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Longitudinal changes in intracardiac repolarization lability in patients with implantable cardioverter-defibrillator

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Background: While it is known that elevated baseline intracardiac repolarization lability is associated with the risk of fast ventricular tachycardia (FVT)/ventricular fibrillation (VF), the effect of its longitudinal changes on the risk of FVT/VF is unknown.

Methods and Results: Near-field (NF) right ventricular (RV) intracardiac electrograms (EGMs) were recorded every 3–6 months at rest in 248 patients with structural heart disease [mean age 61.2 ± 13.3; 186 (75.3%) male; 162 (65.3%) ischemic cardiomyopathy] and implanted cardioverter-defibrillator (ICD) or cardiac resynchronization therapy defibrillator (CRT-D) [201 (81%) primary prevention]. Intracardiac beat-to-beat QT variability index (QTVINF) was measured on NF RV EGM. During the first study phase (median 18 months), participants made on average 2.4 visits. Then remote follow-up was continued for an additional median period of 3 years. Average QTVINF did not change during the first year after ICD implantation (−0.342 ± 0.603 at baseline vs. −0.262 ± 0.552 at 6 months vs. −0.334 ± 0.603 at 12 months); however, it decreased thereafter (−0.510 ± 0.603 at 18 months; P = 0.042). Adjusted population-averaged GEE model showed that the odds of developing FVT/VF increased by 75% for each 1 unit increase in QTVINF. (OR 1.27 ± 1.334 [95%CI 1.05–2.92]; P = 0.031). However, individual patient–specific QTVINF trends (increasing, decreasing, flat) varied from patient to patient. For a given patient, the odds of developing FVT/VF were not associated with increasing or decreasing QTVINF over time [OR 1.27; (95%CI 0.05–30.10); P = 0.881].

Conclusion: While on average the odds of FVT/VF increased with an increase in QTVINF, patient-specific longitudinal trends in QTVINF did not affect the odds of FVT/VF.

Keywords: intracardiac electrograms, repolarization lability, ventricular tachyarrhythmia, longitudinal analysis, QT variability index
demonstrated that the single baseline measurement of intracardiac QT variability index (QTVI_{NF}), was associated with fast ventricular tachycardia (FVT)/VF during the subsequent 16 months of follow-up. However, the effect of longitudinal changes in intracardiac repolarization lability on the risk of FVT/VF is unknown. The goal of the present study was to determine if patients with increasing intracardiac QTVI_{NF} over time experience a greater probability of having FVT/VF than those with decreasing or stable intracardiac QTVI_{NF}.

METHODS
The ICD-EGMs study (Tereshchenko et al., 2009) protocol was approved by the Johns Hopkins University and the Washington University Human Studies Committees and all participants gave written informed consent before entering the study.

STUDY POPULATION
The ICD-EGMs study design (NCT00916435) was previously described (Tereshchenko et al., 2009). Briefly, patients with structural heart disease of either sex older than 18 years were enrolled in the study if they had a transvenous ICD or a cardiac resynchronization therapy defibrillator (CRT-D) device implanted for primary or secondary prevention of SCD. In this study we included only participants who (1) had ICD or CRT-D implanted 1 week before enrollment, (2) made at least 2 consecutive office follow-up visits during the first study phase (2005–2007), (3) had at least 2 analyzable digital recordings of intracardiac EGMs at rest that were at least 30 days apart, (4) had EGMs recorded in sinus rhythm, with (5) identical type of ventricular activation [either ventricular-sensed (VS), or ventricular-paced (VP)] at baseline and at all follow-up visits.

RECORDING OF INTRACARDIAC EGMs AND FOLLOW-UP OF STUDY PARTICIPANTS
Recording of intracardiac EGMs was performed at every office follow-up visit (every 3–6 months) during the first 2 years of the study (2005–2007). Patients were then followed remotely via Carelink® and Latitude® during next 4 years (2007–2011). Near-field (NF) and far-field (FF) RV intracardiac EGMs were recorded at rest for 5–15 min simultaneously with surface electrocardiogram (ECG) via ICD programmer as previously described (Tereshchenko et al., 2009).

Duration of time periods between follow-up visits varied from patient to patient, due to the observational nature of the study. In order to standardize assessment of longitudinal changes in EGM parameters, we categorized follow-up periods as the following. All follow-up visits that occurred in a period of 1–6 months after the baseline (Visit 1) were considered as Visit 2. Visit 3 EGM recording was performed at any time in a period of 181–365 days after baseline EGM recording. Visit 4 was performed during the 1st half of the 2nd year of follow-up.

INTRACARDIAC REPOLARIZATION LABILITY ANALYSIS
Intracardiac repolarization lability was measured on NF RV EGM as previously described (Tereshchenko et al., 2009) by Berger’s method (Berger et al., 1997), using customized MATLAB (MathWorks, Inc., Natick, MA) software. The R-wave peak was automatically detected on NF EGM channel. Two investigators (AG, JL) defined an intracardiac intervals template by selecting the beginning and the end of major NF EGM deflection, and the end of the T wave. The algorithm then determined how much the repolarization segment of each beat had to be stretched or compressed to match the template. Appropriate selection of fiducial points was verified by the third investigator (LGT). Premature ventricular and atrial beats with one post-ectopic sinus beat were excluded from the analysis. Recordings with more than 15% of ectopic, or noise-distorted beats were excluded.

ENDPOINTS
Appropriate ICD shocks for FVT/VF served as the endpoints in this study. Programming of the ICD device was based on clinical evaluation of the attending electrophysiologist. ICD interrogation data was adjudicated by an endpoint committee composed of 3 members. ICD therapy occurring for VT or VF was classified as appropriate (Tereshchenko et al., 2009). FVT/VF was defined as VT/VF with an average cycle length (CL) ≤ 240 ms. After the 1st FVT/VF event follow-up was continued, and all subsequent sustained FVT/VF events with appropriate ICD shocks were included in the analysis as the study endpoints.

STATISTICAL ANALYSIS
The association of baseline clinical characteristics and ECG parameters with the type of presenting rhythm was measured by the χ²-tests and ANOVA or t-test, respectively, for categorical and continuous variables with normal distribution. A test of equality of medians or Wilcoxon rank-sum test was used in case the distribution of parameter was not normal. A P-value of <0.05 was considered significant. Data analysis was performed using STATA 12.1 (StataCorp LP, College Station, TX).

As office visits were unequally spaced in time, QTVI variation was explored, and follow-up time periods were equalized with incremental 6-months-intervals. Possible effects of VP on longitudinal QTVI_{NF} changes were explored in patients with different devices types (single-chamber ICD, dual-chamber ICD, CRT-D), as well as in patients who predominantly (at least 99% of follow-up time and 100% of recorded EGM) had VS, in comparison to VP rhythm. “Spaghetti” plots were examined to study variations of QTVI_{NF} across time for each individual. Smoothed plots were used to explore group response of QTVI_{NF} as a function of time, to study variations of QTVI_{NF} across different individuals. Average changes in QTVI_{NF} per 6 months of follow-up were determined. Patterns of QTVI_{NF} changes over time in patients with and without FVT/VF were compared. Since repeated measures made on the same subject are correlated, within-person correlations matrix of QTVI_{NF} across multiple visits was estimated, and the correlation structure was described. The correlation structure for the residuals was explored after removing the mean trend effect. To standardize QTVI_{NF} at each visit, we subtracted observations in each category (each visit) by the mean for that visit and then divided them by the standard deviation for that visit. Further longitudinal regression analyses took into account the
visit-to-visit QTVinF correlation structure to obtain valid inferences.

We compared the association of FVT/VF events with preceding longitudinal QTVinF changes in an average study participant (in the population-averaged model), and in specific study subject (in the subject-specific model). Population-averaged marginal model accounting for correlation structure [Generalized Estimating Equations (GEE) model] was developed. Multivariate GEE model was used to determine an association between a population-averaged longitudinal QTVinF changes, and a subsequent outcome. FVT/VF events with appropriate ICD shocks that occurred after respective QTVinF measurements served as an outcome. GEE model was adjusted by age, sex, race, left ventricular ejection fraction (LVEF), New York Heart Association (NYHA) heart failure class (dichotomized as NYHA = II), indication for ICD (primary or secondary prevention of SCD), type of cardiomyopathy (ischemic or non-ischemic), history of revascularization procedure (either PCI or CABG), type of implanted device (single-chamber ICD, dual-chamber ICD, CRT-D), type of analyzed rhythm (VS or VP), and use of class III anti-arrhythmic medications.

In order to determine the patient-specific association of longitudinal QTVinF changes with subsequent FVT/VF, we ran a random intercept model for FVT/VF. We accounted for correlation of the repeated QTVinF observations by including a random intercept for each patient and control for patient’s QTVinF (centered). Adequate fitting of the model was checked to ensure that the specified quadrature has adequately approximated the likelihood.

RESULTS

STUDY POPULATION

We analyzed the data of 248 study participants: 185 (74.6%) men, 201 Whites (81%), mean age 61.2 ± 13.3 y. Clinical characteristics of study participants are shown in Table 1. We categorized study participants based on their presenting rhythm during follow-up office visits. VS participants were paced <1% during the study duration (Table 1) and were not paced from ventricular(s) during study EGM recordings. Patients who presented with a sinus rhythm, and were 100% VP during the study EGM recordings, comprised VP group. Figure 1 shows representative examples of longitudinal changes in RR’ and QT variability in patients with and without ventricular arrhythmia.

As expected, due to the differences in HF severity, CRT-D patients had significantly higher mean heart rate as compared to single-and dual-chamber ICD patients (Table 2). However, QT interval on NF RV EGM (QTVinF) was longer in patients with dual-chamber ICDs as compared to those with single chamber ICDs and CRT-Ds. There were no significant differences in heart rate variance, QTVinF variance, and QTVinF amongst patients with different device types, nor in patients with presenting VS vs. those with VP sinus rhythm (Table 2).

Table 1 | Comparison of demographic and clinical characteristics of patients with single-, dual-chamber ICD, and CRT-D, and in patients with sinus ventricular-sensed and ventricular-paced rhythm.

<table>
<thead>
<tr>
<th></th>
<th>Single chamber ICD (n = 139)</th>
<th>Dual chamber ICD (n = 97)</th>
<th>CRT-D (n = 12)</th>
<th>ANOVA P</th>
<th>V-sensed (n = 195)</th>
<th>V-paced (n = 53)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age(SD), y</td>
<td>58.2 (13.0)</td>
<td>64.5 (13.3)</td>
<td>69.8 (7.5)</td>
<td>0.0001</td>
<td>60.3 (13.4)</td>
<td>64.5 (12.6)</td>
<td>0.036</td>
</tr>
<tr>
<td>Males, n(%)</td>
<td>101 (72.7)</td>
<td>74 (76.3)</td>
<td>10 (83.3)</td>
<td>0.636</td>
<td>145 (74.4)</td>
<td>40 (75.5)</td>
<td>0.869</td>
</tr>
<tr>
<td>African American, n(%)</td>
<td>35 (25.2)</td>
<td>10 (10.3)</td>
<td>2 (16.7)</td>
<td>0.016</td>
<td>40 (20.5)</td>
<td>7 (13.2)</td>
<td>0.229</td>
</tr>
<tr>
<td>CHF NYHA class = II, n(%)</td>
<td>92 (66.2)</td>
<td>52 (53.6)</td>
<td>12 (100.0)</td>
<td>0.003</td>
<td>118 (60.5)</td>
<td>38 (71.7)</td>
<td>0.135</td>
</tr>
<tr>
<td>Ischemic CM, n(%)</td>
<td>85 (61.2)</td>
<td>69 (28.9)</td>
<td>4 (33.3)</td>
<td>0.283</td>
<td>70 (35.9)</td>
<td>16 (30.2)</td>
<td>0.439</td>
</tr>
<tr>
<td>Primary prevention of SCD, n(%)</td>
<td>28 (20.1)</td>
<td>19 (19.6)</td>
<td>0</td>
<td>0.228</td>
<td>157 (80.5)</td>
<td>44 (63.0)</td>
<td>0.680</td>
</tr>
<tr>
<td>Presenting VP rhythm, n(%)</td>
<td>2 (1.4)</td>
<td>40 (41.2)</td>
<td>11 (91.7)</td>
<td>&lt;0.0001</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Atrial pacing %, median(IQR)</td>
<td>–</td>
<td>11.5 (0–76)</td>
<td>0 (0–0)</td>
<td>&lt;0.0001</td>
<td>16 (0–76)</td>
<td>1.5 (0–74)</td>
<td>0.328</td>
</tr>
<tr>
<td>Ventricular pacing %, median(IQR)</td>
<td>0 (0–0)</td>
<td>4.5 (0–29.5)</td>
<td>100 (98–100)</td>
<td>&lt;0.0001</td>
<td>0 (0–1)</td>
<td>16 (1–91)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LVEF(SD), (%)</td>
<td>31.9 (12.2)</td>
<td>32.4 (11.3)</td>
<td>25.0 (12.4)</td>
<td>0.127</td>
<td>32.4 (12.1)</td>
<td>29.3 (11.2)</td>
<td>0.075</td>
</tr>
<tr>
<td>Diabetes mellitus Hx, n(%)</td>
<td>50 (36.0)</td>
<td>23 (24.0)</td>
<td>3 (25.0)</td>
<td>0.132</td>
<td>65 (35.5)</td>
<td>11 (20.8)</td>
<td>0.075</td>
</tr>
<tr>
<td>Hypertension Hx, n(%)</td>
<td>108 (77.7)</td>
<td>67 (69.8)</td>
<td>10 (83.3)</td>
<td>0.306</td>
<td>150 (77.3)</td>
<td>35 (66.0)</td>
<td>0.093</td>
</tr>
<tr>
<td>CABG or PTCA Hx, n(%)</td>
<td>65 (46.8)</td>
<td>51 (62.6)</td>
<td>7 (88.3)</td>
<td>0.561</td>
<td>94 (48.2)</td>
<td>29 (54.7)</td>
<td>0.400</td>
</tr>
<tr>
<td>History of AF, n(%)</td>
<td>32 (23.0)</td>
<td>43 (44.3)</td>
<td>7 (58.3)</td>
<td>&lt;0.0001</td>
<td>55 (28.2)</td>
<td>27 (50.9)</td>
<td>0.002</td>
</tr>
<tr>
<td>Beta blockers, n(%)</td>
<td>126 (90.7)</td>
<td>78 (80.4)</td>
<td>8 (72.7)</td>
<td>0.038</td>
<td>171 (87.7)</td>
<td>41 (78.9)</td>
<td>0.104</td>
</tr>
<tr>
<td>ACE-Inhibitors or ARBs, n(%)</td>
<td>111 (79.9)</td>
<td>78 (80.4)</td>
<td>11 (91.7)</td>
<td>0.609</td>
<td>155 (79.5)</td>
<td>45 (84.9)</td>
<td>0.376</td>
</tr>
<tr>
<td>Digitalis, n(%)</td>
<td>45 (32.4)</td>
<td>39 (40.2)</td>
<td>5 (45.5)</td>
<td>0.375</td>
<td>69 (35.4)</td>
<td>20 (38.5)</td>
<td>0.681</td>
</tr>
<tr>
<td>Statin, n(%)</td>
<td>97 (69.8)</td>
<td>68 (70.1)</td>
<td>8 (72.7)</td>
<td>0.979</td>
<td>137 (70.3)</td>
<td>36 (69.2)</td>
<td>0.886</td>
</tr>
<tr>
<td>Nitrates, n(%)</td>
<td>36 (26.1)</td>
<td>20 (20.6)</td>
<td>5 (45.5)</td>
<td>0.170</td>
<td>50 (25.8)</td>
<td>11 (21.2)</td>
<td>0.493</td>
</tr>
<tr>
<td>Aldosterone antagonists, n(%)</td>
<td>53 (38.1)</td>
<td>37 (38.1)</td>
<td>5 (45.4)</td>
<td>0.888</td>
<td>76 (39.0)</td>
<td>19 (36.5)</td>
<td>0.748</td>
</tr>
<tr>
<td>Antidepressants, n(%)</td>
<td>30 (21.6)</td>
<td>33 (34.0)</td>
<td>3 (27.3)</td>
<td>0.105</td>
<td>47 (24.1)</td>
<td>19 (36.5)</td>
<td>0.072</td>
</tr>
<tr>
<td>Class III antiarrhythmics, n(%)</td>
<td>24 (17.3)</td>
<td>33 (34.0)</td>
<td>5 (45.5)</td>
<td>0.004</td>
<td>42 (21.5)</td>
<td>20 (38.5)</td>
<td>0.012</td>
</tr>
</tbody>
</table>

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**Table 2 | Comparison of all-visits averaged ECG parameters in patients with single-, dual-chamber ICD, and CRT-D, and in patients with sinus ventricular-sensed and ventricular-paced rhythm.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single chamber ICD (n = 332)</th>
<th>Dual chamber ICD (n = 230)</th>
<th>CRT-D (n = 24)</th>
<th>ANOVA P</th>
<th>V-sensed (n = 464)</th>
<th>V-paced (n = 122)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (SD), bpm</td>
<td>74.2 (14.5)</td>
<td>71.1 (13.3)</td>
<td>78 (17.5)</td>
<td>0.009</td>
<td>72.8 (14.3)</td>
<td>74.5 (14.2)</td>
<td>0.231</td>
</tr>
<tr>
<td>QT interval (SD), ms</td>
<td>469 (116)</td>
<td>496 (110)</td>
<td>478 (180)</td>
<td>0.030</td>
<td>479 (116)</td>
<td>467 (123)</td>
<td>0.477</td>
</tr>
<tr>
<td>Heart rate variance, median(IQR), ms²</td>
<td>40.2 (7.9–91.5)</td>
<td>47.1 (12.8–99.4)</td>
<td>45.7 (14.0–117.7)</td>
<td>0.549</td>
<td>41.0 (9.1–93.2)</td>
<td>48.6 (13.0–106.7)</td>
<td>0.209</td>
</tr>
<tr>
<td>QT variance, median(IQR), ms²</td>
<td>748 (122–1693)</td>
<td>729 (167–1704)</td>
<td>556 (269–1190)</td>
<td>0.699</td>
<td>726 (130–1699)</td>
<td>715 (196–1678)</td>
<td>0.617</td>
</tr>
<tr>
<td>QTVI (SD)</td>
<td>−0.307 (0.548)</td>
<td>−0.402 (0.648)</td>
<td>−0.293 (0.641)</td>
<td>0.163</td>
<td>−0.344 (0.570)</td>
<td>−0.345 (0.679)</td>
<td>0.983</td>
</tr>
</tbody>
</table>

**VENTRICULAR TACHYARRHYTHMIA DURING FOLLOW-UP**

During the first study phase participants made on average 2.4 visits. FVT/VF events with appropriate ICD shocks were diagnosed in 26 (10.5%) patients. Multiple FVT/VF during follow-up were observed in 20 (77%) out of 26 patients, frequently in clusters. Baseline clinical characteristics in patients with or without FVT/VF during follow-up did not differ (Table 3). Importantly, QTVI\textsubscript{NF} was the only ECG parameter that differentiated patients...
Table 3 | Comparison of baseline clinical and demographic characteristics in patients with and without FVT/VF during follow-up.

<table>
<thead>
<tr>
<th></th>
<th>No FVT/VF (n = 222)</th>
<th>FVT/VF (n = 26)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (SD), y</td>
<td>61.9 (12.8)</td>
<td>55.3 (16.6)</td>
<td>0.058</td>
</tr>
<tr>
<td>Males, n(%)</td>
<td>165 (74.3)</td>
<td>20 (76.9)</td>
<td>0.773</td>
</tr>
<tr>
<td>African American, n(%)</td>
<td>43 (19.4)</td>
<td>4 (15.4)</td>
<td>0.624</td>
</tr>
<tr>
<td>CHF NYHA class = II, n(%)</td>
<td>138 (62.3)</td>
<td>18 (69.2)</td>
<td>0.480</td>
</tr>
<tr>
<td>Ischemic CM with MI history, n(%)</td>
<td>145 (65.3)</td>
<td>17 (65.4)</td>
<td>0.994</td>
</tr>
<tr>
<td>Primary prevention of SCD, n(%)</td>
<td>180 (81.1)</td>
<td>21 (80.8)</td>
<td>0.969</td>
</tr>
<tr>
<td>Single-chamber ICD, n(%)</td>
<td>124 (55.9)</td>
<td>15 (57.7)</td>
<td>0.963</td>
</tr>
<tr>
<td>Dual-chamber ICD, n(%)</td>
<td>87 (39.2)</td>
<td>10 (38.5)</td>
<td>0.963</td>
</tr>
<tr>
<td>Bi-Ventricular ICD, n(%)</td>
<td>11 (5.0)</td>
<td>1 (3.9)</td>
<td>0.963</td>
</tr>
<tr>
<td>Atrial pacing1 %, median(IQR)</td>
<td>9.5 (0–71.5)</td>
<td>32 (1–92)</td>
<td>0.053</td>
</tr>
<tr>
<td>Ventricular pacing2 %, median(IQR)</td>
<td>0 (0–3)</td>
<td>0 (0–0)</td>
<td>0.152</td>
</tr>
<tr>
<td>LVEF(SD), %</td>
<td>31.7 (11.8)</td>
<td>32.5 (13.5)</td>
<td>0.777</td>
</tr>
<tr>
<td>Diabetes mellitus, n(%)</td>
<td>68 (30.8)</td>
<td>8 (30.8)</td>
<td>1.00</td>
</tr>
<tr>
<td>Hypertension, n(%)</td>
<td>165 (74.7)</td>
<td>20 (76.9)</td>
<td>0.901</td>
</tr>
<tr>
<td>CABG or PTCA, n(%)</td>
<td>111 (50.0)</td>
<td>12 (46.2)</td>
<td>0.711</td>
</tr>
<tr>
<td>History of AF, n(%)</td>
<td>74 (33.3)</td>
<td>8 (30.8)</td>
<td>0.793</td>
</tr>
<tr>
<td>Beta blockers, n(%)</td>
<td>192 (86.9)</td>
<td>20 (76.9)</td>
<td>0.169</td>
</tr>
<tr>
<td>ACE-Inhibitors or ARBs, n(%)</td>
<td>181 (81.5)</td>
<td>19 (73.1)</td>
<td>0.302</td>
</tr>
<tr>
<td>Digitals, n(%)</td>
<td>76 (34.4)</td>
<td>13 (50.0)</td>
<td>0.117</td>
</tr>
<tr>
<td>Statin, n(%)</td>
<td>156 (70.6)</td>
<td>17 (65.4)</td>
<td>0.584</td>
</tr>
<tr>
<td>Nitrates, n(%)</td>
<td>55 (25.0)</td>
<td>6 (23.1)</td>
<td>0.830</td>
</tr>
<tr>
<td>Aldosterone antagonists, n(%)</td>
<td>86 (38.9)</td>
<td>9 (34.6)</td>
<td>0.670</td>
</tr>
<tr>
<td>Antidepressants, n(%)</td>
<td>58 (26.2)</td>
<td>8 (30.8)</td>
<td>0.622</td>
</tr>
<tr>
<td>Class III antiarrhythmic medication, n(%)</td>
<td>55 (24.9)</td>
<td>7 (26.9)</td>
<td>0.821</td>
</tr>
</tbody>
</table>

1 Percentage of atrial pacing during study phase 1 (counters data) in patients with dual-chamber ICD or CRT-D; 2 percentage of ventricular pacing, accordingly, in patients with ICD only (CRT-D excluded).

with and without arrhythmia. QT1NF was significantly higher in patients with FVT/VF than in patients without FVT/VF (Table 4).

THE MEAN TREND IN LONGITUDINAL CHANGES OF INTRACARDIAC REPOLARIZATION LABILITY

Average QT1NF in study participants with single-chamber ICD did not change during the study period. However, average QT1NF in patients with dual-chamber ICDs increased during the first year after ICD implantation, but slightly decreased thereafter (Figure 2). At the same time, no statistically significant differences were observed in all VS, as compared to all VP patients (Figure 3). Averaged trend in QT1NF was different in patients with FVT/VF, as compared to patients without FVT/VF (Figure 4).

SUBJECT-SPECIFIC CHANGES IN REPOLARIZATION LABILITY OVER TIME

Individual patients demonstrated drastically different trends: in some patients intracardiac QT1NF increased while in others QT1NF decreased, stayed flat, or fluctuated over time. There were no differences in the behavior of the subject-specific longitudinal relationships in patients with different device type (Figure 5), or any between groups of VS and VP patients (Figure 6). Moreover, no differences in subject-specific QT1NF longitudinal trends were observed in patients with FVT/VF, as compared to patients without FVT/VF (Figure 7). Multiple cross-overs of the lines indicated that the relative order of patients, ordered by their baseline QT1NF, changed over time. The study population-averaged QT1NF longitudinal relationship (Figures 2–4) was not consistent with the subject-specific longitudinal relationship (Figures 5–7).

We observed weak positive correlation between QT1NF at the 1st and the 4th visits, and at the 1st and the 2nd visits in patients with single-chamber ICD (r = 0.312; P = 0.047 and r = 0.269; P = 0.024, respectively) and VS patients (r = 0.297; P = 0.026 and r = 0.384; P < 0.0001, respectively), and weak negative correlation in QT1NF at the 3rd and 4th visit (r = –0.604; P = 0.003 in single-chamber ICD group; r = –0.426; P = 0.021 in VS patients). Thus, in a given patient with single-chamber ICD who did not experience ventricular pacing, QT1NF 1 week after ICD implantation more likely positively correlated with QT1NF 1.5 years after ICD implantation. If such a patient experienced elevation of QT1NF during the 1st year post-ICD implantation, then during the next 6 months QT1NF was more likely decreasing (negative correlation in QT1NF between the 3rd and the 4th visits). No significant correlations between QT1NF observations at different visits in VP patients, both with dual-chamber ICDs and CRT-D devices were found.

ASSOCIATION BETWEEN LONGITUDINAL CHANGES IN REPOLARIZATION LABILITY AND SUBSEQUENT FVT/VF

The mean QT1NF trend in patients without FVT/VF demonstrated slight, but significant decrease 1.5 years after device implantation (Figure 4A), whereas no changes in mean QT1NF were observed in patients in FVT/VF (Figure 4B). Patterns of the subject-specific relationships between QT1NF and time looked alike in patients with and without FVT/VF (Figures 7A,B). QT1NF correlations structure in patients without FVT/VF revealed weak positive correlation between the 1st and the 2nd visit (r = 0.257; P = 0.004) and negative correlation of approximately the same strength between the 3rd and the 4th visit (r = –0.339; P = 0.040). However, QT1NF measured at different visits in a given patient who experienced FVT/VF during follow-up, did not correlate.

In order to study patient-specific dynamic changes in intracardiac RL before FVT/VF, we plotted QT1NF before each FVT/VF event. We used the actual time from then EGM recording to the FVT/VF event as a continuous variable (Figure 8). Noticeably, QT1NF distribution in patients without FVT/VF (Figure 8A) looked similar to that in patients before FVT/VF (Figure 8B). Trends of increasing, decreasing, and flat over time QT1NF were observed before FVT/VF events (Figure 8C). Of note, consistent pattern of increasing over time QT1NF before all FVT/VF events was observed in some (but not all) individual patients.
Table 4 | Comparison of all-visits averaged ECG parameters in patients with and without FVT/VF during follow-up.

<table>
<thead>
<tr>
<th></th>
<th>No FVT/VF (n = 525 visits)</th>
<th>FVT/VF (n = 61 visits)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (SD), bpm</td>
<td>73.1 (14.0)</td>
<td>73.4 (16.3)</td>
<td>0.899</td>
</tr>
<tr>
<td>QT interval (SD), s</td>
<td>0.479 (0.116)</td>
<td>0.498 (0.129)</td>
<td>0.278</td>
</tr>
<tr>
<td>Heart rate variance, median (IQR), ms²</td>
<td>45.1 (10.4–99.4)</td>
<td>31.9 (12.8–70.4)</td>
<td>0.143</td>
</tr>
<tr>
<td>QT variance, median (IQR), ms²</td>
<td>697.0 (147.0–1642.3)</td>
<td>1008 (175.0–2022.4)</td>
<td>0.238</td>
</tr>
<tr>
<td>QTV (SD)</td>
<td>−0.362 (0.601)</td>
<td>−0.186 (0.512)</td>
<td>0.015</td>
</tr>
</tbody>
</table>

FIGURE 2 | Comparison of population-averaged longitudinal trends in QTVI NF in patients with (A) single-chamber ICD, (B) dual-chamber ICD, (C) CRT-D. Scatterplot of QTVI NF at each standardized study visit is shown. Lowess smoother curve shows mean trend in QTVI NF over time.

FIGURE 3 | Comparison of population-averaged longitudinal trends in QTVI NF in patients with (A) presenting ventricular-sensed (VS), and (B) presenting ventricular-paced (VP) sinus rhythm. Scatterplot of QTVI NF at each standardized study visit is shown. Lowess smoother curve shows mean trend in QTVI NF over time.

with multiple FVT/VF events. In contrast, patients with a single FVT/VF event tended to demonstrate rather decreasing over time QTVI NF. However, small subgroups size did not allow us to quantify observed differences.

GEE POPULATION-AVERAGED MODEL
In multivariate GEE analysis with independent correlation structure, increasing over a time course of several months QTVI NF was significantly associated with FVT/VF event [OR 1.75 (95%CI 1.05–2.92); P = 0.031]. Thus, on average, for patients in our study, the odds of developing FVT/VF increased by 75% for each 1 unit increase in QTVI NF.

SUBJECT-SPECIFIC RANDOM INTERCEPT MODEL
Association between patient-specific dynamic changes in QTVI NF and FVT/VF was studied in the random-effects logistic regression. In order to determine if a specific patient with increasing QTVI NF over time experiences a greater probability of having FVT/VF, as compared to patient with decreasing or stable QTVI NF, we ran random-effects logistic regression analysis. For a given patient, the odds of developing FVT/VF were not associated with increasing or decreasing QTVI NF [OR 1.27; (95%CI 0.05–30.10); P = 0.881] over time. We used 194 integration points in this model for assurance that the likelihood is appropriately approximated, which was confirmed. In addition, we explored potential...
FIGURE 4 | Comparison of population-averaged longitudinal trends in QTVI_{NF} in patients (A) without FVT/VF, and (B) with sustained FVT/VF and appropriate ICD shocks. Scatterplot of QTVI_{NF} at each standardized study visit is shown. Lowess smoother curve shows mean trend in QTVI_{NF} over time.

FIGURE 5 | “Spaghetti” plots of individual patient-specific longitudinal relationships between QTVI_{NF} and time for each subject with (A) single-chamber ICD, (B) dual-chamber ICD, (C) CRT-D.

FIGURE 6 | “Spaghetti” plots of individual patient-specific longitudinal relationships between QTVI_{NF} and time for each subject with (A) presenting ventricular-sensed (VS), and (B) presenting ventricular-paced (VP) sinus rhythm.

FIGURE 7 | “Spaghetti” plots of individual patient-specific longitudinal relationships between QTVI_{NF} and time for each subject (A) without FVT/VF, and (B) with sustained FVT/VF and appropriate ICD shocks.

interactions and adjusted patient-specific models for the effect of VP in preceding follow-up interval, for percentage of beats, included in QTVI analysis by automated software, and for the differences in follow-up time interval. Subject-specific longitudinal QTVI_{NF} trend was associated neither with study outcome (FVT/VF), nor with any other measured in this study clinical, demographic, or ECG parameter.

DISCUSSION
Our study revealed differences in population-averaged and patient-specific intracardiac QTVI_{NF} trends over 1.5 years after device implantation. In patients without FVT/VF events population-averaged QTVI_{NF} decreased after the 1st year since ICD implantation, whereas in patients with FVT/VF events averaged QTVI_{NF} did not change. Group-averaged QTVI_{NF} was independently associated with the odds of life-threatening FVT/VF. On average, the odds of FVT/VF increased by 75% for each 1 unit increase in QTVI_{NF}. In contrast, individual subject-specific QTVI_{NF} trends in many patients differed from the mean trend for the whole study population. Individual subject-specific trends in intracardiac QTVI_{NF} were not associated with subsequent FVT/VF.

LONGITUDINAL STUDIES OF REPOLARIZATION LABILITY: MEAN TREND VS. SUBJECT-SPECIFIC CHANGES OVER TIME
Population-averaged trends in repolarization lability and TWA changes immediately before VT/VF have been previously studied. The vast majority of investigators explored short-term (24–48 h)
Mechanistically, each individual’s longitudinal out-
and population-averaged longitudinal trends in intracardiac
dynamics. Shusterman et al. (2006) described an
upsurge of alternating and non-alternating RL 10 min before the
onset of VT/VF in HF patients. Analysis of 24-h Holter ECG
revealed pronounced diurnal variations in QTVI (higher QT
variability in the morning and during the day, and lower QT vari-
ability during the night) in HF patients (Dobson et al., 2009).
At the same time, no significant changes in the mean QTVI trend was detected during 12 h of ECG monitoring before the
onset of spontaneous VT/VF in the acute intensive cardiac care
unit patients (Sachdev et al., 2010). In this study population-
averaged model reflected absolute difference in QTVI_{12–18}
month after ICD implantation in patients with and without sub-
sequent FVT/VF (Table 4; Figure 4), and re-confirmed our previ-
ous finding of association between elevated QTVI_{I} and VT/VF
(Tereshchenko et al., 2009).

Very few investigators studied subject-specific trends in
repolarization lability. Swerdlow and co-investigators (2011)
used subject-specific longitudinal analysis approach and showed
increased intracardiac TWA/variability immediately before VT/VF onset in ICD patients. To the best of our knowl-
dge, our study is the first that compared patient-specific and population-averaged longitudinal trends in intracardiac
QTVI_{I}. Mechanistically, each individual’s longitudinal outcome is governed by subject-specific disease dynamics over
time. Hence, each subject’s repolarization lability trajectory neither necessarily progresses in accord with a rigid population
mean curve nor varies with bounded variation. Evidently, some “latent” factors (not measured in this study) impacted
individual subject-specific trends in QTVI_{I}. In patients with
structural heart disease and systolic HF multiple parameters might change over time: coronary perfusion, myocardial
contractility and compliance, use of medications, affecting repolarization (Tereshchenko et al., 2009), level of physical
activity and autonomic balance, kidney function, and many others. Any of these unmeasured in this study factors might play a major role in the observed subject-specific QTVI_{I} changes.

Recently we showed that both high and low repolarization
lability is associated with the risk of SCD in general pop-
ulation (Tereshchenko et al., 2012). In our previous analysis of ICD-EGMs study we observed that QTVI_{I} was decreased
after premature ventricular contraction. Paradoxically, decreased,
but not increased QTVI_{I} was associated with VT/VF (Das
et al., 2012). While arrhythmogenesis, associated with elevated
repolarization lability is well understood (Tereshchenko and
Berger, 2011), observation of association between decreasing
QTVI_{I} and subsequent FVT/VF is novel and prompts fur-
ther investigations. As previously shown, static QT/RR rela-
tionships (Batchvarov et al., 2002), as well as the dynamic
pattern of QT/RR hysteresis (Malik et al., 2008) is highly
patient-specific. It was even suggested that the individual
QT-RR relationship has unique “finger-print-like” properties
(Malik et al., 2008). This fact might contribute to the high
degree inter-subject variability of the dynamic QTVI_{I} pat-
terns, observed in this study. Especially intriguing was observa-
observation of consistent increasing QTVI_{I} trend before each
FVT/VF event in some (but not all) patients with multiple
FVT/VF events. Further mechanistic studies are needed to explore possible mechanisms of arrhythmogenesis, associated with decreasing QTVI_{I}, in order to explain subject-specific trends fully.

**EFFECT OF VENTRICULAR PACING ON REPOLARIZATION LABILITY**

In this study we did not find significant differences in intracardiac QTVI_{I} between VS and VP patients in sinus rhythm. This observation is in concordance with our earlier study (Tereshchenko et al., 2011) of intracardiac QTVI_{I} in CRT patients. Of note, we longitudinally studied only patients with consistently identical type of the presenting rhythm across multiple visits.

Since deleterious effect of RV pacing is well known (Wilkoff
et al., 2002), we focused our analysis on evaluation of the possible longitudinal effects of amount of RV pacing on QTVI_{I} and study outcomes. We did not find significant differences in percentage of VP in patients with and without FVT/VF. Furthermore, the percentage of VP did not influence QTVI_{I} and was not responsible for fluctuations of QTVI_{I} from visit-to-visit.

**CLINICAL PERSPECTIVE**

In clinical practice and clinical research multiple physiological
parameters are measured repetitively and are studied longitudinally. In the vast majority of longitudinal studies
population-averaged analysis is the only analysis applied. Very few
longitudinal studies in electrophysiology report results of subject-specific longitudinal analysis. However, the physician manages the specific individual patient, rather than the “population-averaged” patient, and understanding of the patient-specific trends is extremely important for clinical decisions in the era of individualized medicine. In this study, population-averaged and subject-specific longitudinal trend in repolarization lability demonstrated different degree of association with subsequent FVT/VF. Further prospective longitudinal studies of repolarization lability should be conducted in order to understand behavior and predictors of subject-specific longitudinal trends in repolarization lability, and to determine its association with clinically-meaningful outcomes.

**LIMITATIONS**

Several limitations have to be acknowledged. First of all, the EGM recordings were obtained not exactly at the same time of the day (Dobson et al., 2009). All EGMs were recorded during the morning and middle-day hours (8 am–3 pm), which minimized possible circadian effect.

Time intervals between follow up visits varied due to the observational nature of the study. In order to overcome this limitation, we standardized time intervals for longitudinal analysis. In addition, we employed specific analytical approach, which incorporated actual time from EGM recording to outcome.

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Conflict of Interest Statement: This study was supported by Medtronic, Inc., as an Investigator-initiated Research Project. Ronald Berger holds a patent on the technology for QT variability analysis. The other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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