T-wave alternans (TWA), a beat-to-beat fluctuation in T-wave morphology and ST segment, is mechanistically linked to vulnerability to life-threatening ventricular tachyarrhythmias.1,2 Macroscopic TWA has frequently been reported, sometimes accompanied by torsade de pointes (TdP), in patients with congenital3–6 and acquired7–10 long QT syndrome (LQTS). Hence, macroscopic TWA is not only one of the diagnostic criteria for LQTS11 but is also a risk marker for cardiac events.4

See Editorial by Davis

Presently, microvolt-level TWA can be quantified using 24-hour continuous ECG.1,12 Ambulatory ECG recorders with 2 or 3 bipolar leads have been commonly used to monitor microvolt TWA.1 The utility of the simplified 2- or 3-lead ECG recorder to monitor TWA, however, may be limited by the regionally specific nature of the phenomenon, as in patients with acute myocardial ischemia.13–16 Indeed, we previously reported that an acquired LQTS patient exhibited regionally specific macroscopic TWA preceding the onset of TdP.10 In this patient, the precordial leads were superior to the standard telemetry lead II in terms of macroscopic TWA detection. Therefore, we hypothesized that assessment by 24-hour multilead continuous ECG would provide more complete and accurate detection of microvolt TWA in LQTS patients than would ECG recorders with fewer leads.

The goals of this study were (1) to determine the prevalence of microvolt TWA in both healthy subjects and LQTS patients using 24-hour continuous 12-lead ECGs; (2) to assess the association of microvolt TWA with TdP history; and (3) to describe the distribution of peak TWA among ECG leads.

Methods

Study Participants

We studied 10 healthy volunteers and 32 consecutive patients with LQTS. A cardiac channel gene screen for LQTS-causing mutations in KCNQ1 (LQT1), KCNH2 (LQT2), and SCN5A (LQT3) was

Background—Prevalence of microvolt T-wave alternans (TWA) and the strength of its association with torsade de pointes (TdP) history have not been fully investigated in patients with long QT syndrome (LQTS).

Methods and Results—Twenty-four–hour continuous 12-lead ECGs were recorded in 10 healthy subjects (5 men; median age, 21.5 years) and 32 patients (13 men; median age, 13 years) with LQTS types 1 (n=18), 2 (n=4), 3 (n=4), and unidentified (n=6). Peak TWA was determined by the Modified Moving Average method. None of the healthy subjects had TWA ≥42 µV. All 8 (100%) LQTS patients with a history of TdP exhibited TWA ≥42 µV, whereas only 14 (58.3%) of the 24 LQTS patients without TdP history reached ≥42 µV (p=0.04). Thus, the 42-µV cut point provided 100% sensitivity and 41.7% specificity for an association with TdP history. In the 22 (68.8%) LQTS patients with TWA ≥42 µV, only 2 (median; interquartile range, 1–3) leads exhibited TWA ≥42 µV. Highest TWA levels were recorded in precordial leads (V1–V6) in 30 (93.8%) patients, most frequently in lead V2 (43.8%). A single ECG lead detected only ≤63.6% of TWA ≥42 µV episodes, whereas the combined leads V2 to V5 detected 100% of TWA ≥42 µV.

Conclusions—Microvolt TWA is far more prevalent in LQTS patients than previously reported and is strongly associated with TdP history. TWA should be monitored from precordial leads in LQTS patients. The use of a limited set of ECG leads in conventional monitoring has led to underestimation of TWA and its association with TdP.

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WHAT IS KNOWN

• Macroscopic T-wave alternans (TWA) is not only one of the diagnostic criteria for long QT syndrome (LQTS) but is also a marker of risk for cardiac events.
• Previous clinical studies on the relationship between microvolt TWA and arrhythmia risk in patients with LQTS drew negative conclusions about its significance.

WHAT THE STUDY ADDS

• Automated monitoring of microvolt TWA with the Modified Moving Average method in 24-h continuous 12-lead ECGs identifies a greater prevalence of microvolt TWA episodes and a stronger association with history of torsade de points in LQTS patients than has been previously reported.
• Microvolt TWA is narrowly distributed in the precordial leads in LQTS patients. Thus, use of a limited set of ECG leads in conventional monitoring has led to underestimation of TWA and its association with torsade de points.

performed in 27 patients at National Cerebral and Cardiovascular Center (Osaka, Japan). Twenty-six of the 27 patients were genotyped: LQT1 (n=18), LQT2 (n=4), and LQT3 (n=4). Unidentified LQTS (n=6) included 1 patient with non-1, non-2, non-3 LQTS, 1 patient awaiting genetic test result and 4 patients who did not agree to undergo genetic testing. All unidentified LQTS patients fulfilled the diagnostic criteria for LQTS (score ≥24).14 Average heart rate of 24 hours was automatically calculated. The maximum QT interval within the first minute of supine rest was taken as the index value. The QT interval was automatically measured in lead II or V_{1}, whichever was longer) every 15 s using MARS Holter Analysis Workstation Software Version 8 (GE Healthcare, Milwaukee, WI). Bazett formula was then applied using the averaged R–R interval, which was automatically computed every 15 s. Exclusion criteria were the presence of atrial fibrillation or high-grade atrioventricular block.

Ten healthy subjects were enrolled with the following exclusion criteria: chest symptoms, medication therapy, abnormal resting 12-lead ECG, known cardiovascular disease, sudden death in family history, history of syncope, and current participation in another clinical trial. The LQTS patients were enrolled between December 2012 and February 2014, and the healthy control subjects were enrolled between September and November 2015 at Gifu University Hospital and Gifu Prefectural General Medical Center (Gifu, Japan). This study was approved by the Ethics Committee of Gifu University Hospital, and written informed consent was obtained from all participants.

Measurement of TWA

All participants underwent 24-hour continuous 12-lead ECG recording (SEER 12 Ambulatory Recorder; GE Healthcare). Careful skin preparation and high-resolution electrodes (Blue Sensor L; Ambu A/S, Ballerup, Denmark) were used to minimize noise. Microvolt TWA values were calculated by the time-domain Modified Moving Average (MMA) method using MARS Holter Analysis Workstation Software version 8 (GE Healthcare). The MMA method has been described in detail.13 In brief, a stream of beats is divided into odd and even bins, and the morphology of the beats in each bin is averaged over a few beats successively to create a moving average complex. Average morphologies of both the odd and even beats are continuously updated by a weighting factor of 1/8 of the difference between the ongoing average and the new incoming beats. TWA is computed as the maximum difference in amplitude between the odd-beat and the even-beat average complexes from the J point to the end of the T wave for each 15-s beat stream. TWA values at heart rates >120 beats per minute or those with noise levels >20 μV were excluded from the analysis. The data were visually inspected and scored by 1 cardiologist who was blinded to the patient information.

Peak TWA was determined and used for analysis of an association with TdP even if the TWA episodes lasted for <1 min, as is standard for the MMA method. This approach is in agreement with the determination of Kaufman et al17 that nonsustained TWA carries predictive value. Then, TWA values in the other 11 leads at the time of peak TWA were also measured in each LQTS patient. The lead with the peak TWA values was termed the highest lead. In LQTS patients with TWA ≥42 μV, the sensitivity for detecting TWA ≥42 μV was evaluated in each of the 12 leads.

Statistical Analysis

Statistical analyses were performed using EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), which is a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria). Diagnostic performance of microvolt TWA was assessed by receiver-operating characteristic curve analysis, and the cut point TWA value for associations with TdP history was determined via Youden’s index. Continuous variables were presented as median (interquartile range). Comparisons between 2 groups were performed using the Mann–Whitney U test. Differences between 3 groups were assessed using Kruskal–Wallis test. If the differences were significant, the post hoc Steel–Dwass test was performed for multiple comparisons. Categorical variables were summarized as frequencies and percentages and were compared by Fisher’s exact test. The P values for pairwise group comparisons were adjusted for multiplicity by use of the Holm method. All significance tests were 2 sided. Results were considered statistically significant when the P value was <0.05.

Results

Patient Characteristics

The clinical characteristics of the 32 LQTS patients with types 1 (LQT1, n=18), 2 (LQT2, n=4), 3 (LQT3, n=4), and unidentified (n=6) are summarized in Table 1. The patients were divided into 2 groups: 8 patients with a history of TdP (TdP group) and 24 without (non-TdP group). The clinical characteristics of the 2 groups and healthy controls are shown in Table 2. β-Blocker use rate was significantly higher in the TdP group than in the non-TdP group (87.5% versus 41.7%; P=0.04). There were no significant differences in other clinical characteristics of LQTS patients comparing TdP and non-TdP groups at the time of microvolt TWA test. TWA ≥42 μV, which was observed in none of the healthy subjects and in all 8 LQTS patients with a history of TdP, characterized 22 (68.8%) of the 32 LQTS patients studied (Table 3).

Peak TWA Values in Healthy Subjects and Comparison With LQTS Patients

No healthy subjects exhibited visible macroscopic TWA or TWA ≥42 μV. Peak TWA values in healthy subjects were significantly lower than those in LQTS patients (median [interquartile range], 30 [26–37] versus 55 [39–73.5] μV; P<0.001).

Peak TWA Values and Hourly Distribution of Peak TWA in LQTS Patients

Peak TWA values among all of the 32 LQTS patients were the highest in lead V_{2} (36.5 [17.0–58.0] μV) and the second
Takasugi et al  Prevalence of TWA in LQTS and Association With TdP

Table 1. Patient Characteristics

<table>
<thead>
<tr>
<th>Group</th>
<th>Total</th>
<th>LQT1</th>
<th>LQT2</th>
<th>LQT3</th>
<th>Unidentified LQT Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients (n)</td>
<td>32</td>
<td>18</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Families (n)</td>
<td>27</td>
<td>15</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Age, y</td>
<td>13 (11–17.5)</td>
<td>13 (11–14)</td>
<td>11.5 (5.5–12.5)</td>
<td>21 (7.5–35.5)</td>
<td>61 (47–76)</td>
</tr>
<tr>
<td>Men, n (%)</td>
<td>13 (40.6)</td>
<td>8 (44.4)</td>
<td>1 (25)</td>
<td>2 (50)</td>
<td>2 (33.3)</td>
</tr>
<tr>
<td>Women, n (%)</td>
<td>19 (59.4)</td>
<td>10 (55.6)</td>
<td>3 (75)</td>
<td>2 (50)</td>
<td>4 (66.7)</td>
</tr>
<tr>
<td>QTc interval, ms</td>
<td>499 (472–529.5)</td>
<td>487 (466–507)</td>
<td>523 (509–535)</td>
<td>512 (440.5–603.5)</td>
<td>500 (476–542)</td>
</tr>
<tr>
<td>Symptomatic, n (%)</td>
<td>11 (34.4)</td>
<td>2 (11.1)</td>
<td>1 (25)</td>
<td>2 (50)</td>
<td>4 (66.7)</td>
</tr>
<tr>
<td>TdP (n)</td>
<td>8 (25)</td>
<td>2 (11.1)</td>
<td>1 (25)</td>
<td>1 (25)</td>
<td>4 (66.7)</td>
</tr>
<tr>
<td>Syncope (n)</td>
<td>11 (34.4)</td>
<td>3 (16.7)</td>
<td>1 (25)</td>
<td>2 (50)</td>
<td>5 (83.3)</td>
</tr>
<tr>
<td>Family history, n (%)</td>
<td>15 (46.9)</td>
<td>8 (44.4)</td>
<td>1 (25)</td>
<td>4 (100)</td>
<td>1 (16.7)</td>
</tr>
<tr>
<td>Sudden death (n)</td>
<td>5 (15.6)</td>
<td>4 (22.2)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1 (16.7)</td>
</tr>
<tr>
<td>LQTS (n)</td>
<td>13 (40.6)</td>
<td>8 (44.4)</td>
<td>1 (25)</td>
<td>4 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>ICD, n (%)</td>
<td>4 (12.5)</td>
<td>1 (5.6)</td>
<td>0 (0)</td>
<td>1 (25)</td>
<td>2 (33.3)</td>
</tr>
<tr>
<td>Medication, n (%)</td>
<td>22 (68.8)</td>
<td>11 (61.1)</td>
<td>4 (100)</td>
<td>3 (75)</td>
<td>3 (50)</td>
</tr>
<tr>
<td>β-Blocker</td>
<td>17 (53.1)</td>
<td>11 (61.1)</td>
<td>2 (50)</td>
<td>1 (25)</td>
<td>3 (50)</td>
</tr>
<tr>
<td>Propranolol (dose range, 20–60 mg)</td>
<td>7 (21.9)</td>
<td>3 (16.7)</td>
<td>2 (50)</td>
<td>1 (25)</td>
<td>1 (16.7)</td>
</tr>
<tr>
<td>Atenolol (dose range, 25–50 mg)</td>
<td>5 (15.6)</td>
<td>5 (27.8)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Bisoprolol (dose range, 1.25–5 mg)</td>
<td>4 (12.5)</td>
<td>2 (11.1)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (33.3)</td>
</tr>
<tr>
<td>Carvedilol (dose, 25 mg)</td>
<td>1 (3.1)</td>
<td>1 (5.6)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Mexiletine (dose range, 30–300 mg)</td>
<td>5 (15.6)</td>
<td>0 (0)</td>
<td>3 (75)</td>
<td>2 (50)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Values are presented as median (interquartile range). ICD indicates implantable cardioverter defibrillator; LQTS, long QT syndrome; and TdP, torsade de pointes.

highest in lead $V_3$ (32.5 [19.5–41.5] μV; Figure 1A). Hourly distribution of peak TWA in a 24-hour period is shown in Figure 1B. The incidence of peak TWA was higher during daytime (8:00–20:00) than during nighttime (20:00–8:00) in LQT1 patients, whereas all the peak TWA episodes were distributed during nighttime in LQT3 patients.

Association of TWA With TdP History in LQTS Patients

Eight (25%) of the 32 LQTS patients enrolled had a history of TdP. The association of TdP with a history of TdP in LQTS patients was assessed with receiver-operating characteristic curve analysis. The area under the receiver-operating characteristic curve was 0.61 (95% confidence interval, 0.41–0.82). The cut point TWA value of 42 μV with a sensitivity of 100% (95% confidence interval, 51.8–100) and a specificity of 41.7% (95% confidence interval, 22.1–63.4) was derived using Youden’s index. The group results for characteristics associated with TdP history including TWA ≥42 μV are shown in Table 3. There was no significant difference in peak TWA value between the TdP group and the non-TdP group. However, the TdP group exhibited a significantly higher incidence of TWA ≥42 μV than the non-TdP group (100% versus 58.3%; $P=0.04$). The median duration of peak TWA ≥42 μV was 15 s (interquartile range, 15–30 s; minimum–maximum, 15–45 s). One or more episodes of TWA ≥42 μV were observed in the same region of the heart at different times of the day in 16 (72.7%) of the 22 LQTS patients with TWA ≥42 μV.

Figure 2 shows representative continuous 12-lead ECGs with visible TWA in a 2-year-old boy with LQT1 (Figure 2A) and a 58-year-old woman with LQTS (Figure 2B) with a history of TdP whose LQT type could not be identified. TWA ≥42 μV was narrowly distributed in the precordial leads. Specifically, visible TWA of 56 μV in lead $V_2$ (Figure 2A) and of 44 and 54 μV in leads $V_5$ and $V_6$, respectively (Figure 2B), are marked with arrows.

Continuous 12-lead ECG of an 8-year-old boy with LQT3 with frequent episodes of TdP is shown in Figure 3. In this patient, a total of 112 episodes of macroscopic TWA with beat-to-beat alternating polarity of the T wave, that is, T-wave polarity alternans (TWA), were recorded. However, all of the episodes of TWA were overlooked because of technical problems of MARS Holter Analysis Workstation Software version 8. By visual estimation, the amplitude of TWA was ≥5000 μV (Figure 3), but the peak TWA value automatically generated by MARS version 8 Software was 611 μV, a significant underestimation. In some TWA episodes, the dynamics of TWA, that is, the time of onset, peak, and termination of the alternans, varied from region to region, suggesting that alternation in polarity is a regionally independent property of TWA (Figure 3).

At this time, 3 LQTS patients have experienced TdP since enrollment (at 28, 44, and 463 days after TWA testing, respectively), and all 3 exhibited TWA ≥42 μV at the time of joining the study.

Distribution of the Lead With the Highest TWA Level in LQTS Patients

Figure 4 represents the distribution of highest lead among all 32 LQTS patients enrolled (Figure 4A) and in the 22 LQTS patients with TWA ≥42 μV (Figure 4B). In the group as a whole, the most frequent highest lead was $V_1$ in 14 (43.8%) LQTS patients. Highest lead was distributed in the precordial leads $V_1$ through $V_4$ and...
V6 in 30 (93.8%) LQTS patients (Figure 4A). Similarly, in the 22 LQTS patients with TWA ≥ 42 µV, the most frequent highest lead was V2 in 11 (50%) LQTS patients. Highest lead was distributed in the precordial leads V2 through V4 and V6 in 20 (90.9%) LQTS patients with TWA ≥ 42 µV (Figure 4B).

Sensitivity for TWA ≥ 42 µV Detection in Each Lead in LQTS Patients

In the 22 LQTS patients with TWA ≥ 42 µV, the median number of ECG leads with TWA of this level was only 2 (interquartile range, 1–3; minimum–maximum, 1–7). There was no significant difference in the number of ECG leads with TWA ≥ 42 µV comparing the TdP and the non-TdP groups (Table 3). The sensitivity for TWA ≥ 42 µV detection using a single ECG lead was the highest (63.6%) in lead V2 (Figure 5). By contrast, combined leads V2 through V5 detected 100% of the TWA ≥ 42 µV episodes.

Discussion

In the present study, we demonstrated that TWA ≥ 42 µV was found in 68.8% of all LQTS patients enrolled and in 100% of LQTS patients with a history of TdP, whereas none of the healthy subjects exhibited TWA ≥ 42 µV. Microvolt TWA ≥ 42 µV is narrowly distributed in the precordial leads (median, 2 ECG leads) in LQTS patients. Indeed, the sensitivity for TWA detection using a single ECG lead was 63.6% at maximum in lead V2, whereas the combined leads V2 through V5 detected 100% of the ≥ 42 µV TWA episodes.

Table 3. Association of ECG Characteristics With Torsade de Pointes

<table>
<thead>
<tr>
<th>Group</th>
<th>H (n=10)</th>
<th>T (n=8)</th>
<th>N (n=24)</th>
<th>PValue</th>
<th>Group Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average heart rate of 24-h, beats per minute</td>
<td>78 (69–86)</td>
<td>65.5 (58.5–73.5)</td>
<td>70 (65.5–76.5)</td>
<td>0.05*</td>
<td>NA</td>
</tr>
<tr>
<td>Notched T wave, n (%)</td>
<td>2 (20)</td>
<td>7 (87.5)</td>
<td>13 (54.2)</td>
<td>0.02*</td>
<td>H&lt;T (P=0.046‡)</td>
</tr>
<tr>
<td>Peak TWA without TWPA, µV</td>
<td>30 (26–37)</td>
<td>55 (46–79)</td>
<td>53.5 (36–73.5)</td>
<td>&lt;0.001*</td>
<td>H&lt;T (P&lt;0.001§); H&lt;N (P=0.001§)</td>
</tr>
<tr>
<td>TWPA episodes, n (%)</td>
<td>0 (0)</td>
<td>2 (25)</td>
<td>2 (8.3)</td>
<td>0.19*</td>
<td>NA</td>
</tr>
<tr>
<td>TWA ≥ 42 µV, n (%)</td>
<td>0 (0)</td>
<td>8 (100)</td>
<td>14 (58.3)</td>
<td>&lt;0.001*</td>
<td>H&lt;T (P&lt;0.001‡); H&lt;N (P=0.003‡); T&gt;N (P=0.04¶)</td>
</tr>
</tbody>
</table>

Values are presented as median (interquartile range). H indicates healthy control; LQTS, long QT syndrome; N, non–torsade de pointes; NA, not applicable; T, Tdp; and Tdp, torsade de pointes.

*P values compare 3 groups.
†P values compare TdP with non-TdP patients.
‡P values adjusted by the Holm method.
§P values determined by the Steel–Dwass test.
Macroscopic TW A was reported to be a risk marker for cardiac events. In addition, several case reports demonstrated a direct link between macroscopic TW A and TdP, as reported in the study by Kaufman et al. Later, Kaufman et al demonstrated that unsustained TW A lasting <1 min carries predictive value in patients with left ventricular dysfunction.

Furthermore, in these 3 studies, TWA testing was performed during a cardiac stress test: exercise or catecholamine-provocation. It has been reported that only 13% of cardiac events occurred during exercise in patients with LQTS and 3. Moreover, only 427 of 1325 (32.2%) LQTS patients experienced their first cardiac events during acute arousal caused by exercise, swimming, emotion, or noise. In the present study, all the episodes of peak TWA in LQT3 patients were recorded during nighttime. These facts suggest that TWA in some of the patients with LQT3, as in the Brugada syndrome, may be rate suppressed.

These facts underscore the benefit of multilead precordial continuous ECG recordings during daily activities for TWA monitoring in LQTS patients. This approach is particularly appropriate for infants or young children, who are an important group for LQTS screening but who cannot undergo an exercise stress test. Indeed, in the study by Kaufman et al., more than half of the patients studied could not undergo microvolt TWA testing during exercise stress.

In the present study, we used the time-domain MMA method for continuous microvolt TWA monitoring during daily activities. The templates of superimposed complexes provided by the MMA technology allow the clinician to confirm the transient surges in TWA of ≥20 µV that may dis-appear within 1 minute in LQTS patients and thus may be missed during routine review.

Regional Specificity of TWA in LQTS Patients

Information about regional distribution of TWA in LQTS patients is sparse. In the present study, we demonstrated that the distribution of TWA is narrowly localized in a median of 2 (interquartile range, 1–3; minimum–maximum, 1–7) ECG leads and is frequently recorded in the precordial leads. Moreover, in our patient with LQT3, TWA exhibited striking regionally independent dynamics (Figure 3).

The usefulness of microvolt TWA testing using simplified 2- or 3-lead ambulatory ECG recordings in risk stratification...
Figure 2. A. Twelve-lead electrocardiogram from a representative case (12-year-old boy) with long QT syndrome (LQTS) type 1, a history of torsade de pointes, and microvolt T-wave alternans (TWA). Left. Templates of superimposed waveforms in each lead at the time of peak TWA. Peak TWA of 56 µV was visible in lead V2 (indicated by red and blue arrows). TWA ≥42 µV could be detected only in lead V2. B. Representative 12-lead electrocardiogram exhibiting TWA in a 58-year-old woman with LQTS but in whom the subtype was not identified. Left. Templates of superimposed waveforms in each lead at the time of peak TWA (54 µV) in lead V6. Red and blue arrows indicate TWA ≥42 µV detected only in leads V5 and V6.
for arrhythmic events in patients with ischemic/nonischemic cardiomyopathy has been established in several clinical studies. It is possible that patients with cardiomyopathy have widespread myocardial damage, and thus the simplified 2- or 3-lead ECG recorder is sufficient to detect TWA, which may be distributed extensively. By contrast, the regionally specific nature of TWA has been reported in the setting of acute myocardial ischemia. In this context, TWA appears in the ischemic zone, probably because myocardial damage is localized in the ischemic area, whereas the rest of the myocardium is normal. Thus, TWA may be more narrowly distributed in patients with acute myocardial ischemia than in those with cardiomyopathy.

A potential explanation for the regionally independent dynamics or narrow distribution of TWA is that the preceding diastolic interval, that is, the TQ interval, plays an important role in the initiation, maintenance, and termination of TWA. Gettes et al demonstrated that premature impulse with a diastolic interval >150 ms did not shorten the action potential duration (APD), whereas a significant abbreviation occurred when the diastolic interval lasted <150 ms in the isolated ventricular fiber of pig heart. We hypothesized that the APD of some myocardial layers in the anterior chest area may be longer than in other regions in LQTS patients. The postulated mechanism of the regional specificity of TWA in LQTS patients is illustrated in Figure 6. When an abrupt increase in heart rate occurs (beat ≈3) in site A with the shortest baseline APD, beat 3 with a sufficiently long preceding diastolic interval does not shorten the APD. On the contrary, in site C with

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**Figure 3.** Twelve-lead electrocardiogram of a patient with the long QT syndrome showing an episode of macroscopic T-wave alternans (TWA) with regionally independent dynamics. Note that the dynamics of TWA in terms of onset, peak, and termination time varied regionally.

**Figure 4.** A, Distribution of highest T-wave alternans (TWA) levels in each lead in the group of 32 patients with long QT syndrome (LQTS). The most frequent highest lead was V2 in 14 (43.8%) patients. Peak TWA appeared frequently in the precordial leads in 30 (93.8%) patients. B, Distribution of highest lead in the 22 patients with microvolt TWA ≥42 µV. The most frequent highest lead was V2 in 11 (50%) patients. Highest lead was distributed in the precordial leads V2 through V4 and V6 in 20 (90.9%) patients.
the longest baseline APD, beat 3 with a very short preceding diastolic interval behaves as a premature beat and results in a shortening of the APD. This shortening, in turn, results in a prolongation of the following diastolic interval. Thus, beat 4 behaves like a nonpremature impulse and its APD returns to the baseline. This again shortens the following diastolic interval, and the process repeats until heart rate is reduced. Therefore, APD alternans, that is, TWA, occurs only in the regions with disproportionately long APD relative to heart rate.

Medications and Microvolt TWA
β-adrenergic blocking agents were used significantly more frequently in the TdP group than in the non-TdP group. This difference may have contributed to the absence of significant differences in peak TWA values in the 2 groups. TWA amplitude is reduced by antiarrhythmic agents such as metoprolol and β-l-sotalol in patients with a history of documented or suspected ventricular tachyarrhythmias. Case reports provide evidence that β-blockade also reduces TWA in parallel with arrhythmias in LQTS patients. It will be worthwhile to evaluate in a prospective study whether these observations characterize LQTS patients as a whole.

Limitations
First, our sample size was too limited to allow multivariate analysis to determine an independent relationship between TWA and TdP history although a significant association was demonstrated. Second, the Holter Analysis Workstation Software, MARS version 8, may overlook millivolt-level TWA, which is macroscopic, including TWPA. However, it is highly possible that LQTS patients with prominent millivolt-level TWA have more frequent episodes of microvolt-level TWA, as did our patient who exhibited peak microvolt-level TWA of 611 µV, which was automatically calculated by MARS. In this patient, all episodes of prominent TWA or TWPA were preceded by microvolt-level TWA when they were initiated by gradual R–R interval shortening. Third, we derived and used a cut point of 42 µV for an association with TdP history; this level varies from the 47-µV cut point recommended for assessing arrhythmia risk in patients with cardiovascular disease and may relate to the particular genetic basis for TdP in this highly arrhythmogenic syndrome. We noted that in all 3 LQTS patients who experienced TdP after enrollment, TWA met the 42-µV cut point. Fourth, TWA testing was not performed on multiple occasions to assess reproducibility of the findings; however, multiple episodes of TWA ≥42 µV were observed in the same region of the heart at different times of day in >70% of the LQTS patients with TWA ≥42 µV. Fifth, body position might have had a non-negligible effect on the lead distribution of TWA in freely moving subjects. Finally, clinical considerations dictated initiation of β-blockade or changes in medications after TWA testing in our LQTS patients. Thus, it was not possible to determine whether in the absence of therapy, TWA would have predicted arrhythmic events in the present study.

Conclusions
Automated monitoring of microvolt TWA identifies a greater prevalence of microvolt TWA episodes and a stronger association with TdP history in patients with LQTS than has been previously reported. Microvolt TWA is narrowly distributed and more common in the precordial leads than in other leads in patients with LQTS. Multilead ambulatory ECGs including precordial leads V2 through V5 should be used to avoid underestimating TWA, which may be a risk marker for TdP. The high prevalence of TWA in the precordial leads may provide insights into mechanisms.

Disclosures
Dr Verrier receives royalty income from Georgetown University and Beth Israel Deaconess Medical Center for intellectual property on the Modified Moving Average method of T-wave alternans analysis, which has been licensed by GE Healthcare and was used in this study. The other authors report no conflicts.
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