-proBNP ($r = 0.440$, $P < 0.001$) and HsTnT ($r = 0.380$, $P < 0.001$) in our cohort (Fig. 1). However, EAT-d exhibited week linear correlations with age ($r = 0.211$, $P = 0.011$, Supplementary Figure S6).

4. Discussion

In this study, we quantified the volume and density of EAT by

Table 3
Demographic and clinical characteristics of EAT-d.

Characteristics	(≤-80.51)LOW(n = 72)	(> -80.51)HIGH(n = 71)	P
Age (y)	61.50 (54.00,66.75)	55.00(49.00,65.00)	0.027
Women , %	34(47.2 %)	20(28.2 %)	0.019
Heart rate	71.50 (64.25,78.75)	69.00(61.00,79.00)	0.341
NYHA			0.232
II	4(5.5 %)	1(1.4 %)	
III	41(56.9 %)	36(50.7 %)	
IV	27(37.5 %)	34(47.9 %)	
BMI (kg/m^2)	24.92 (21.89,27.36)	23.44(21.55,25.82)	0.076
Drinking , %	17(23.6 %)	22(28.2 %)	0.322
Smoking , %	20(27.8 %)	31(43.7 %)	0.047
COPD , %	8(11.1 %)	8(11.3 %)	0.976
Hypertension , %	29(40.3 %)	26(36.6 %)	0.653
Diabetes mellitus , %	5(6.9 %)	1(1.4 %)	0.217
POAF, %	24(33.3 %)	31(43.1 %)	0.204
Preoperative ultrasonic parameters			
LAD (mm)	38.00 (34.25,42.00)	41.00(38.00,44.00)	0.003
IVST(mm)	12.00 (11.25,14.00)	12.00(11.00,14.00)	0.923
PWT(mm)	12.00 (11.00,13.00)	12.00(11.00,14.00)	0.562
LVEDV(ml)	103.00 (86.25,145.50)	156.00 (115.00,213.00)	<0.001
LVESV(ml)	43.50 (34.25,62.75)	71.00(48.00,109.00)	<0.001
LVEF	0.58(0.56,0.60)	0.55(0.49,0.58)	<0.001
SV (ml)	60.00 (49.25,83.75)	80.00(61.00,104.00)	<0.001
Preoperative laboratory parameters			
White blood cell(*10^9/L)	6.00(4.90,6.78)	5.30(4.60,6.60)	0.053
Neutrophil(*10^9/L)	3.69(2.83,4.18)	3.34(2.47,4.04)	0.099
Monocyte(*10^9/L)	0.37(0.30,0.48)	0.36(0.28,0.46)	0.430
Lymphocyte(*10^9/L)	1.83(1.43,2.14)	1.64(1.42,1.98)	0.167
PCT , ‰	17.75 (15.55,21.10)	18.30(15.20,22.00)	0.595
Blood Urea(mmol/L)	5.88(5.03,7.35)	6.46(5.50,7.57)	0.059
serum creatinine(mg/dL)	67.75 (57.95,79.42)	72.69(60.78,84.17)	0.287
CYCS(mg/L)	0.91(0.81,1.04)	0.91(0.82,1.04)	0.607
NT-proBNP(pg/mL)	383.15 (127.4,797.78)	1071.00 (383.30,2194.00)	<0.001
HsTnT(ng/mL)	9.00(7.00,13.00)	14.00(9.00,22.00)	<0.001
Intraoperative parameter			
CPB	96.25 (78.50,118.75)	90.00(77.00,99.00)	0.114
ACC	60.00 (49.25,75.50)	56.00(48.00,64.00)	0.125

Values are media(first, third quartile) or n(%). COPD: chronic obstructive pulmonary disease; AS: aortic stenosis; LAD: left atrial diameter; IVST: interventricular septal thickness; PWT: posterior wall thickness; LVEDV: left ventricular end diastolic volume; LVESV: left ventricular end systolic volume; SV:stroke volume; LVEF: left ventricular ejection fraction; PCT: platelet Compression Cubic Tract; CYCS: Cystatin C; CPB: extracorporeal circulation time; ACC: aortic block time; EATV: epicardial adipose tissue volume; EATVI: epicardial adipose tissue volume index.

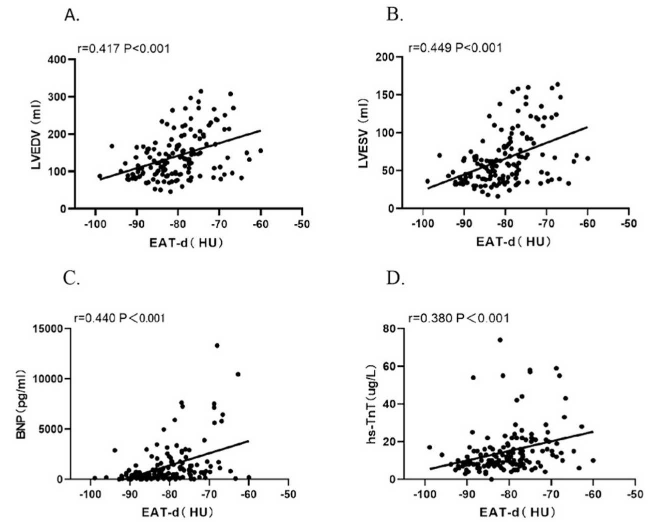

Fig. 1. The correlation between EAT-d and LVEDV(A), LVESV(B), NT-proBNP (C), and HsTnT(D). Correlation coefcient (r) and p value were acquired by Spearman rank correlation test.

coronary CT. We showed that EAT with higher density was associated with the incidence of POAF in patients underwent isolated AVR.

Studies have shown that POAF increased the incidence of strokes and death peri operation. Patients with POAF are more likely to be readmitted to hospital in the month after the surgery [7]. Also, in the following years after the surgery, patients have higher risk of stroke and death [7]. As the prevalence and impact of POAF, we need more accurate prediction to identify patients who is more likely to develop POAF. Then we could take more attention for both intensive monitoring and targeted prophylaxis. EAT could be quantitatively evaluated by CT image [20]. This approach arises our attention. Besides, the coronary artery CT is the routine examination before valvar surgery, we can assess the volume and density of EAT without extra cost. Here, our study applied CT to measure the volume and density of EAT and results demonstrated that the density of EAT was significantly correlated with POAF. Therefore, our study provided a no-invasive and low-price way to predict POAF in patients underwent isolated AVR. Although, EAT-d is an independent predictor of POAF after simple AVR. The poor performance of EAT-d as a classifier limited its direct clinical application. EAT-d could be as combined diagnosis biomarker for POAF.

The EAT directly contact with the myocardium and they shared the same microcirculation. EAT is an endocrine organ that secretes cytkines to increase the inflammation and fibrosis in atrial pathophysiological changes. The crosstalk between EAT and myocardium was widely reported in the modulation of arrhythmogenesis [13,25]. Some clinical [26–28] findings showed that the EATV are higher in the persistent AF patients and associated with higher infammatory biomarkers. Furthermore, some studies [15,29,30] also found that the EAT in the left atrium are strongly correlated with the prevalence and severity of AF. Mechanically, EAT regulated AF through inflammation, fibrosis and neurological factors [31]. It is reported that serum levels of inflammatory markers are directly correlated with the EATV and EAT-d [13,32]. However, our study didn't find the association between EAT-d and CRP in plasma before and after surgery. Therefore, we believed that local crosstalk between EAT and cardiomyocyte plays an important role in POAF. In persistent AF patients, regional IL-1 beta in EAT is an independent risk factor [33]. Similarly, various proinflammatory and profibrotic cytokines in EAT are correlated with atrial fibrosis and AF.

It is well documented that EAT was significantly associated with coronary artery disease and major adverse cardiovascular events (MACEs) [34–37]. In patients of heart failure with preserved ejection fraction, EAT-d was an independent impact factor of cardiometabolic risk [38]. In line, our data clearly showed higher EAT-d were correlated with larger size of left ventricle and lower LVEF. The increased LVEDV and LVESV are the directly index for cardiac structure changes. Therefore, the EAT-d may decrease after the cardiac remodeling owning to aortic valve stenosis or regurgitation in our study. There are two mechanisms. On one side, EAT infiltrated into myocardium and facilitated fibrosis; on the other side, the deposited triacylglycerol droplets changed the cardiac fatty acid metabolism [13].

5. Limitations

There are several potential limitations to this study, which is a retrospective, single-centre study with a small sample size that may be subject to some selection bias. Future prospective, multi-centre, randomised controlled clinical trials may be able to overcome these limitations and provide better results. Secondly, we excluded those undergoing mitral or tricuspid, Because, mitral valve disease frenquently change the size of left atrium, which was significant associated with POAF. The patient's selection may also limit our findings.

6. Conclusion

Age and EAT-d were independent predictors of POAF in patients underwent isolated AVR. What's more, EAT-d was related with age and cardiac structure changes.

Data availability statement

The essential data are available from the corresponding author on reasonable request.

Ethics statement

The protocol was approved by the Ethics Committee of the General Hospital of the Northern Theatre (Y (2023)182). Written informed consent was not required because of the retrospective nature of the study and anonymity of the patients. Personal information will be kept confidential.

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CRediT authorship contribution statement

Rui Li: Software, Funding acquisition, Data curation. **Jian Zhang:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Lingling Ke:** Validation, Software, Resources, Methodology, Data curation. **Xiaohui Zhang:** Resources, Investigation. **Jiawei Wu:** Investigation. **Jinsong Han:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijcha.2024.101481.

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