Analysis of 12-Lead T-Wave Morphology for Risk Stratification After Myocardial Infarction

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Background—The stratification of post–myocardial infarction (MI) patients at risk of sudden cardiac death remains important. The aim of the present study was to assess the prognostic value of novel T-wave morphology descriptors derived from resting 12-lead ECGs.

Methods and Results—In 280 consecutive post-MI patients, a 12-lead ECG was recorded before discharge, optically scanned, and digitized. For the present study, 5 T-wave morphology descriptors were automatically calculated after singular value decomposition of the ECG signal. The total cosine R-to-T (TCRT [describes the global angle between repolarization and depolarization wavefront]) and the T-wave loop dispersion were univariately associated ($P=0.0002$ and $P<0.002$, respectively, $U$ test) with 27 prospectively defined clinical events in 261 patients (mean follow-up $32\pm10$ months). Kaplan-Meier event probability curves for strata above and below the median confirmed the strong risk discrimination by TCRT and T-wave loop dispersion ($P<0.003$ and $P<0.001$, respectively, log-rank test). On Cox regression analysis, with the entering of age, left ventricular ejection fraction, heart rate, QRS width, reperfusion therapy, $\beta$-adrenergic–blocker treatment, and standard deviation of R-R intervals on 24-hour Holter monitoring, TCRT ($P<0.03$) yielded independent predictive value, whereas T-wave loop dispersion was of borderline independence ($P=0.064$). Heart rate ($P<0.02$), left ventricular ejection fraction ($P<0.02$), and reperfusion therapy ($P<0.02$) also remained in the final model.

Conclusions—Computerized T-wave morphology analysis of the 12-lead resting ECG permits independent assessment of post-MI risk and an improved risk stratification when combined with other risk markers. (Circulation. 2000;102:1252-1257.)

Key Words: myocardial infarction ■ death, sudden ■ risk factors ■ waves ■ electrocardiography

The noninvasive identification of individuals at risk for sudden cardiac death still presents a significant clinical dilemma. Lately, interest has focused on ECG T-wave heterogeneity, reflecting a dispersion of myocardial repolarization, which may facilitate ventricular tachycardia (VT) or fibrillation (VF). Although a variety of studies have assessed QT variability, QT dispersion (QTD), repolarization alternans$^9$, $^{10}$ have shown promise for VT risk stratification and are being evaluated in large controlled trials. However, none of these approaches embodies combined the temporospatial features of repolarization dispersion.

We hypothesized that composite temporospatial measures of ECG repolarization dispersion would improve risk stratification for post–myocardial infarction (MI) ventricular arrhythmias and sudden cardiac death in comparison with stratifiers such as QTD, left ventricular ejection fraction (LVEF), or thrombolytic therapy. In particular, we applied recently developed novel quantitative repolarization analyses that are accessible from a single ECG beat.$^{11}$ The total cosine R-to-T (TCRT) reflects the spatial angle between depolarization and repolarization, akin to the venerable concept of the ventricular gradient.$^{12}$ T-wave loop dispersion extends this concept, reflecting variability of the T-wave vector loop. The normalized T-wave loop area measures heterogeneity of principal components of the T wave within its loop, whereas T-wave morphology dispersion expresses morphological heterogeneity within the 12-lead ECG. Conceptually similar but distinct examinations of repolarization complexity were recently successful in stratifying arrhythmic risk in the long QT syndrome$^{13}$ and arrhythmogenic right ventricular dysplasia.$^{14}$

We therefore set out to determine the usefulness of our analyses in temporospatial dispersion for the stratification of arrhythmic risk and death in a series of prospectively studied post-MI patients.$^{15}$ This analysis resulted in a surprisingly
powerful accuracy of the prediction of cardiac mortality from the 12-lead resting ECG.

Methods

Patient Population and ECG Recordings
For the present study, the digital ECG recordings of a recently published prospective study on the prognostic value of QTD were reevaluated with the new T-wave morphology analysis. Characteristics of the patient group have been described elsewhere. In brief, 280 consecutive patients (229 men and 51 women, mean age 58±11 years) were enrolled into the study 9±3 days after their index MI. Twelve-lead resting surface ECGs were recorded with a paper speed of 50 mm/s and converted into digital ECGs with a customized method that involved scanning, editing of the resulting image file, and digitization at 1 kHz by means of a custom-written Labview program. For each ECG, the digital signal of 1 beat of each lead was used in this study.

T-Wave Morphology Descriptors
Analysis of the digital ECG recordings was performed in a fully automatic manner with a custom-developed software implemented on a personal computer. The study was conducted in a strictly blinded manner: digital ECGs were sent from Germany to London for processing without any clinical data. The analytical results were returned to the German center as an unlabeled numerical spreadsheet. Only after completion of the statistical analyses were the German center workers given the description of the analytical procedures.

The analysis program performs a singular value decomposition of the ECG signal into a minimum dimensional space. From singular value components, principal component analysis (PCA) was performed as recently described. Complexity ratio (CR) was the ratio of the singular value of the second most significant component to the square root of the sum of the squares of all 8 singular values.

Based on the decomposition, several descriptors were calculated (Figure 1). The so-called T-wave loop dispersion measures the variation of the ECG vector (ie, the variation of the interlead relations among domain of interlead relations spanned by the ECG vector). This variable is unitless; its maximum value is 100. (2) The so-called normalized T-wave loop area describes the shape and irregularity of the T-wave loop by expressing its area as a fraction of the rectangle that encompasses the loop. The variable is unitless. (3) The so-called TCRT measures the vector deviation between the depolarization and repolarization waves by calculating cosine values between the 3-dimensional R- and T-wave loop vectors within the optimized decomposition space. Negative values correspond to large differences in the orientation of the 2 loops. The variable is unitless. (4) The so-called T-wave morphology dispersion expresses the dissimilarities between the T-wave shapes in individual leads, based on the differences between reconstruction vectors of individual ECG leads created from the 3-dimensional T-wave loop. It is calculated as the average of angles between all possible pairs of reconstruction vectors. A small value indicates that reconstruction vectors are close to each other, indicating similar T-wave morphology between leads.

The fully automatic processing ensures 100% reproducibility of all variables for any given ECG. For serial ECGs in the same subject, a high reproducibility, of up to 99.7%, was previously reported.

Follow-Up
Follow-up data and information on clinical end points were unchanged from the initial publication of the same post-MI patient group. The prospectively defined primary end point combined all-cause mortality, sustained VT, and resuscitated VF. The secondary end points consisted of arrhythmic events: sudden cardiac death, documented sustained VT, and resuscitated VF.

Figure 1. Schematic 3-dimensional view of QRS and T-wave vector loops. Main vectors of 2 loops are depicted by arrows, and angle between them is shown (determines TCRT). Bottom left, T-wave loop is shown in 2-dimensional plane with axes U1 and U2. A rectangle encompasses loop in this plane and is divided into 100 subdivisions. In this example, loop passes 35 marked subdivisions; thus, T-wave loop dispersion is 35. Normalized T-wave loop area is calculated as fraction of loop area (marked by stripes) of encompassing rectangle. Bottom right, reconstruction vectors of different ECG leads onto T-wave loop. T-wave morphology dispersion is calculated by averaging angle between all possible reconstruction vector pairs. Angle between V4 and V6 reconstruction vectors is shown in figure. See Methods for more detailed explanation.

Statistical Analysis
Statistical evaluation was processed independent of the T-wave analyses. For comparison, the results for conventional QTD variables (QRS width, QTD, JT dispersion, T peak-to-end interval, area under the T wave), for other risk stratifiers (SDNN from Holter recordings, LVEF), and for clinical variables (age, reperfusion therapy, ß-blocker treatment, heart rate from the study ECG) were taken from the previous study of this cohort.

Data were analyzed with SPSS Version 7.0 for Windows for Cox regression analyses and JMP-3.1 software (SAS Institute) for all other statistics. Continuous variables are reported as mean±SD. Comparisons between patients with and without events during follow-up were performed by the nonparametric U test. Pearson’s correlations between ECG and clinical variables was tested by a x² test. Kaplan-Meier event probability curves were computed, with patient groups stratified according to the median value of the respective variable. The cumulative probability of events of 2 patient groups was compared by the log-rank test. The independent correlation of multiple variables with the timing of events during follow-up as the dependent variable was determined by Cox regression analysis. Because of the strong correlation of left bundle-branch block
TABLE 1. Overview of Clinical Variables in Patients With and Without Primary Events During Follow-Up

<table>
<thead>
<tr>
<th>Variable</th>
<th>Negative (n=234)</th>
<th>Positive (n=27)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>58±11</td>
<td>65±8</td>
<td>&lt;0.004</td>
</tr>
<tr>
<td>HR, bpm</td>
<td>68±11</td>
<td>75±15</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>LVEF</td>
<td>48±11</td>
<td>39±13</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>SDNN, ms</td>
<td>98±42*</td>
<td>72±25†</td>
<td>&lt;0.004</td>
</tr>
<tr>
<td>β-Blockers, n (%)</td>
<td>196 (84)</td>
<td>18 (67)</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Reperfusion therapy, n (%)</td>
<td>129 (55)</td>
<td>6 (22)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*LBBB (n=99, fn=24).

HR=heart rate, LVEF=left ventricular ejection fraction, SDNN=standard deviation of RR intervals on 24 h Holter.

Clinical Events

During a 32±10-month follow-up, 20 patients died (10 of sudden cardiac death, 5 of pump failure, 5 of noncardiac causes). Sustained VT was noticed in 5 patients, and 2 patients were resuscitated from VF. According to the prospective criteria, a total of 27 of 261 patients reached the primary end point. The secondary end point (arrhythmic events) was met in 17 patients. Of 9 patients with LBBB, 4 reached a primary end point, including 3 arrhythmic events. Table 1 shows the relationships of clinical variables included in the multivariate analysis to the occurrence of primary end points.

T-Wave Morphology Analysis: Correlations With Conventional QTD Variables and Clinical Data

Pearson’s correlation coefficients were determined for pairs of T-wave morphology variables. All r values were <0.25 and thus of no clinical relevance. Specifically, TCRT and T-wave loop dispersion were unrelated (r=0.11, P=NS). For pairs with conventional QTD variables and QRS width, an intermediate inverse relationship with the average area under the T wave was found for CR (r=-0.40, P<0.001). Patients with LBBB (n=9) had TCRT of −0.77±0.25, whereas patients without LBBB (n=252) had an average TCRT of 0.11±0.12 (P=0.005). T-wave loop dispersion exhibited a borderline difference related to LBBB (33±4 with LBBB versus 35±5 without LBBB, P=0.044), whereas all other T-wave variables were not influenced by LBBB. All other correlations were not practically relevant, including several significant r values between 0.17 and 0.25. Right bundle-branch block was not associated with the T-wave morphology variables. Moreover, none of the continuous clinical variables, including heart rate, age, SDNN from Holter, and LVEF, were related to the T-wave morphology variables. This was also true for other clinical variables, such as sex, use of reperfusion therapy, β-blocker treatment, or infarct location.

T-Wave Morphology Analysis: Univariate Prognostic Information

Of 280 ECGs, 19 were excluded due to insufficient data quality or missing leads. Tables 2 and 3 summarize the values for T-wave morphology variables for 27 patients with events compared with 234 event-free patients. Tables 2 and 3 also show the same comparison between 17 patients with and 244 patients without arrhythmic events. CR exhibited paradoxically lower rather than theoretically expected higher values in the event group, with a borderline significance (P<0.07). The comparison for patients with and without arrhythmic events was not significant. TCRT was lower in the patient group with events (P<0.0002) and in patients with arrhythmic events (P<0.004). Similarly, T-wave loop dispersion was lower in patients with primary end points (P<0.002) and arrhythmic events (P<0.003). No difference was found for T-wave morphology dispersion and normalized T-wave loop area.

T-Wave Morphology Analysis: Kaplan-Meier Event Probabilities

Patients with a TCRT below the median had decreased survival (P<0.003, Figure 2A) and a higher incidence of arrhythmic events (P<0.007). The median value of T-wave loop dispersion also discriminated patients at risk of overall end points (P<0.001, Figure 2B) and arrhythmic events (P<0.004). CR, T-wave morphology dispersion, and normalized T-wave loop area did not result in different Kaplan-Meier event probabilities. In an analysis of the patients without LBBB (n=252), the results were similar with TCRT (P=0.022 and P<0.04, respectively, for primary and arrhythmic end points) and T-wave loop dispersion (P=0.003 and P<0.014, respectively).

TABLE 2. T-Wave Morphology Variables for Patients With and Without Primary Events During Follow-Up

<table>
<thead>
<tr>
<th>Variable</th>
<th>Primary End Points</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Patients (n=261)</td>
<td>Patients Without LBBB (n=252)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Negative (n=234)</td>
<td>Positive (n=27)</td>
<td>Negative (n=234)</td>
<td>Positive (n=27)</td>
</tr>
<tr>
<td>Complexity ratio</td>
<td>0.26±0.15</td>
<td>0.21±0.13</td>
<td>0.07</td>
<td>0.26±0.15</td>
</tr>
<tr>
<td>T-wave morphology dispersion, °</td>
<td>57.0±27.5</td>
<td>63.7±23.8</td>
<td>NS</td>
<td>56.7±27.4</td>
</tr>
<tr>
<td>TCRT</td>
<td>0.16±0.57</td>
<td>−0.31±0.57</td>
<td>0.0002</td>
<td>0.18±0.56</td>
</tr>
<tr>
<td>Normalized T-wave loop area</td>
<td>0.56±0.16</td>
<td>0.48±0.20</td>
<td>0.031</td>
<td>0.56±0.16</td>
</tr>
<tr>
<td>T-wave loop dispersion</td>
<td>35.6±4.7</td>
<td>32.9±6.2</td>
<td>&lt;0.002</td>
<td>35.7±4.7</td>
</tr>
</tbody>
</table>

*Despite the strong relationship of total cosine R-to-T to LBBB, the univariate relationship with primary end points remains significant for patients without LBBB.
Multivariate Analysis of Risk Factors
Clinical variables (age, reperfusion therapy, LVEF, β-blocker treatment, QRS width, heart rate), Holter parameters (SDNN), and T-wave morphology descriptors (TCRT, T-wave loop dispersion) that were univariately predictive of follow-up end points were entered as independent variables into a Cox regression model with stepwise backward removal (Tables 4 and 5). At least 1 T-wave morphology variable remained in the equation at the last regression step, namely, TCRT for the prediction of primary end points and T-wave loop dispersion for the prediction of arrhythmic events. By entering only univariately predictive T-wave morphology variables into the Cox regression model (TCRT, T-wave loop dispersion, normalized T-wave loop area) and by considering only patients without LBBB (n=252), we showed that T-wave loop dispersion (P=0.009 and P=0.003, respectively) and TCRT (P=0.006 and P=0.07, respectively) were independently predictive of primary end points and arrhythmic events.

Discussion
This post hoc analysis of a prospective study in 280 consecutive post-MI patients demonstrates that novel T-wave morphology descriptors from the 12-lead surface ECG permit the accurate risk stratification of post-MI patients. This was found in a patient population where conventional variables of ventricular repolarization dispersion had failed to discriminate risk. The new variables require digital recording of the ECG but otherwise are readily accessible at the patient’s bedside. On multivariate analysis, ≥1 T-wave morphology descriptor remained in the model, adding independent information to other risk stratifiers such as heart rate, LVEF, and the administration of reperfusion therapy.

Comparison With PCA and Conventional QTD
In a comparison with PCA of the T wave, the proposed T-wave morphology descriptors were superior. At best, PCA yielded borderline significance in the univariate model with stepwise backward removal (Tables 4 and 5).

### TABLE 3. T-Wave Morphology Variables in Patients With and Without Arrhythmic Events During Follow-Up

<table>
<thead>
<tr>
<th>Variable</th>
<th>All Patients (n=261)</th>
<th>Patients Without LBBB (n=252)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Negative (n=244)</td>
<td>Positive (n=17)</td>
</tr>
<tr>
<td>Complexity ratio</td>
<td>0.26±0.15</td>
<td>0.20±0.13</td>
</tr>
<tr>
<td>T-wave morphology dispersion, °</td>
<td>57.3±27.3</td>
<td>63.4±25.6</td>
</tr>
<tr>
<td>TCRT</td>
<td>0.14±0.58</td>
<td>−0.31±0.60</td>
</tr>
<tr>
<td>Normalized T-wave loop area</td>
<td>0.56±0.16</td>
<td>0.50±0.20</td>
</tr>
<tr>
<td>T-wave loop dispersion</td>
<td>35.5±4.9</td>
<td>31.8±4.4</td>
</tr>
</tbody>
</table>

Values are given for patient groups including (n=261) and excluding (n=252) LBBB.

Figure 2. A, Kaplan-Meier event probability curves (primary end points) for patient groups stratified by a TCRT above and below median value (P<0.003 by log-rank test). B, Kaplan-Meier event probability curves (primary end points) for patient groups stratified by a T-wave loop dispersion above and below median value (P<0.001 by log-rank test).
comparison for the prediction of overall events. In contrast, 2 T-wave morphology variables were strong risk predictors for overall or arrhythmic events, confirmed by the calculation of Kaplan-Meier curves. This strong prognostic value contrasts with the disappointing results with conventional QT interval variables\textsuperscript{13} from the same ECGs. A major aspect of the new variables is the technical improvement over QT interval in both reproducibility and measurement objectivity. Importantly, the proposed algorithms do not rely on an accurate T-wave offset measurement, which is the major source of inaccuracy in automatic QT interval measurements.\textsuperscript{16–18} In most studies, however, QTID was analyzed manually, which is even less reliable due to subjective variations in waveform assessment between centers. The intra-subject reproducibility is also improved.\textsuperscript{11}

Pathophysiological Concept of Novel T-Wave Morphology Descriptors
The prognostic content of abnormal repolarization had been suspected because the early experiments demonstrated the role of ventricular repolarization pathologies in the arrhythmogenesis.\textsuperscript{1,19–21} Initially, this concept was followed with the use of body surface potential mapping.\textsuperscript{21–24} QTID from 12-lead ECGs was proposed as a more practical surrogate.\textsuperscript{25} After the initial enthusiastic reports,\textsuperscript{5,6,25–27} meticulous methodological studies\textsuperscript{16,28} and reviews\textsuperscript{28–30} cast doubt on the true value of QTID. Finally, the first truly prospective study in a large post-MI population established that none of the conventional QTID variables carried post-MI prognosis.\textsuperscript{15} Although this finding is contradicted by recent epidemiological studies,\textsuperscript{7,8} a more sophisticated concept of repolarization analysis for the purpose of risk stratification is clearly required.\textsuperscript{31} It was therefore attempted to explore more accurate repolarization qualities from 12-lead surface ECGs, such as PCA\textsuperscript{13,14} and T-wave loop morphology.\textsuperscript{32} or to explore dynamic QT changes on Holter monitoring.\textsuperscript{4,33,34} None of these newer repolarization markers have been tested in a post-MI population. Although PCA had been shown to be predictive in long QT syndrome\textsuperscript{13} and in patients with arrhythmogenic right ventricular dysplasia,\textsuperscript{14} it was not found to be very useful in the present study. Beyond the approach of PCA, Acar et al\textsuperscript{1} developed a set of novel T-wave morphology descriptors to quantify various abnormal temporospatial repolarization indices. With an analysis of these novel T-wave descriptors in a set of prospectively

TABLE 5. Independent Prognostic Value of Risk Stratifiers After Entering All Univariately Predictive Clinical, Holter, and T-Wave Morphology Variables Into a Stepwise Backward Cox Regression Analysis (P Values at Last Regression Step) and With Arrhythmic Events as the Dependent Variable

<table>
<thead>
<tr>
<th>Risk Stratifier</th>
<th>P (all patients, n=261)</th>
<th>P (patients without LBBB, n=252)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reperfusion therapy</td>
<td>0.012</td>
<td>0.008</td>
</tr>
<tr>
<td>T-wave loop dispersion</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>LVEF</td>
<td>0.010</td>
<td>NS</td>
</tr>
<tr>
<td>HR</td>
<td>0.056</td>
<td>NS</td>
</tr>
</tbody>
</table>

to the ventricular gradient introduced by Wilson et al\textsuperscript{15} in 1934 and later expanded with QRST area distributions\textsuperscript{20–24} from body surface mapping. Importantly, with TCRT, the amplitude of depolarization and repolarization processes is not considered, but rather only the difference in their direction is considered and thus represents a modification of the earlier concepts. The variable was found to be associated with LBBB but not with a prolonged QRS duration alone. With or without consideration of LBBB, it proved to be a powerful risk predictor in the present study.

When values for the present post-MI population are compared with the reported normal values,\textsuperscript{11} increased T-wave morphology dispersion and lowered values for TCRT, T-wave loop dispersion, and normalized T-wave area are pathological as such and differentiate event from non-event patients. Although a low TCRT relates to a large deviation between the QRS and T-wave loops, a large T-wave morphology dispersion is associated with increased dissimilarities among the T waves in ECG leads, and a low value of normalized T-wave area as well as T-wave loop dispersion may be explained as arrhythmogenic with a pathologically compressed and narrowed T-wave loop. Furthermore, irregularity of the loop and deviation from an ellipsoid would also result in a decreased normalized T-wave area. Beyond these considerations and due to the novelty of the algorithms used in the present study, they lack a more detailed experimental basis of the electrophysiological mechanisms involved. Although basic research is under way, other approaches to noninvasive risk stratification of arrhythmia substrates, such as PCA, T-wave alternans, or QT variability, likewise fell short of a precise pathophysiological explanation during their clinical evaluation.

Importantly, only very weak relationships between the various novel descriptors and conventional variables of QTID were found, demonstrating that the proposed variables assess as yet undetected qualities of repolarization and do not reproduce or refine the more conventional measurements. Specifically, we could not confirm the result of the study by Kors et al,\textsuperscript{36} which correlated T-wave loop characteristics with QTID in a database of 1220 ECGs.

Comparison With Other Risk Markers
In testing the independent contribution of T-wave morphology descriptors by means of Cox regression, at least 1 T-wave morphology marker provided independent risk stratification. LVEF, heart rate, reperfusion therapy, and, finally, TCRT or T-wave loop dispersion; all added independently to the risk prediction of overall events.

Study Limitations
Although a large post-MI patient population was studied, the overall number of general end points as well as arrhythmic events was low, which reflects the modern treatment strategies. In particular, the statistics with regard to arrhythmic end points should be viewed with this limitation the number of events in more strictly defined subcategories is not sufficient for further detailed comparisons.

The present study was the first attempt to apply detailed T-wave morphology descriptors in a set of prospectively
collected ECG data. Consequently, we have used the same algorithmic settings as in the technical report by Acar et al. It is likely that for the purposes of post-MI risk stratification, the original algorithms that quantify T-wave morphology abnormalities should be further refined. It is also possible that the values of the T-wave morphology variables undergo dynamic changes after MI, particularly during the first year. However, such an influence is not expected to yield a false-positive relationship with outcome but rather would weaken the predictive value of the ECG descriptors.

In terms of other risk variables, we restricted our present investigation to the set of risk factors used in the previous report on this population. Other variables, such as recently described factors of heart rate turbulence, were not considered. It is unlikely, however, that heart rate turbulence would be pathophysically linked to T-wave morphological abnormalities.

**Implications**

The present results are important for future risk stratification studies such as those of prophylactic post-MI treatment. The risk stratifiers proposed represent 2 easily accessible measurements available from a single surface ECG recording. Technically, the algorithms can be incorporated into commercially available ECG recorders with digital capabilities. Additional studies are warranted that investigate the usefulness of T-wave morphology descriptors in other populations at risk of sudden cardiac death.

**References**

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_Circulation_. 2000;102:1252-1257
doi: 10.1161/01.CIR.102.11.1252

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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