

Percutaneous Pulmonary Valve Implantation Alters Electrophysiologic Substrate

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Background—Percutaneous pulmonary valve implantation (PPVI) is first-line therapy for some congenital heart disease patients with right ventricular outflow tract dysfunction. The hemodynamics improvements after PPVI are well documented, but little is known about its effects on the electrophysiologic substrate. The objective of this study is to assess the short- and medium-term electrophysiologic substrate changes and elucidate postprocedure arrhythmias.

Methods and Results—A retrospective chart review of patients undergoing PPVI from May 2010 to April 2015 was performed. A total of 106 patients underwent PPVI; most commonly these patients had tetralogy of Fallot (n=59, 55%) and pulmonary insufficiency (n=60, 57%). The median follow-up time was 28 months (7-63 months). Pre-PPVI, 25 patients (24%) had documented arrhythmias: nonsustained ventricular tachycardia (NSVT) (n=9, 8%), frequent premature ventricular contractions (PVCs) (n=6, 6%), and atrial fibrillation/flutter (AF/AFL) (n=10, 9%). Post-PPVI, arrhythmias resolved in 4 patients who had NSVT (44%) and 5 patients who had PVCs (83%). New arrhythmias were seen in 16 patients (15%): 7 NSVT, 8 PVCs, and 1 AF/AFL. There was resolution at medium-term follow-up in 6 (86%) patients with new-onset NSVT and 7 (88%) patients with new-onset PVCs. There was no difference in QRS duration pre-PPVI, post-PPVI, and at medium-term follow-up ($P=0.6$). The median corrected QT lengthened immediately post-PPVI but shortened significantly at midterm follow-up ($P<0.01$).

Conclusions—PPVI reduced the prevalence of NSVT. The majority of postimplant arrhythmias resolve by 6 months of follow-up. (*J Am Heart Assoc.* 2016;5:e004325 doi: 10.1161/JAHA.116.004325)

Key Words: arrhythmia (heart rhythm disorders) • arrhythmia burden • electrocardiography • electrophysiology • percutaneous pulmonary valve placement • pulmonary valve

Congenital heart disease patients with right ventricular outflow tract (RVOT) dysfunction have an increased prevalence of arrhythmias associated with increasing age, prior cardiac surgeries, QRS duration (QRSd), and degree of

pulmonary regurgitation and stenosis.^{1,2} Percutaneous pulmonary valve implantation (PPVI) using the Melody (Medtronic Inc, Minneapolis, MN) valve has become a safe and feasible alternative treatment option to surgical pulmonary valve replacement.^{3,4} Because PPVI does not include incisions in the RV myocardium, it serves as a better model to evaluate any hemodynamics and electrophysiologic substrate changes with pressure and volume load reduction. Improvements in hemodynamics parameters after the procedure have been demonstrated in several reports.⁵⁻⁹ However, few reports have investigated changes in ECG parameters along with the prevalence and type of arrhythmias post-PPVI.^{10,11}

The goals of this study are to (1) describe the short-term and medium-term changes to the electrophysiologic substrate (as identified by surface ECG) in patients following PPVI and (2) determine the type and prevalence of arrhythmias (including premature ventricular complexes [PVCs], nonsustained ventricular tachycardia [NSVT], and atrial fibrillation/atrial flutter [AF/AFL]) in post-PPVI patients.

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Accompanying Figures S1 through S3 are available at <http://jaha.ahajournals.org/content/5/10/e004325/DC1/embed/inline-supplementary-material-1.pdf>

Presented as an oral abstract at the Heart Rhythm Society Scientific Sessions, May 4-7, 2016, in San Francisco, CA.

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Received July 21, 2016; accepted September 9, 2016.

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Methods

On obtaining full approval from the institutional review board at Washington University in St. Louis School of Medicine (waiver of consent), we undertook a retrospective chart review of patients who underwent PPVI in the pulmonary valve position at St. Louis Children's Hospital from May 1, 2010 to April 30, 2015. The previously described inclusion criteria for PPVI include (1) RV systolic pressure greater than two thirds of systemic with symptoms or (2) RV systolic pressure greater than three fourths of systemic in absence of symptoms or (3) moderate/severe pulmonary regurgitation with either symptoms or severe RV dysfunction or severe RV dilatation or impaired exercise capacity.^{5,12} Patients were excluded if the Melody valve (Medtronic Inc, Minneapolis, MN) was implanted in the branch pulmonary arteries or tricuspid position (n=4). Patients were classified as having predominantly pulmonary insufficiency (PI) if they had at least moderate pulmonary regurgitation on echocardiography; they were classified as having predominantly pulmonary stenosis (PS) if they had a mean RVOT gradient ≥ 35 mm Hg on echocardiogram. When the gradient could not be determined due to poor acoustic windows, a systolic gradient ≥ 35 mm Hg during the catheterization was used as the inclusion criterion for the pulmonary stenosis group. Patients with both stenosis and insufficiency were included in the mixed-lesion group (PS/PI). Charts were then reviewed for demographic information, clinical and procedural characteristics, and electrophysiologic data (including ECGs, 24-hour Holter monitors, electrophysiology studies [EPS], cardiac rhythm device reports and transmissions, and telemetry). ECGs preprocedure, 24 hours postprocedure, and at last follow-up visit were analyzed. Corrected QT (QTc) intervals were calculated using the Bazett formula. Postprocedural overnight telemetry alarms and Holter monitors pre- and postprocedure were reviewed for ECG changes and arrhythmia. Right bundle branch block (RBBB) was defined as a QRS duration of ≥ 120 milliseconds. NSVT was defined as 3 or more consecutive PVCs with rates faster than 180 beats per minute.

Statistical Analysis

Summary data are presented as frequency with percentage. Continuous data are not normally distributed and therefore are presented as median with interquartile range. The Wilcoxon signed-ranks test and the Friedman test were used to compare continuous data. The Fisher exact test was used to compare nominal variables between pre- and post-PPVI groups. Statistical significance was defined as $P < 0.05$. All statistical analyses were performed using SPSS statistical software (version 22.0; IBM Corp, Armonk, NY).

Results

Patient Clinical Data

A total of 106 patients, 40 female (38%) and 66 male (62%), were included in this study. Median age at the time of the

Table 1. Patient Clinical and Demographic Data

Total Patients	n=106
Sex	
Female	40 (38%)
Male	66 (62%)
Age, y	20.7 (16.7)
Weight, kg	65.5 (32)
Cardiac diagnosis	
Tetralogy of Fallot	59 (55%)
Pulmonary stenosis	14 (13%)
Aortic stenosis	14 (13%)
Truncus arteriosus	7 (7%)
Double-outlet right ventricle	6 (6%)
Other	6 (6%)
RVOT dysfunction type	
Pulmonary insufficiency	60 (57%)
Pulmonary stenosis	26 (25%)
Mixed pulmonary insufficiency/stenosis	20 (18%)
Antiarrhythmic medication*	
Class II	22 (21%)
Class III	3 (3%)
Class IV	5 (5%)
Cardiac medication*	
Diuretics	22 (21%)
ACE inhibitor	19 (18%)
ARB	2 (2%)
Digoxin	19 (18%)
PHTN medications	2 (2%)
Previous electrophysiology study	
With ablation	3 (3%)
Without ablation	7 (7%)
Cardiac rhythm device	
Single-chamber pacemaker	2 (2%)
Dual-chamber pacemaker	5 (5%)
Biventricular pacemaker	1 (1%)
Intracardiac defibrillator	8 (7%)

ACE indicates angiotensin-converting enzyme; ARB, angiotensin II receptor blocker; PHTN, pulmonary hypertension; RVOT, right ventricular outflow tract.

*Numbers indicate instances medications were used and not the numbers of patients. All medications are pre-PPVI.

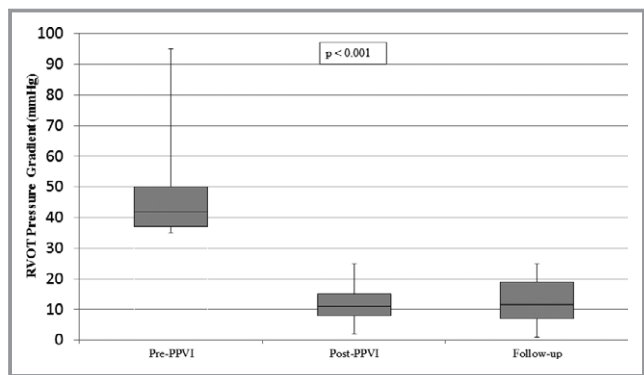


Figure 1. Comparison of RVOT pressure gradients of predominantly PS patients. There was a significant reduction in RVOT pressure gradients immediately post-PPVI. These pressure gradients remained stable at follow-up. RVOT indicates right ventricular outflow tract.

procedure was 20.7 years (IQR 14.5-31.2). The most common congenital anatomic diagnosis was tetralogy of Fallot (ToF) (55%), and the most common type of RVOT dysfunction was pulmonary insufficiency (57%). Prior to the procedure, 10 (9%) patients had undergone EPS, 3 of which included an ablation attempt. All the EPS with ablation attempts occurred more than 3 years prior to the PPVI. Implanted cardiac rhythm devices were present in 16 (15%) patients (Table 1). Two patients were deceased during follow-up. One patient died from complications of epithelioid hemangioendothelioma. This patient did not have documented arrhythmia or ST/T changes

pre- or post-PPVI. The second patient developed endocarditis of the Melody valve 2 years postimplant that was being treated with intravenous antibiotics. He had documented PVCs pre- and post-PPVI. He had an out-of-hospital sudden cardiac arrest.

Hemodynamics Data

A total of 46 patients had pulmonary stenosis (26 PS patients and 20 PS/PI patients) with a median pre-PPVI RVOT gradient of 42 mm Hg (IQR 37-50). Median RVOT gradient significantly lowered immediately post-PPVI to 11 mm Hg ($P < 0.001$). Forty patients had echocardiographic data available at medium-term follow-up. In these patients the median RVOT gradient remained stable at 11.5 mm Hg (IQR 7-19) (Figure 1). Of the PI patients, only 1 patient had more than a mild degree of pulmonary regurgitation at last follow-up. This patient developed endocarditis of the Melody valve, leading to free pulmonary regurgitation. He had an out-of-hospital sudden cardiac arrest. No patients had reintervention on the Melody valve.

Electrocardiographic Changes

Sixteen patients with cardiac rhythm devices were excluded from this portion of the data analysis. There was no difference between the pre- and post-PPVI median QRSd (141 [IQR 110-157] milliseconds vs (140 [IQR 101-157] milliseconds,

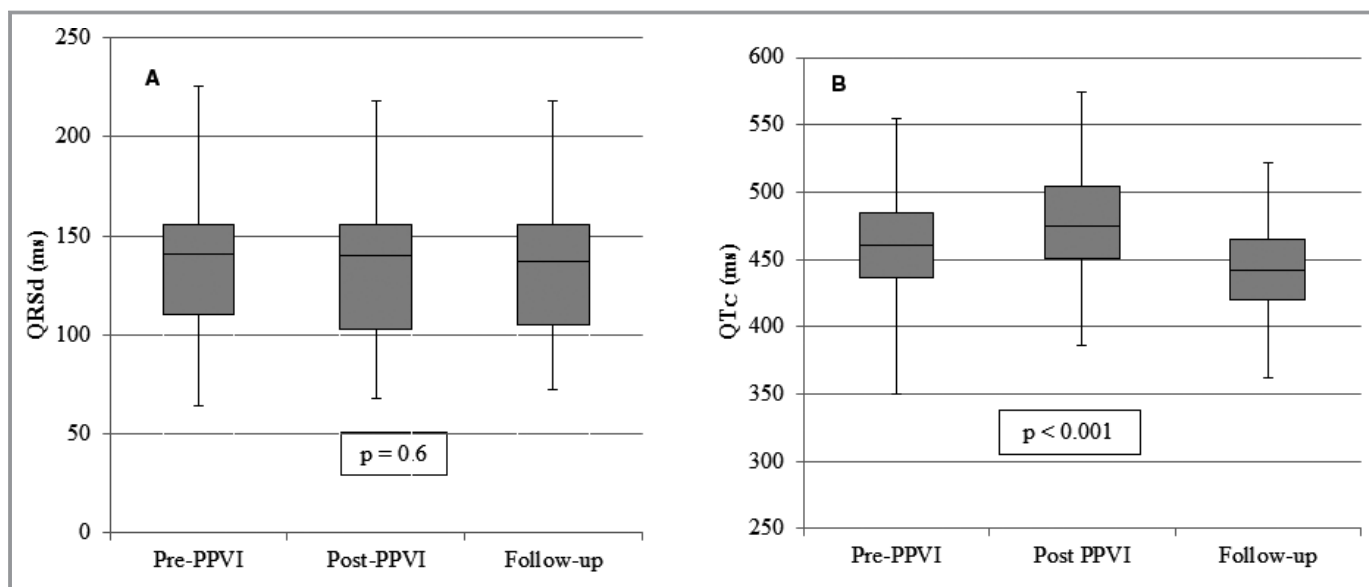


Figure 2. Comparison of ECG parameters. A, QRS duration (QRSd) is compared pre-PPVI, post-PPVI, and at follow-up. There was no significant difference in QRSd among time points ($P=0.6$). B, Corrected QT interval (QTc, calculated using the Bazett formula) compared pre-PPVI, post-PPVI, and at follow-up. The QTc was prolonged immediately post-PPVI, but it significantly shortened at follow-up ($P < 0.01$). PPVI indicates percutaneous pulmonary valve implantation; QRSd, QRS duration; QTc, corrected QT interval.

Table 2. ECG Parameter Changes by Cardiac Diagnosis and Type of RVOT Dysfunction

ECG Parameters	Pre-PPVI	Post-PPVI	Follow-Up	P Value
Tetralogy of Fallot				
QRSd, ms	144 [IQR 120-161]	140 [IQR 107-159]	139 [IQR 108-160]	0.9
QTc, ms	469 [IQR 439-487]	480 [IQR 454-518]	447 [IQR 417-464]	<0.001
Pulmonary insufficiency				
QRSd, ms	132 [IQR 95-156]	133 [IQR 96-153]	137 [IQR 100-156]	0.9
QTc, ms	469 [IQR 436-484]	470 [IQR 445-496]	442 [IQR 420-465]	<0.001
Pulmonary stenosis				
QRSd, ms	144 [IQR 119-155]	140 [IQR 101-154]	140 [IQR 107-162]	0.7
QTc, ms	437 [IQR 433-460]	475 [IQR 454-513]	439 [IQR 405-467]	0.006
Mixed PS/PI				
QRSd, ms	144 [IQR 99-149]	146 [IQR 92-158]	134 [IQR 108-162]	0.7
QTc, ms	474 [IQR 460-504]	503 [IQR 484-519]	445 [IQR 421-471]	0.004

There was no statistical significance in the QRSd across time points regardless of cardiac diagnosis or type of RVOT dysfunction. The QTc prolonged significantly immediately post-PPVI but shortened significantly at follow-up in all subgroups. ECG indicates electrocardiogram; PPVI, percutaneous pulmonary valve implantation; PS/PI pulmonary stenosis/pulmonary insufficiency; RVOT right ventricular outflow tract.

$P=0.07$). The baseline median QTc was 460 [IQR 436-486] milliseconds, which lengthened immediately post-PPVI (475 [IQR 450-504] milliseconds, $P<0.01$). Medium-term follow-up ECGs were available in 58 patients with median follow-up time of 28 months (7-63 months). At follow-up time of at least 7 months post-PPVI, there was no statistical significance in the median QRSd (pre-PPVI=137 [IQR 107-155] milliseconds, post-PPVI=137 [IQR 98-154] milliseconds, follow-up=137 [IQR 103-157] milliseconds, $P=0.8$). The median QTc shortened significantly to 442 [IQR 420-465] milliseconds at follow-up when compared to pre-PPVI (463 [IQR 435-483] milliseconds, $P<0.001$) and immediately post-PPVI (476 [IQR 452-507] milliseconds, $P<0.001$) (Figure 2). Subgroup analysis by cardiac diagnosis or type of RVOT dysfunction yielded similar results (Table 2). Interestingly, the median pre-PPVI QTc of patients with pulmonary stenosis was shorter than that of patients with pulmonary regurgitation ($P=0.07$), whereas the median post-PPVI QTc of patients with pulmonary stenosis was longer than that of patients with pulmonary regurgitation ($P<0.001$).

At baseline, 23/90 (26%) patients had ST/T changes: 5 patients (6%) had ST depression, 7 patients (8%) had T-wave inversion, and 11 patients (12%) had nonspecific ST/T changes. Immediately post-PPVI, there were new-onset ST depression ($n=1$), T-wave inversion ($n=5$), and nonspecific ST/T changes ($n=5$). However, at follow-up all these new ST/T changes had resolved. Overall, ST/T changes resolved in 100% of cases with ST depression, 88% of cases with T-wave inversion, and 80% of cases with ST/T changes (Figures 3 through 5; Figure S1).

Arrhythmia Burden

Pre-PPVI, 27/106 patients (25%) had documented arrhythmias. Nine patients (8%) had NSVT, 6 patients (6%) had frequent PVCs, 10 patients (10%) had atrial AF/AFL, and 2 patients (2%) had supraventricular tachycardia. Only 2/8

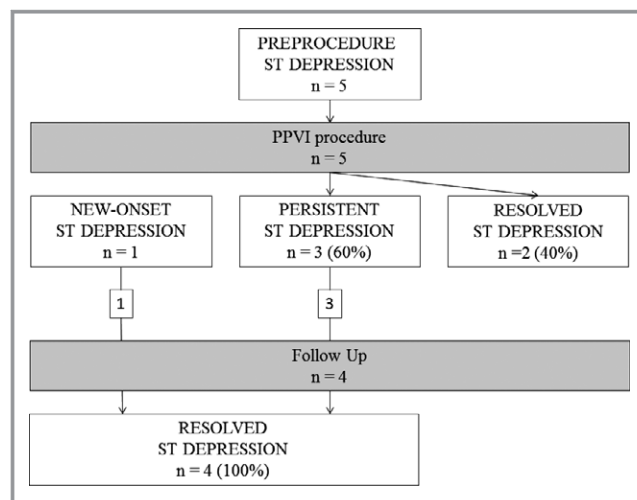


Figure 3. ST depression on ECG. Five patients had ST depression pre-PPVI. Immediately postprocedure, there was resolution of ST depression in 2 (40%) patients, while 3 (60%) patients continued to have unchanged ST depression. Patients who had resolved ST depression post-PPVI did not have further ECGs at follow-up. Additionally, 1 patient had a new-onset ST depression on ECG. Both the new-onset and persistent ST depression postprocedure resolved at follow-up. PPVI indicates percutaneous pulmonary valve implantation.

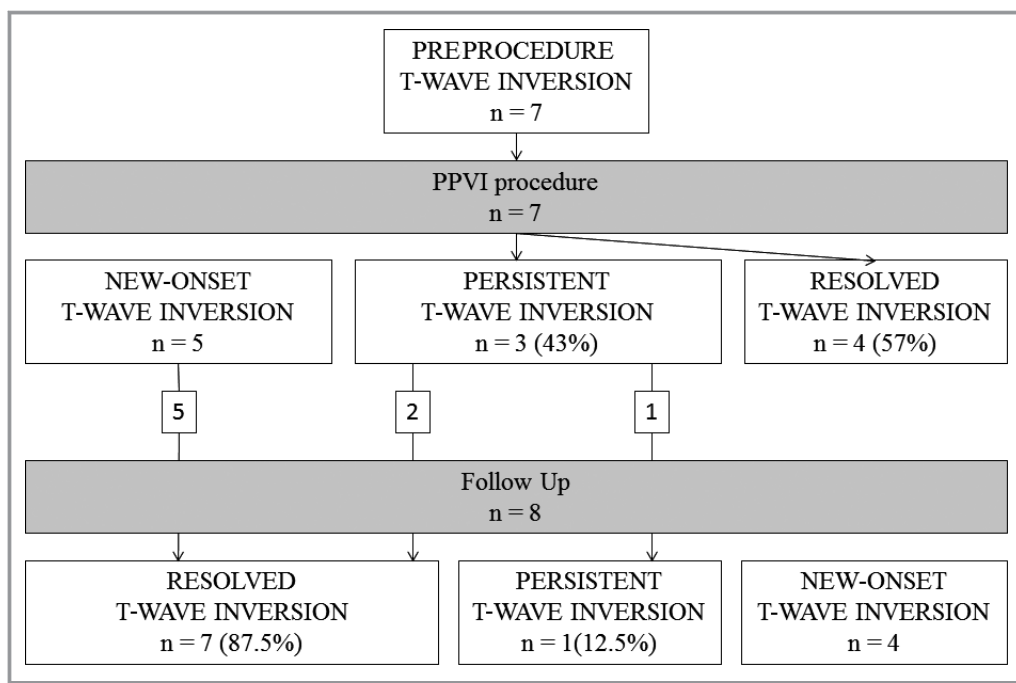


Figure 4. T-wave pattern on ECG. Seven patients had T-wave inversion pre-PPVI. Immediately postprocedure, there was resolution of T-wave inversion in 4 (57%) patients, while 3 (43%) patients continued to have unchanged T-wave inversion. Patients who had resolved T-wave inversion post-PPVI did not have further ECGs at follow-up. Additionally, 5 patients had a new finding of T-wave inversion on ECG. All new-onset T-wave inversions and 2 of 3 persistent T-wave inversions postprocedure resolved at follow-up. One patient with persistent postprocedure T-wave inversion continued to have T-wave inversion at follow-up. Finally, 4 patients had new T-wave inversions at follow-up. PPVI indicates percutaneous pulmonary valve implantation.

(25%) patients with pre-PPVI VT, and no patient with pre-PPVI AF/AFL was in the PS group. New-onset arrhythmias immediately post-PPVI include 7 patients with NSVT, 8 patients with PVCs, and 1 patient with AF/AFL. These arrhythmias were recorded on overnight telemetry. Once again, there were very few PS-only patients (3/16, 19%) in this cohort. At follow-up, these new-onset arrhythmias resolved in 86% of NSVT cases and 88% of PVCs cases. Two out of 8 patients with new-onset PVCs were started on β -blockers, which were discontinued at their 6-month follow-up. Two out of 7 patients with new-onset NSVT were started on amiodarone. One of these patients was taken off the amiodarone at 6 months of follow-up. The second patient continued to be maintained on amiodarone without documented recurrence of NSVT. One patient was started on a β -blocker and continued to be on this medication because he had persistent documented PVCs. Overall, 12/16 (75%) patients no longer had documented NSVT, and 12/14 (86%) patients no longer had PVCs. One patient with PVCs prior to the procedure continued to have PVCs postprocedure. This patient also developed endocarditis of the Melody valve. He had an out-of-hospital sudden cardiac arrest. Finally, AF/AFL resolved in 6/11 (55%) cases (Figures 6 through 8; Figures S2

and S3). Arrhythmia burden was determined by Holter monitoring, internal rhythm devices reports, and telemetry during subsequent hospitalizations.

Imaging Correlation

Forty patients had cardiac MRI pre-PPVI, but only 4 had post-PPVI studies for comparison (3 PS, 1 PI). Notably, the patient with PI had markedly improved RVEDV post-PPVI. This patient had nonspecific ST changes both pre- and post-PPVI, but these changes resolved at follow-up. One patient with PS had aneurysmal dilatation of the RVOT on follow-up MRI. This patient had new-onset T-wave inversion at follow-up. The remaining 2 patients did not have ECG changes or appreciable structural changes on follow-up MRI.

Of the 39 patients with ECG changes (baseline + new onset post-PPVI + new onset at follow-up), 27 patients had ECG for analysis (Figures 5 through 7). Specifically, there were 19 resolved ST/T changes, 3 persistent ST/T changes, and 5 new-onset ST/T changes. All 27 patients had follow-up ECGs. Although there was improvement in RV size by echocardiogram in 15/27 (56%) patients, there was no change noted in 12/27 (44%) patients. Among patients with

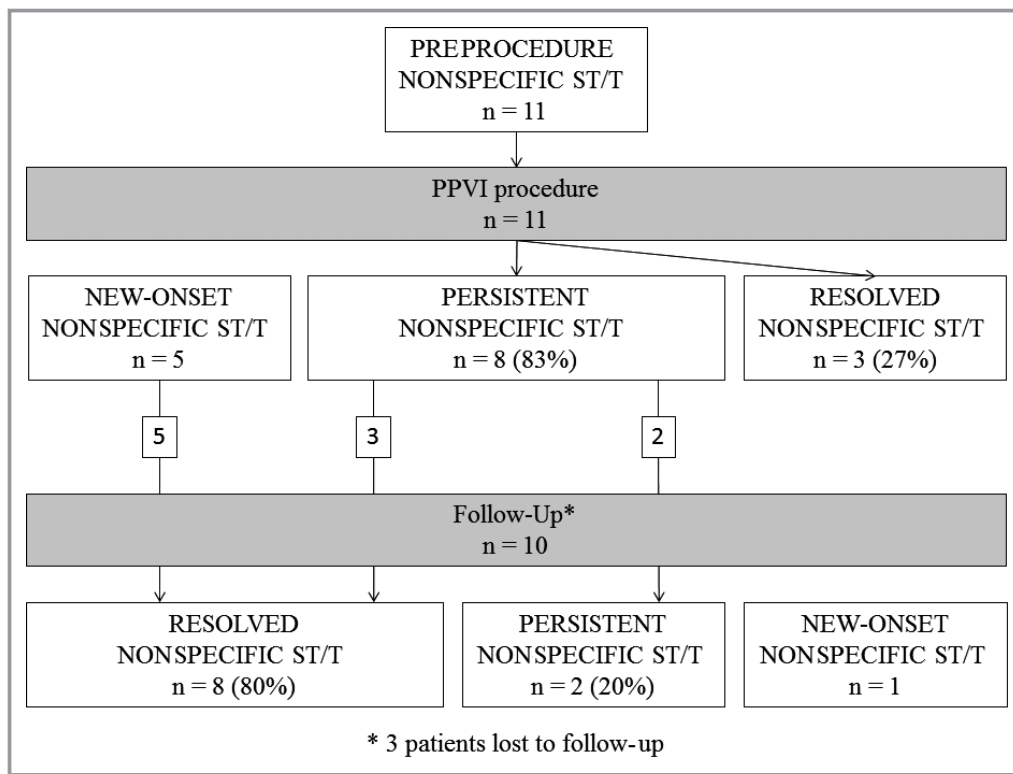


Figure 5. Nonspecific ST/T changes on ECG. Eleven patients had ST/T changes pre-PPVI. Immediately postprocedure, there was resolution of ST/T changes in 3 (27%) patients, while 8 (73%) patients continued to have unchanged ST/T changes. Patients who had resolved ST/T changes post-PPVI did not have further ECGs at follow-up. Additionally, 5 patients had a new finding of ST/T changes on ECG. All new-onset ST/T changes and 3 of 8 (38%) persistent ST/T changes postprocedure resolved at follow-up. Two patients with persistent postprocedure ST/T changes continued to have ST/T changes at follow-up. Finally, 1 patient had new ST/T changes at follow-up. Of note, 3 patients were lost to follow-up. PPVI indicates percutaneous pulmonary valve implantation.

new-onset/persistent ECG changes at follow-up ($n=8$), there were equal numbers of patients who had improved RV size versus no appreciable change by follow-up echo. In the 19 patients who had resolved ECG changes at follow-up, 10 patients had improved RV size, whereas 9 patients did show changes on follow-up echo. There appeared to be no correlation between RV size and ECG changes.

Discussion

To our knowledge, this study is the first to evaluate changes in the electrophysiologic substrate and arrhythmia burden of patients undergoing PPVI. Novel findings of this study include the observations of acute newly developing ST/T changes and arrhythmias such as frequent isolated PVCs and NSVT immediately post-PPVI. Moreover, the study was able to document improvement in the electrophysiologic substrate changes and arrhythmia burden at medium-term follow-up.

Two previous studies have examined the effects of PPVI on surface ECG parameters. Plymen et al¹⁰ studied conduction

(QRSd) and repolarization (QTc, QT, and JT dispersion) parameters, and Piotrowicz et al¹¹ studied parameters of RV hypertrophy. Similar to previous reports, our study did not find a significant change in QRSd post-PPVI in the overall cohort. However, Plymen et al¹⁰ found significant shortening of QRSd in patients with pulmonary regurgitation.

QRSd has served as a marker to assess the risk of arrhythmic death in congenital heart disease patients (particularly ToF) with RVOT dysfunction.^{2,13} Patients with PI who do not undergo pulmonary valve replacement or PPVI have an increase in QRSd of 2 to 4 milliseconds per year that is associated with increasing right ventricular end-diastolic volume (RVEDV).^{1,14,15} Because RVEDV decreases postsurgical pulmonary valve replacement, the procedure has been postulated to improve the arrhythmia burden in patients with chronic PI.¹⁶ Given the fact that PPVI serves as a better model to study the effects of improvements in hemodynamics on QRSd, Plymen et al's¹⁰ particular findings could represent the true proportional relationship between improvement in RVEDV and decreasing QRSd. Unlike Plymen et al,¹⁰ this study did

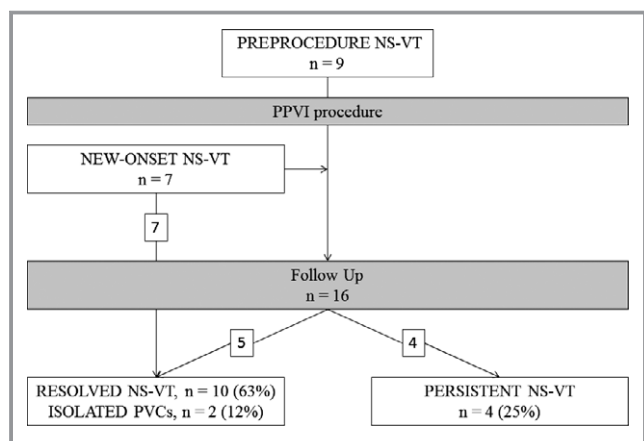


Figure 6. Documented nonsustained ventricular tachycardia (NSVT). Prior to procedure, NSVT was documented in 9 patients. Seven patients had new-onset NSVT immediately postprocedure. At follow-up, 4 of 9 patients who previously had NSVT preprocedure continued to have NSVT, 1 of 9 patients no longer had NSVT but had PVCs, and 4 of 9 patients no longer had NSVT. Among the patients with new-onset NSVT postprocedure, 6 of 7 no longer had nonsustained VT, while 1 patient had PVCs. NSVT indicates nonsustained ventricular tachycardia; PVCs, premature ventricular contractions.

not find a significant shortening of QRSd in the cohort of patients with purely pulmonary insufficiency. The reason for this discrepancy might reside in the fact that our sample size is too small to discern such difference.

Consistent with Plymen et al, the QTc in our study uniformly increased immediately post-PPVI but shortened beyond baseline at follow-up, regardless of type of RVOT dysfunction. QTc is a parameter of repolarization and a surrogate measurement of local action potential duration. It is recognized that myocardial stretch, via contraction-excitation feedback, increases monophasic action potential duration and causes afterdepolarizations, which in turn can cause triggered activity and generate the appropriate conditions for reentrant arrhythmias.¹⁷ Contraction-excitation feedback has been demonstrated in both increased pressure and volume load conditions.¹⁸⁻²⁰ For example, in the lamb, chronic PI led to inhomogeneity of right ventricular activation, decreased conduction velocity, and increased intracellular resistivity. These changes might contribute to the observed increased susceptibility to stretch-induced arrhythmias of the right ventricle.^{19,20} Furthermore, when compared with the hypertrophied human myocardium, the dilated myocardium had longer steady-state action potential duration.²¹ Consistent with this observation, our study showed that patients with PI had longer QTc than PS patients. Contraction-excitation feedback and alterations in the local ventricular repolarization also explain the significant lengthening of QTc post-PPVI as previously demonstrated in the context of pulmonary valve

valvuloplasty in PS patients.¹⁸ According to contraction-excitation theory, repolarization duration is inversely proportional to the mechanical stress on the myocardium. Therefore, repolarization duration should be the longest after successful reduction in afterload seen with repetitive balloon occlusions of the RVOT during placement of stents and the pulmonary valve in PPVI. Consistent with this observation, our study showed that patients with PS had significantly longer QTc than PI patients immediately post-PPVI. It is important, therefore, to recognize that abnormalities in both depolarization and repolarization contribute to the increased risks of developing arrhythmia in patients with RVOT dysfunction.²¹ The finding that QRSd and QTc stabilized and improved post-PPVI suggests that favorable changes in hemodynamics would translate into more stable myocardial depolarization and repolarization and reduce the risk of arrhythmias. Longer-term follow-up would be needed to monitor QRSd and QTc changes.

Other ST/T changes (such as nonspecific ST/T changes, T-wave inversion, and ST depression) were also observed immediately post-PPVI. These changes most likely reflect transient ischemic injury that follows repeated total balloon occlusions of the RVOT during RVOT angioplasty, transient absent cardiac output during the check for coronary artery compression, and rapid ventricular pacing during 3-dimensional rotational angiography in certain cases, or perhaps coronary artery spasm caused by selective coronary angiographies. These changes could also reflect the acute changes in hemodynamics with the newly placed valve, anesthesia effect, or possibly mechanical trauma of catheter manipulation during the procedure. Interestingly, the majority of these ST/T changes disappeared over time.

Despite favorable changes in measurable surface ECG parameters, the long-term effects of RV remodeling on the arrhythmias burden are unknown. Our mean follow-up period is 31 months, which exceeds that of Plymen et al¹⁰ and Piotrowicz et al¹¹ and is on a par with previous surgical pulmonary valve replacement series.^{16,22-26} Previously, Gengsakul et al²⁵ and Harrild et al²⁶ studied matched pairs of patients with repaired ToF with and without surgical pulmonary valve replacement and showed no significant change in QRSd and impact on arrhythmia burden. Specifically, Harrild et al²⁶ reported no survival benefit in death or sustained ventricular tachycardia at a mean of 3 years of follow-up. However, the myocardial incision incurred with the surgical pulmonary valve replacement may represent another confounding factor in their analysis. Therrien et al¹⁶ studied a cohort of 70 patients who underwent pulmonary valve replacement late after ToF repair with some patients with preexisting arrhythmias undergoing intraoperative EP mapping and cryoablation. They found that the QRSd stabilized at a mean of 4.7 years of follow-up and that there was a

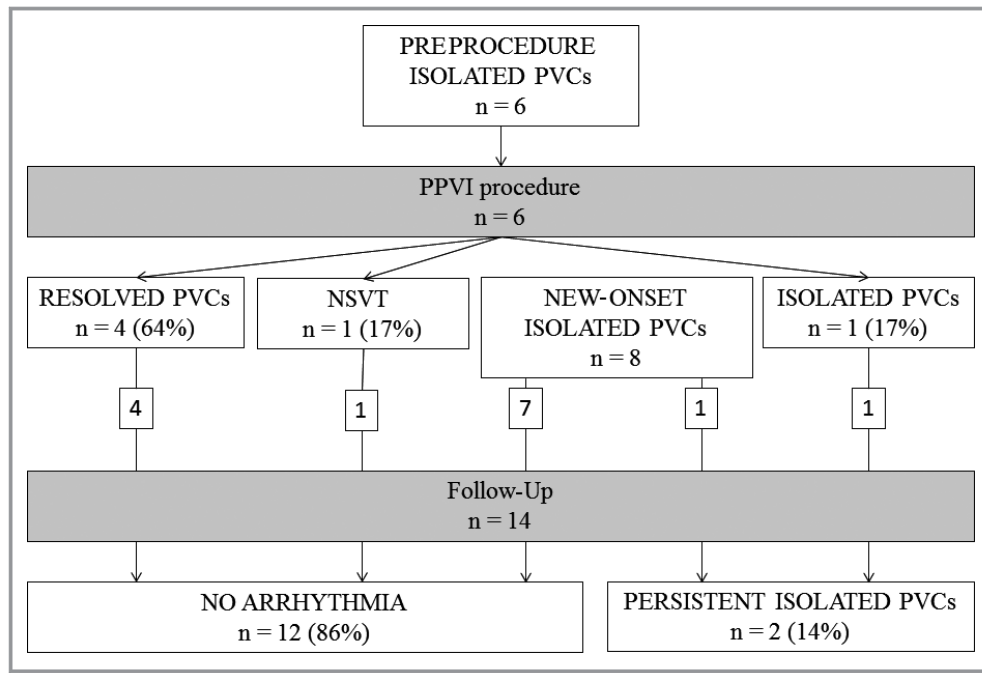


Figure 7. Isolated premature ventricular contractions (PVCs). Six patients had documented frequent isolated PVCs pre-PPVI. Immediately postprocedure, there was resolution of PVCs in 4 (64%) patients, while 1 (17%) patient continued to have persistent PVCs, and 1 (17%) patient had nonsustained ventricular tachycardia (NSVT). Additionally, 8 patients had new-onset PVCs immediately postprocedure. Seven out of 8 patients with new-onset PVCs and both of the persistent PVCs postprocedure no longer had any arrhythmia at follow-up. One patient with new-onset PVCs and the patient with persistent PVCs immediately postprocedure continued to have PVCs at follow-up. The patient with persistent PVCs throughout had an out-of-hospital sudden cardiac arrest. NSVT indicates nonsustained ventricular tachycardia; PPVI, percutaneous pulmonary valve implantation; PVCs, premature ventricular contractions.

significant decrease in the prevalence of monomorphic VT. The prevalence of AF/AFL also decreased, albeit nonsignificantly. Overall, our study reported a substantial decrease in

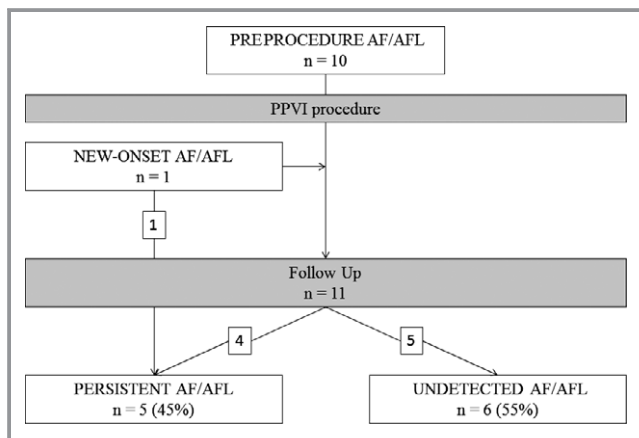


Figure 8. Atrial fibrillation/atrial flutter (AF/AFL). Ten patients had documented AF/AFL pre-PPVI. One patient had new-onset AF/AFL immediately postprocedure. At follow-up, 5 patients continued to have AF/AFL (4 preprocedure and 1 new onset), while 6 patients no longer had AF/AFL. AF/AFL indicates atrial fibrillation/atrial flutter; PPVI, percutaneous pulmonary valve implantation.

the prevalence of NSVT and PVCs post-PPVI. There was a significant incidence of new PVCs and NSVT immediately post-PPVI. Importantly, most of these new arrhythmias resolved after 6 months postprocedure. Some of the patients required short-term antiarrhythmic therapy with a β -blocker or amiodarone that was discontinued at their 6-month follow-up. We attribute these changes to the irritability caused by stents placed in the RVOT prior to the Melody valve placement and possibly due to contraction-excitation feedback caused by myocardial stretch associated with the repetitive balloon occlusion of the RVOT during placement of stents and the pulmonary valve in PPVI. Moreover, previous studies have shown that ventricular ectopy may be caused by afterdepolarizations associated with increase in mechanical stress.^{28,29} These arrhythmias would resolve once the stents completely endothelialized and hemodynamics reached a better steady state. Unfortunately, many of the patients in our cohort received prestening of the RVOT, precluding any analysis of the effect of prestening on arrhythmia burden. Finally, PVCs and NSVT may be related to the underlying anatomical heart defect, focal scarring, fibrosis, or surgical suture lines rather than to right ventricular outflow tract dysfunction.

Limitations

This is a single-center retrospective study, with patient attrition over time, which limited the power of our analysis. Additionally, our cohort was heterogeneous in their anatomical lesions, hemodynamics, and clinical status prior to the procedure. Therefore, we predict that there is variability in the beneficial effects of improved hemodynamics on the electrophysiology substrate and measurable ECG parameters. An improved sample size would allow us to perform more detailed subgroup analyses to better tease out the different effects of PPVI. Despite most patients with previously or newly diagnosed arrhythmias undergoing follow-up Holter monitor evaluation at 6-month follow-up, there was no uniform protocol for monitoring of PVCs and NSVT over the follow-up period, which may lead to an overestimation in the prevalence reduction of these arrhythmias. Although our mean follow-up period is reasonable at 31 months, long-term follow-up is still needed to both assess the measurable ECG parameters and provide better correlation with the arrhythmia burden. Last, a potential limitation is that changes to the QTc may be secondary to anesthesia, other medications, or electrolyte anomalies. Patients in this study had ECGs obtained the morning following PPVI placement, and changes to the QTc were based on preprocedural ECG—as a result, each patient was his or her own control.

Conclusions

Our study demonstrates that PPVI stabilizes the QRSd and shortens the QTc in congenital heart disease patients with RVOT dysfunction. Furthermore, there is a substantial decrease in the prevalence of NSVT and PVCs post-PPVI. Finally, acute changes to the electrophysiologic substrate and arrhythmia burden immediately post-PPVI improve over time at midterm follow-up. These findings suggest that PPVI is a beneficial procedure from an electrophysiologic standpoint. Further prospective and long-term studies would be needed to further define and assess the causal effects of PPVI on electrophysiologic changes in these patients.

Disclosures

Balzer is a proctor for Medtronic, Inc. Silva receives research and fellowship support from Medtronic, Inc. The remaining authors have no disclosures to report.

References

- Gatzoulis MA, Balaji S, Webber SA, Siu SC, Hokanson JS, Poile C, Rosenthal M, Nakazawa M, Moller JH, Gillette PC, Webb GD, Redington AN. Risk factors for arrhythmia and sudden cardiac death late after repair of tetralogy of Fallot: a multicentre study. *Lancet*. 2000;356:975–981.
- Khairy P, Aboulhosn J, Gurvitz MZ, Opatowsky AR, Mongeon FP, Kay J, Valente AM, Earing MG, Lui G, Gersony DR, Cook S, Ting JG, Nickolaus MJ, Webb G, Landzberg MJ, Broberg CS; Alliance for Adult Research in Congenital Cardiology (AARCC). Arrhythmia burden in adults with surgically repaired tetralogy of Fallot: a multi-institutional study. *Circulation*. 2010;122:868–875.
- Khambadkone S, Coats L, Taylor A, Boudjemline Y, Derrick G, Tsang V, Cooper J, Muthurangu V, Hegde SR, Razavi RS, Pellerin D, Deanfield J, Bonhoeffer P. Percutaneous pulmonary valve implantation in humans: results in 59 consecutive patients. *Circulation*. 2005;112:1189–1197.
- Bonhoeffer P, Boudjemline Y, Saliba Z, Merckx J, Aggoun Y, Bonnet D, Acar P, Le Bidois J, Sidi D, Kachaner J. Percutaneous replacement of pulmonary valve in a right-ventricle to pulmonary-artery prosthetic conduit with valve dysfunction. *Lancet*. 2000;356:1403–1405.
- Zahn EM, Hellenbrand WE, Lock JE, McElhinney DB. Implantation of the Melody transcatheter pulmonary valve in patients with a dysfunctional right ventricular outflow tract conduit. Early results from the U.S. clinical trial. *J Am Coll Cardiol*. 2009;54:1722–1729.
- McElhinney DB, Hellenbrand WE, Zahn EM, Jones TK, Cheatham JP, Lock JE, Thambo JB, Walker F, Cullen S, Derrick G, Taylor AM, Bonhoeffer P. Early versus late functional outcome after successful percutaneous pulmonary valve implantation. Are the acute effects of altered right ventricular loading all we can expect? *J Am Coll Cardiol*. 2011;57:724–731.
- Armstrong AK, Balzer DT, Cabalka AK, Gray RG, Javois AJ, Moore JW, Rome JJ, Turner DR, Zellers TM, Kreutzer J. One-year follow-up of the Melody transcatheter pulmonary valve multicenter post-approval study. *JACC Cardiovasc Interv*. 2014;7:1254–1262.
- Cheatham JP, Hellenbrand WE, Zahn EM, Jones TK, Berman DP, Vincent JA, McElhinney DB. Clinical and hemodynamic outcomes up to 7 years after transcatheter pulmonary valve replacement in the US Melody valve investigational device exemption trial. *Circulation*. 2015;131:1960–1970.
- Plymen CM, Bolger AP, Lurz P, Nordmeyer J, Lee TY, Kabir A, Coats L, Cullen S, Walker F, Deanfield JE, Taylor AM, Bonhoeffer P, Lambiase PD. Electrical remodeling following percutaneous pulmonary valve implantation. *Am J Cardiol*. 2011;107:309–314.
- Piotrowicz E, Biernacka EK, Mazgaj M, Fronczak A, Demkow M, Rużyłło W, Kowalski M, Spiewak M, Hoffman P, Piotrowski W, Piotrowicz R. Electrocardiographic characteristics of the right ventricle following hemodynamic improvement after percutaneous pulmonary valve implantation, one year follow-up. *J Electrocardiol*. 2014;47:612–617.
- Lurz P, Coats L, Khambadkone S, Nordmeyer J, Boudjemline Y, Schievano S, Muthurangu V, Lee TY, Parenzan G, Derrick G, Cullen S, Walker F, Tsang V, Deanfield J, Taylor AM, Bonhoeffer P. Percutaneous pulmonary valve implantation: impact of evolving technology and learning curve on clinical outcome. *Circulation*. 2008;117:1964–1972.
- Gatzoulis MA, Till JA, Somerville J, Redington AN. Mechano-electrical interaction in tetralogy of Fallot. QRS prolongation relates to right ventricular size and predicts malignant ventricular arrhythmias and sudden death. *Circulation*. 1995;92:231–237.
- Abd El Rahman MY, Abdul-Khalik H, Vogel M, Alexi-Meskishvili V, Gutberlet M, Lange PE. Relation between right ventricular enlargement, QRS duration, and right ventricular function in patients with tetralogy of Fallot and pulmonary regurgitation after surgical repair. *Heart*. 2000;84:416–420.
- Neffke JG, Tulevski II, van der Wall EE, Wilde AA, van Veldhuisen DJ, Dodge-Khatami A, Mulder BJ. ECG determinants in adult patients with chronic right ventricular pressure overload caused by congenital heart disease: relation with plasma neurohormones and MRI parameters. *Heart*. 2002;88:266–270.
- Therrien J, Siu SC, Harris L, Dore A, Niwa K, Janousek J, Williams WG, Webb G, Gatzoulis MA. Impact of pulmonary valve replacement on arrhythmia propensity late after repair of tetralogy of Fallot. *Circulation*. 2001;103:2489–2494.
- Quinn TA. The importance of non-uniformities in mechano-electric coupling for ventricular arrhythmias. *J Interv Card Electrophysiol*. 2014;39:25–35.
- Levine JH, Guarnieri T, Kadish AH, White RI, Calkins H, Kan JS. Changes in myocardial repolarization in patients undergoing balloon valvuloplasty for congenital pulmonary stenosis: evidence for contraction-excitation feedback in humans. *Circulation*. 1988;77:70–77.
- Gray R, Greve G, Chen R, Fry C, Barron D, Lab MJ, White PA, Redington AN, Penny DJ. Right ventricular myocardial responses to chronic pulmonary regurgitation in lambs: disturbances of activation and conduction. *Pediatr Res*. 2003;54:529–535.
- Chen RL, Penny DJ, Greve G, Lab MJ. Stretch-induced regional mechano-electric dispersion and arrhythmia in the right ventricle of anesthetized lambs. *Am J Physiol Heart Circ Physiol*. 2004;286:H1008–H1014.

21. Gatzoulis M, Till J, Redington A. Depolarization-repolarization inhomogeneity after repair of tetralogy of Fallot. *Circulation*. 1997;95:401–404.
22. Doughan AR, McConnell ME, Lyle TA, Book WM. Effects of pulmonary valve replacement on QRS duration and right ventricular cavity size late after repair of right ventricular outflow tract obstruction. *Am J Cardiol*. 2005;95:1511–1514.
23. van Huysduynen BH, van Straten A, Swenne CA, Maan AC, van Eck HJ, Schaliij MJ, van der Wall EE, de Roos A, Hazekamp MG, Vliegen HW. Reduction of QRS duration after pulmonary valve replacement in adult Fallot patients is related to reduction of right ventricular volume. *Eur Heart J*. 2005;26:928–932.
24. Oosterhof T, Vliegen HW, Meijboom FJ, Zwinderman AH, Bouma B, Mulder BJ. Long-term effect of pulmonary valve replacement on QRS duration in patients with corrected tetralogy of Fallot. *Heart*. 2006;93:506–509.
25. Gengsakul A, Harris L, Bradley TJ, Webb GD, Williams WG, Siu SC, Merchant N, McCrindle BW. The impact of pulmonary valve replacement after tetralogy of Fallot repair: a matched comparison. *Eur J Cardiothorac Surg*. 2007;32:462–468.
26. Harrild DM, Berul CI, Cecchin F, Geva T, Gauvreau K, Pigula F, Walsh EP. Pulmonary valve replacement in tetralogy of Fallot: impact on survival and ventricular tachycardia. *Circulation*. 2009;119:445–451.
27. Cranefield PF. Action potentials, afterpotentials, and arrhythmias. *Circ Res*. 1977;41:415–423.
28. Damiano BP, Rosen MR. Effects of pacing on triggered activity induced by early afterdepolarizations. *Circulation*. 1984;69:1013–1025.
29. Lab MJ, Taggart P, Sachs F. Mechano-electric feedback. *Cardiovasc Res*. 1996;32:1–2.