Right Parasternal Lead Placement Increases Eligibility for Subcutaneous Implantable Cardioverter Defibrillator Therapy in Adults With Congenital Heart Disease

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Background: The subcutaneous implantable cardioverter defibrillator (S-ICD) provides an attractive option for patients with congenital heart disease (CHD) in whom a transvenous defibrillator is contraindicated. Given the unusual cardiac anatomy and repolarization strain, the surface electrocardiogram (ECG) is frequently abnormal, potentially increasing the screen failure rate.

Methods and Results: We prospectively screened 100 adult CHD patients regardless of the presence of clinical indication for ICD utilizing a standard left sternal lead placement, as well as a right parasternal position. Baseline patient and 12-lead ECG characteristics were examined to assess for predictors of screen failure. Average patient age was 48±14 years, average QRS duration was 134±37 ms, and 13 patients were pacemaker dependent. Using the standard left parasternal electrocardiographic position, 21 patients failed screening. Of these 21 patients with screen failure, 9 passed screening with the use of right parasternal electrode positioning, reducing screening failure rate from 21% to 12%. QT interval and inverted T wave anywhere in V2–V6 leads were found to be independent predictors of left parasternal screening failure (P=0.01 and P=0.04, respectively).

Conclusions: Utilization of both left and right parasternal screening should be used in evaluation of CHD patients for S-ICD eligibility. ECG repolarization characteristics were also identified as novel predictors of screening failure in this group. (Circ J 2016; 80: 1328–1335)

Key Words: Congenital heart disease; Right parasternal screening; Screening; Subcutaneous implantable cardioverter defibrillator; T wave

The population of adults with congenital heart disease (CHD) continues to grow and, despite the substantial advances in management over the last several decades, ventricular arrhythmia remains an important cause of mortality. Consequently, many adults with CHD undergo implantable cardioverter defibrillator (ICD) implantation for primary or secondary prevention. The subcutaneous implantable cardioverter defibrillator (S-ICD) provides an alternative in these patients when the traditional transvenous implant is commonly contraindicated or unfeasible secondary to venous anomalies or intracardiac shunts that introduce a risk of systemic thromboembolism from transvenous lead thrombus.

Due to the absence of an electrode in contact with the myocardium, T-wave oversensing leading to inappropriate shock is a specific concern for the S-ICD. Screening using a modified electrocardiogram (ECG) with patches positioned over planned electrode sites (due to the equivalence of skin and subcutaneous electrodes) is required to ensure that the R-wave/T-wave ratio is sufficiently large to avoid T-wave oversensing. To detect ventricular arrhythmias, the S-ICD uses 1 of the 3 subcutaneous electrograms acquired between the 2 electrodes embedded in the subcutaneous lead and the defibrillator can. If the patient does not pass the screening ECG test in any of the 3 ECG vectors, S-ICD implantation is contraindicated due to the high risk of inappropriate shock. This T/R ratio is the major determinant of screening. The pass rate in non-congenital patients is generally reported at around 85–95%.

Although the S-ICD is especially well-designed for certain CHD syndromes, many patients may fail screening due to the unique anatomy and resultant surface ECG characteristics found in CHD. The aim of this study was to investigate the screening failure rate in a series of adult patients with CHD. Additionally, given the variation in cardiac anatomy in these patients,
Data Collection
Demographic data such as age, gender, diagnosis, body weight and body mass index (BMI) were obtained from electronic medical records. The complexity of the underlying CHD was defined according to the task force statement on CHD published in 2008.2,12 Additionally, ECG parameters, such as QRS width, QT interval, and dependency on ventricular pacing were obtained from the patients’ most recent 12-lead ECG when available. Bundle branch block in patients with QRS >120 ms was defined based on the standard definition.13

Potential predictors of screen failure in left parasternal screening were assessed on univariate logistic regression analysis. Factors associated with screening failure with P<0.05 were implemented in a multivariate analysis model. With at least 10 outcomes required for each to be included as an independent variable in the model, only 2 of 5 univariately significant variables (QT interval and inverted T wave anywhere in leads V2–V6) were used. Given that 4 of them (QRS width, QRS >120 ms, inverted T wave anywhere in leads V2–V6 and dependency on ventricular pacing) were highly correlated, inverted T wave anywhere in leads V2–V6 was selected based on clinical significance to be included in the multivariate logistic regression model. Receiver operating characteristics (ROC) analysis was used to evaluate the optimal cut-offs for predicting left-side screening failure.

All tests were 2-sided, and P<0.05 was considered statistically significant. Data were analyzed using JMP (version 11.0.0, SAS, Cary, NC, USA).
screening ECG as well as the 12-lead ECG were positioned right and left reversed supposing the device implantation on the right-side chest, which resulted in pass on both sides.

**Screening ECG**

Table 3 summarizes the results of the screening ECG both on the left and right parasternal electrode position. Standard left parasternal screening failed in 21 patients (21%), but 9 of these patients subsequently passed right parasternal screening, and thus decreased the failure rate from 21% to 12%. Figure 2 shows a typical screening surface ECG from a patient who failed left parasternal lead position in all ECG vectors, but passed right parasternal screening both in the supine and in the standing positions.

**Predictors of Failure on Screening ECG**

Table 2 also lists the clinical characteristics for patients who passed left parasternal screening (n=79) vs. those who failed (n=21). QRS and QT duration were significantly longer in the subgroup who failed screening compared with those who passed (165.7±28.4 ms vs. 125.7±35.1 ms, P<0.001; and 466.2±34.3 ms vs. 434.0±45.4 ms, P<0.01, respectively).

There was a significant difference in patients who failed vs. those who passed standard left-sided screening for QRS duration >120 ms (95% vs. 46%, P<0.001), but the distribution of bundle branch block pattern in patients with QRS >120 ms was not significantly different (P=0.59). In addition, there were more patients in the failed subgroup with inverted T wave anywhere in leads V2–V6 (90% vs. 63%, P=0.02) and dependency on ventricular pacing (29% vs. 9%, P=0.03).

The results of both univariate and multivariate analysis for comparison of factors associated with left screening failure are given in Table 4. We identified 5 univariate significant predictors but, due to the limited number of patients who failed standard screening (n=21), only 2 parameters could be tested using a multivariate logistic regression model. With 4 of them (QRS duration, QRS >120 ms, inverted T wave anywhere in leads V2–V6 and dependency on ventricular pacing) being

### Results

**Patient Characteristics**

Composition of CHD and complexity are listed in Table 1. Twenty-one patients were defined as having complex CHD. Baseline subject characteristics are listed in Table 2. Twenty-two patients had a pacemaker or ICD, and 13 patients were dependent on ventricular pacing. In 1 patient with pulmonary stenosis accompanied with dextrocardia, electrodes in the

#### Table 1. Congenital Heart Disease Background

<table>
<thead>
<tr>
<th>Congenital heart disease</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great complexity</td>
<td></td>
</tr>
<tr>
<td>Single ventricle</td>
<td>6</td>
</tr>
<tr>
<td>Transposition of great arteries</td>
<td>7</td>
</tr>
<tr>
<td>Pulmonary atresia</td>
<td>4</td>
</tr>
<tr>
<td>Tricuspid atresia</td>
<td>3</td>
</tr>
<tr>
<td>Truncus arteriosus</td>
<td>1</td>
</tr>
<tr>
<td>Subtotal</td>
<td>21</td>
</tr>
<tr>
<td>Simple or moderate severity</td>
<td></td>
</tr>
<tr>
<td>Bicuspid aortic valve</td>
<td>12</td>
</tr>
<tr>
<td>Coarctation of the aorta</td>
<td>5</td>
</tr>
<tr>
<td>Atrial septum defect</td>
<td>10</td>
</tr>
<tr>
<td>Pulmonary stenosis</td>
<td>9</td>
</tr>
<tr>
<td>Ventricular septum defect</td>
<td>2</td>
</tr>
<tr>
<td>Patent ductus arteriosus</td>
<td>1</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>22</td>
</tr>
<tr>
<td>Ebstein’s anomaly</td>
<td>11</td>
</tr>
<tr>
<td>Atrioventricular canal defects</td>
<td>4</td>
</tr>
<tr>
<td>Anomalous pulmonary venous drainage</td>
<td>1</td>
</tr>
<tr>
<td>Sinus venosus atrial septal defect</td>
<td>2</td>
</tr>
<tr>
<td>Subtotal</td>
<td>79</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2. Patient Characteristics vs. Pass for Left Parasternal Screening**

<table>
<thead>
<tr>
<th></th>
<th>All patients (n=100)</th>
<th>Pass (n=79)</th>
<th>Fail (n=21)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>48.0±14.2</td>
<td>46.9±14.9</td>
<td>51.9±10.9</td>
<td>0.16</td>
</tr>
<tr>
<td>Male</td>
<td>58 (58)</td>
<td>48 (61)</td>
<td>10 (48)</td>
<td>0.28</td>
</tr>
<tr>
<td>BW (kg)</td>
<td>82.4±21.2</td>
<td>83.3±28.0</td>
<td>78.9±21.1</td>
<td>0.38</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>27.8±6.3</td>
<td>28.0±6.5</td>
<td>26.8±5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Diseases of great complexity</td>
<td>21 (21)</td>
<td>18 (23)</td>
<td>3 (14)</td>
<td>0.38</td>
</tr>
<tr>
<td>QRS (ms)</td>
<td>134.2±37.4 (n=99)†</td>
<td>125.7±35.1 (n=78)†</td>
<td>165.7±28.4 (n=21)†</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>QRS &gt;120 ms</td>
<td>56 (56)</td>
<td>36 (46)</td>
<td>20 (95)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>CLBBB</td>
<td>10</td>
<td>7</td>
<td>3</td>
<td>0.59</td>
</tr>
<tr>
<td>CRBBB</td>
<td>31</td>
<td>21</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>NSIVCD</td>
<td>15</td>
<td>8</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>QT (ms)</td>
<td>440.8±45.1 (n=99)†</td>
<td>434.0±45.4 (n=78)†</td>
<td>466.2±34.3 (n=21)†</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Inverted T wave between V2 and V6</td>
<td>68 (69)</td>
<td>49 (63)</td>
<td>19 (90)</td>
<td>0.02</td>
</tr>
<tr>
<td>Existing pacemaker/ICD</td>
<td>22 (22)</td>
<td>15 (19)</td>
<td>7 (33)</td>
<td>0.17</td>
</tr>
<tr>
<td>Dependent on ventricular pacing</td>
<td>13 (13)</td>
<td>7 (9)</td>
<td>6 (29)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Data given as n (%) or mean±SD. †No. patients for whom data were available. BMI, body mass index; BW, body weight; CLBBB, complete left bundle branch block; CRBBB, complete right bundle branch block; ICD, implantable cardioverter defibrillator; NSIVCD, non-specific interventricular conduction disturbance.

Circulation Journal Vol.80, June 2016
Eligibility for SICD in CHD

The high rate of screen failure is most likely secondary to the altered cardiac anatomy such as chamber enlargement, mechanical strain and augmented repolarization, cardiac position in the chest and relation to standard ECG positioning, all of which may result in prominent and/or non-traditional T-wave morphology.\(^2,14\)

The presence of inverted T wave anywhere in V2–V6 (often seen in patients with bundle branch block or dependent on ventricular pacing), appears to be predictive of such failure. Importantly, a significant number of patients who failed left-sided screening were found to remain as candidates for S-ICD implantation if a right-sided lead position was performed. This may be explained by the smaller repolarization vector found from the right side of the sternum, thus lowering the risk of T-wave oversensing on screening ECG.

Discussion

In this prospective investigation, we found that a substantial number of adult CHD patients (21%) are ineligible for S-ICD based on standard left-sided screening.

<table>
<thead>
<tr>
<th>Table 3. Screening ECG Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left pass</td>
</tr>
<tr>
<td>Right pass</td>
</tr>
<tr>
<td>Right failure</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

ECG, electrocardiogram; Left, left parasternal screening; Right, right parasternal screening.

Figure 2. Typical case of effective right parasternal screening. The patient (44-year-old woman with Ebstein’s anomaly) had failed left parasternal screening in all electrocardiogram vectors (arrows) but passed right parasternal screening both in the supine and standing positions.
Furthermore, transvenous lead implantation via a standard superior vena cava route may not be possible due to the absence of a connection to the right ventricle (eg, following a Glenn or bicavopulmonary anastomosis) or may be contraindicated due to the presence of intracardiac shunting, which can result in thromboembolic stroke from lead thrombus.\textsuperscript{2,20,21}

For these reasons, the S-ICD, which does not require transvenous lead placement, provides an attractive treatment option for many CHD patients. Given that the lead is placed outside the thoracic cage, it is subject to much gentler and less frequent excursions of respiration. That, combined with a rugged design (due to the lack of a lumen because the lead does not navigate the vascular space and does not require stylets), results in anticipated longevity of the device lead. Moreover, there are several unique and important considerations regarding implantation of an ICD in patients with CHD. These patients are relatively young compared with most ICD recipients, and therefore the patient’s vasculature will be exposed to foreign material for years, and be at risk for infection, erosion, vascular stenosis, and thrombosis. In addition, with transvenous systems in young patients, the lead will be exposed to the repetitive and damaging effects of cardiac motion for years.\textsuperscript{15} Furthermore, implanted leads are also typically exposed to mechanical trauma given the higher levels of activity in this younger age group, and therefore have a higher incidence of lead fracture.\textsuperscript{16–18} This patient group also will require more generator replacements over the course of a lifetime, and thus have an increased chance of pocket or bloodstream infection, along with the resultant higher likelihood of requiring device system extraction.\textsuperscript{19} Furthermore, transvenous lead implantation via a standard superior vena cava route may not be possible due to the absence of a connection to the right ventricle (eg, following a Glenn or bicavopulmonary anastomosis) or may be contraindicated due to the presence of intracardiac shunting, which can result in thromboembolic stroke from lead thrombus.\textsuperscript{2,20,21}

Table 4. Significant Factors of Screening Failure

<table>
<thead>
<tr>
<th>Factor</th>
<th>Univariate logistic regression</th>
<th>Multivariate logistic regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OR</td>
<td>95% CI</td>
</tr>
<tr>
<td>Age (per 10 years)</td>
<td>1.28</td>
<td>0.91–1.85</td>
</tr>
<tr>
<td>Sex (male)</td>
<td>0.59</td>
<td>0.22–1.55</td>
</tr>
<tr>
<td>BW (per 10 kg)</td>
<td>0.9</td>
<td>0.70–1.13</td>
</tr>
<tr>
<td>BMI (per 10 kg/m²)</td>
<td>0.71</td>
<td>0.30–1.54</td>
</tr>
<tr>
<td>Diseases of great complexity</td>
<td>0.56</td>
<td>0.12–1.91</td>
</tr>
<tr>
<td>QRS duration (per 10 ms)</td>
<td>1.38</td>
<td>1.19–1.65</td>
</tr>
<tr>
<td>QRS &gt;120 ms</td>
<td>23.33</td>
<td>4.51–428.83</td>
</tr>
<tr>
<td>QT interval (per 20 ms)</td>
<td>1.41</td>
<td>1.12–1.82</td>
</tr>
<tr>
<td>Inverted T wave between V2 and V6</td>
<td>5.62</td>
<td>1.48–36.90</td>
</tr>
<tr>
<td>Existing pacemaker/ICD</td>
<td>2.13</td>
<td>0.71–6.13</td>
</tr>
<tr>
<td>Dependent on ventricular pacing</td>
<td>4.11</td>
<td>1.18–14.20</td>
</tr>
</tbody>
</table>

Abbreviations as in Table 2.
when infections occur in patients with S-ICD, they have not resulted in sepsis (a particularly threatening condition in congenital patients with conduits and/or prosthetic valves), because the entire system is extravascular. Recognizing the caveat that this approach does not provide chronic pacing support, the efficacy of S-ICD has been proven in multiple studies.23–28

**Eligibility in CHD Patients for S-ICD**

The potential eligibility of CHD patients for S-ICD has been reported in a small 30-patient cohort that screened 10 patients with tetralogy of Fallot, 10 patients with transposition of great arteries and 10 patients with single ventricle/Fontan circulation.14 This screening was compared with 10 control patients without CHD, and it was found that 87% of CHD patients vs. 100% of the controls met S-ICD eligibility. These authors found a non-significant difference between the 2 groups. In contrast to the present study, patients with permanent pacing were excluded.

In the present study, the failure rate for screening ECG was found to be 21%, and those with permanent pacing were also included to provide a more “real world” insight, given that patients with CHD frequently require pacing and that S-ICD devices have been implanted in patients with pacemakers in place.29 Furthermore, the present cohort encompassed a wide variety of CHD syndromes, including 13 patients with ventricular paced rhythms. Importantly, 6 patients (46%) with ventricular pacing failed the screening; 3 of those patients were eligible for a right-sided system. The failure rate of 21% was significant in this cohort of 100 patients, and is higher than in other reports on acquired heart disease (approximately 10%).30–33

**Efficacy of Right Parasternal Lead Placement**

In this study, we evaluated right-sided electrode placement for T-wave sensing. The only independent predictor for right-side screening failure was wider QRS, which could differentiate the results from left-side screening. The addition of this preemptive screening step substantially reduced the failure rate from 21% to 12%. Evaluation of the ECG vector from these right-sided oriented leads is not known to reduce the sensitivity of R-wave detection and chiefly affects over-detection of the T wave. The efficacy of right parasternal lead position in patients with hypertrophic cardiomyopathy has been previously reported.30 In that study in a small cohort, 2 of 5 patients who failed left parasternal screening during exercise and 8 of 28 patients who failed with paced complexes passed screening with right parasternal electrodes. This decreased the failure rate by 10 and 20%, respectively. Figure 4 shows a chest X-ray (after S-ICD implantation) in a patient who failed left parasternal screening but who passed right parasternal screening and subsequently underwent S-ICD implantation with the defibrillation lead along the right side of the sternum. Defibrillation testing during the procedure was successful with a 65-J shock terminating ventricular fibrillation (VF). Chan et al reported a case in which the right parasternal position resolved the tall T wave detected in the left parasternal position.31 In that study, VF was also successfully converted with 65-J standard polarity shock during the procedure.

**S-ICD Eligibility in Patients Requiring Cardiac Pacing**

Patients who require permanent pacing support are not candidates for isolated S-ICD implantation but, in patients with CHD, it is not rare to encounter patients with longstanding epicardial pacing systems who develop an ICD indication, or for patients with transvenous pacemakers to lack vascular access. ICD sensing is an important concern in patient with pacemakers. With transvenous systems, separate pacemaker and ICD systems could result in inappropriate shock due to spike over-counting or underdetection of VF due to sensing spikes as QRS complexes.32 Currently, there is limited experience with S-ICD therapy in patients with pre-existing pacemakers. In both circumstances, S-ICD had been placed, with subsequent appropriate detection and termination of VF by the S-ICD.30 Therapy delay was absent and no inappropriate shocks delivered.

To avoid undersensing of tachycardia and delayed appropriate therapy, avoidance of large unipolar pacing spikes is fundamental and bipolar pacing should be used preferentially for both atrial and ventricular pacing. The decision to consider this management strategy entailing 2 cardiac devices remains highly individualized and nuanced based on the patient’s anatomy, mode of pacing, location of the leads and the paced QRS complex.

**Inverted T Wave in Precordial Lead as Predictor of Screening Failure**

We found that inverted T wave in any of leads V2–V6 – or prolonged QT interval – predicts failure of left parasternal screening in patients with CHD. This correlates with previous reports (in patients with hypertrophic cardiomyopathy) in which prolonged QT interval was also an independent predictor for screening failure and also an independent predictor of inappropriate shock (largely due to T-wave oversensing).33,34 Putatively, the diurnal change of T-wave morphology in patients with hypertrophic cardiomyopathy might explain the inappropriate shock due to T-wave oversensing, which cannot be detected on screening ECG alone. Patients with Brugada syndrome at high risk of VF should also be considered for S-ICD implantation (give their young age).35 but the clinician should be aware that a positive ST-T segment change in precordial leads during class I blockade has been reported to indicate failure for S-ICD on screening ECG.36 Careful
monitoring of T-wave oversensing appears to be necessary even after S-ICD implantation in patients with inverted T wave in the precordial leads.

**Study Limitations**
Although this is the largest study to date on eligibility for S-ICD in CHD patients, the small number of patients who failed the screening (n=21) was a significant limitation for the univariate and multivariate analysis. ICD indication was not required for study inclusion; thus, it is possible that patients with CHD who require ICD may have different screen failure rates than found in the present study. Another limitation was the paucity of information regarding the impact of right parasternal lead placement on defibrillation threshold (DFT). In the available small experience with right parasternal lead placement, successful defibrillation with 65 J has been reported.33 A study on defibrillation efficacy of S-ICD using a computer simulation model reported that DFT for the coil lead paced at the right parasternal margin may be lower than that for the coil lead placed at the left parasternal margin.34 Additionally, a screening ECG test result cannot guarantee the absence of inappropriate shock due to T-wave oversensing after S-ICD implantation. We tested screening ECG in the supine and standing positions only at rest; screening ECG during exercise may be helpful to detect T-wave oversensing.35

**Conclusions**
This study identified a high eligibility failure rate with standard left-sided screening in adults with CHD. Use of bilateral parasternal ECG screening increases S-ICD eligibility in adult patients in this group, and potentially should be considered in all S-ICD candidates. Interestingly, inverted T wave in precordial leads as well as QT prolongation were strongly associated with screen failure, and may facilitate use of standard 12-lead ECG to identify individuals who are not S-ICD candidates.

**Acknowledgments**
We thank Mrs Patricia C. Roth and Mrs Mary L. Silhasek, registered nurses, and Mrs Jennifer L. Dugan, research coordinator in the Department of Cardiovascular Diseases, Mayo Clinic, Rochester, MN, USA, for enrolling the patients in this study.

**Disclosures**
Okamura H is a recipient of the Medtronic Japan Fellowship for Young Japanese Investigator from the Japanese Heart Rhythm Society. This publication was supported by Grant Number ULIIR000135 from the National Center for Advancing Translational Sciences (NCATS). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the NIH.

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