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COMPLEX SYSTEMS BIOPHYSICS

Quantitative Analysis of Electrocardiographic Variability Typical of Polymorphic Arrhythmias

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Abstract—A new approach is developed for analyzing the electrocardiographic variability typical of polymorphic arrhythmias. The existing methods are frequently inapplicable in this case because of the difficulties in identifying individual QRS complexes. There is no need for their identification in the new approach: the analysis is based on quantitatively comparing two neighboring segments of the electrocardiogram and normalizing the results. The entire electrocardiogram or any fragment thereof is described with two parameters, of which one is an index of electrocardiographic variability and the other shows how this index changes with time. These two parameters are useful in assessing the polymorphism within one electrocardiogram and in comparing different electrocardiograms. The approach proposed is promising in diagnosing polymorphic arrhythmias and in studying their mechanisms.

Key words: polymorphic arrhythmia, electrocardiogram, quantitative analysis

INTRODUCTION

At present, electrocardiography is the most common method for differential diagnosis of cardiac arrhythmias. Moreover, many arrhytmias can be detected only by electrocardiographic analysis. There are sufficient grounds to expect that the role of this method in differential diagnosis of cardiac arrhythmias will increase in the future. With this expected increase in its usage comes the need for continually improving the methods for processing the electrocardiographic data. Developing more precise diagnostic criteria and new processing algorithms may help attain higher sensitivity and better specificity in differential diagnosis of arrhythmias.

When interpreting electrocardiographic data, cardiologists usually analyze the QRS complex (amplitude, duration, and shape of individual waves and the entire complex), determine various intrabeat and interbeat segments (for example, RR intervals), examine temporal variations of these parameters, and take into account whether the recordings contain missing or extra waves. Knowing this information, the cardiologist can judge how electrical excitation propagates over the myocardium.

Over the last decades, mathematical methods have been more and more frequently used to analyze electrocardiograms (ECGs). Among them, there were classic methods for analysis of time series, such as calculating statistical parameters of RR interval sequences or ECG power spectra [1, 2]. Development of the chaos theory has brought a quite new range of analytical tools for processing electrocardiographic data: Poincare maps, phase portrait reconstruction, Lyapunov exponents, Kolmogorov's entropy, and others

Abbreviations: ECG, electrocardiogram; PVT, polymorphic ventricular tachycardia; NVAEV, normalized-value analysis of electrocardiographic variability; SaW, sampling window; ScW, scanning window; AW, averaging window.

[3–6]. For example, Absil *et al.* [7] reported the results of detrended fluctuation analysis of RR interval sequences in long-term (many hours) recordings.

Polymorphic ventricular tachycardias (PVTs), or high-frequency arrhythmias, pose a special problem in analysis of patient electrocardiograms. They are highly variable and, moreover, individual QRS complexes cannot be reliably delimited in them.* Therefore, the methods commonly used in analysis of electrocardiograms are largely inapplicable in such cases.

No difference is often made between polymorphic ventricular tachycardias and ventricular fibrillation, a harbinger of sudden death. The classic definition of fibrillation (as given in the Unabridged Encyclopedia of Medicine) is as follows: cardiac ventricular fibrillation is pathological (chaotic, uncoordinated, and asynchronous) contraction of individual muscle fibers of the cardiac ventricles that cannot sustain their proper functioning. (…) In the electrocardiogram, the waveforms vary with the fibrillation stage, depending on the severity of myocardial hypoxia and the extent of metabolic alterations. Fibrillation is graded according to the oscillation types and the relationship between them (rhythmic isomorphic versus arrhythmic polymorphic) [10]. No doubt, analysis of variability in polymorphic ventricular tachycardia is a problem of considerable interest, which cannot be solved without developing new methods for quantitatively processing electrocardiographic data. In this study, we sought ways to solve this problem.

Earlier [11], following Coumel's recommendations [12], we set down quantitative criteria for identifying the electrocardiogram type (polymorphic, monomorphic, or quasi-monomorphic), which relied on the amplitudes and frequencies of the signals recorded. No criterion was then proposed for quantitatively assessing the amount of polymorphism present in electrocardiograms.

In this study, we focused on the parameters suitable for estimating variations in electrocardiograms of patients with polymorphic ventricular tachycardia. To this end, we developed a new approach to analysis of arrhythmias. This approach is free of the need to identify individual QRS complexes; rather, we assessed the variability by numerically comparing neighboring fragments of the electrocardiogram. The entire electrocardiogram or any its fragment is described with two parameters, of which one is an index of variability and the other specifies how this index changes with time. These two parameters are useful in assessing the polymorphism within one electrocardiogram and in comparing different electrocardiograms. The approach proposed is promising in diagnosing polymorphic arrhythmias and in studying their mechanisms.

NORMALIZED-VALUE ANALYSIS OF ELECTROCARDIOGRAPHIC VARIABILITY IN POLYMORPHIC VENTRICULAR TACHYCARDIA

1. Criteria to be Met by the Methods Using Normalized Values for Analysis of Electrocardiographic Variability in Polymorphic Ventricular Tachycardia

In our opinion, the best index to characterize electrocardiographic variability in polymorphic ventricular tachycardia should meet the following criteria.

(i) It must be a dimensionless quantity or a set of such quantities that makes it possible to compare two fragments or two electrocardiograms of arbitrary lengths.

(ii) It must be normalized in a way that makes it independent of the shape and amplitude of the QRS complexes (in segments where the complexes are discernible).

(iii) This prospective index is expected to afford a possibility of monitoring changes in polymorphism with time in electrocardiograms recorded during

* Note that, because electrocardiographic signals in polymorphic ventricular tachycardia are of irregular shape, the very entity of polymorphic ventricular tachycardia is not defined unambiguously in the known classifications of arrhythmias; its definition frequently overlaps with definitions of other types of cardiac rhythm disorders. For example, according to the 1981 classification of cardiac rhythm and conduction disorders, it is recommended, in diagnosing polymorphic ventricular tachycardia, to discriminate between its (i) bipolar (alternating), (ii) fusion-complex, (iii) *torsado de pointes*, and (iiii) mixed types [8]. In the 1985 classification by the North American Society of Pacing and Electrophysiology, ventricular tachycardia is defined as polymorphic if the QRS configuration varies in the electrocardiogram, whatever the recording lead [9]. The electrocardiographic term fibrillation in the same 1985 classification is defined as ventricular tachycardia in which the QRS complexes are difficult to identify in electrocardiograms measured from the body surface. Leaving aside the qualitative nature of such definitions, we only emphasize that they are almost of no value in constructing a continuous quantitative scale for scoring polymorphic ventricular tachycardias.

episodes of arrhythmia even if individual QRS complexes cannot be identified.

(iiii) It is also expected to yield new information on electrocardiographic abnormalities typical of ventricular tachoarrhythmia; this information should not contradict the results obtained with the qualitative methods that are commonly used at present in analysis of electrocardiograms.

A family of methods that met these criteria will be referred to hereafter as normalized-value analysis of electrocardiographic variability (NVAEV) in polymorphic ventricular tachycardia. The method that we describe in this study belongs to this family.

2. Assessing the Electrocardiographic Variability Index in Simple Cases

Before developing the normalized-value method, let us formulate the rules how to quantitatively assess the electrocardiographic variability in simple cases when individual QRS complexes can be delimited and numerically compared in height and width. This is a necessary step in the development of a new method: the method will be validated against the data obtained according to the rules formulated now. If the estimates obtained using the new method qualitatively coincide with those obtained according to these rules, criterion (iiii) will be met (see above). It is natural to assume that, if the method adequately classifies simple polymorphic electrocardiograms (that is, in accordance with the rules), it would also apply to those cases when individual QRS complexes cannot be reliably delimited.

To assess the amount of electrocardiographic variability in simple cases with identifiable individual QRS complexes, let us define the variability index w_i at a transition from the ith to the $(i+1)$th complex as

$$w_i = w_A w_T - 1, \quad (1)$$

where $w_A = \dfrac{\max(A_i, A_{i+1})}{\min(A_i, A_{i+1})}$; $w_T = \dfrac{\max(T_i, T_{i+1})}{\min(T_i, T_{i+1})}$; A_i and A_{i+1} are the peak-to-peak amplitudes of two consecutive complexes; and T_i and T_{i+1} are their widths. Note that $w_A = 1$ if $A_i = A_{i+1}$ and $w_T = 1$ if $T_i = T_{i+1}$. Hence, the variability index $w_i = 0$ if the ith and the $(i + 1)$th complexes have equal amplitudes and widths: $A_i = A_{i+1}$ and $T_i = T_{i+1}$.

The overall estimate of electrocardiographic variability of a fragment will be a normalized sum of the variability index values for all transitions in this fragment:

$$V = \frac{1}{N}\sum_{i=1}^{N} w_i, \quad (2)$$

where N is the number of transitions.

When validating the normalized-value method proposed for assessing the electrocardiographic variability, we simulated simple cases of polymorphic ventricular tachycardia by using what is called pseudoelectrocardiograms. This approach facilitates the

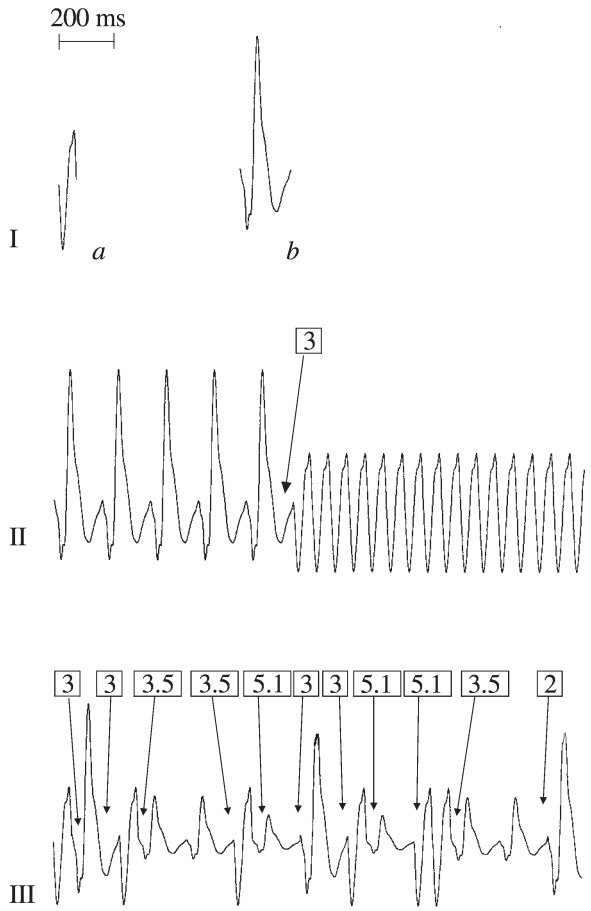

Fig. 1. Pseudoelectrocardiograms and assessment of their variability. (I) Two types of QRS waveforms most common in polymorphic ventricular tachycardia: (*a*) two-component and (*b*) three-component. These waveforms were used to construct pseudoelectrocardiograms. (II) An example of a simple electrocardiogram, constructed of two fragments, one consisting of identical *a* elements and the other of identical *b* elements. In the region of their junction (transition to a different element), the variability index is nonzero. (III) Composite pseudoelectrocardiogram constructed of *a* and *b* elements, with one element varying in amplitude. Scale bar, 200 ms.

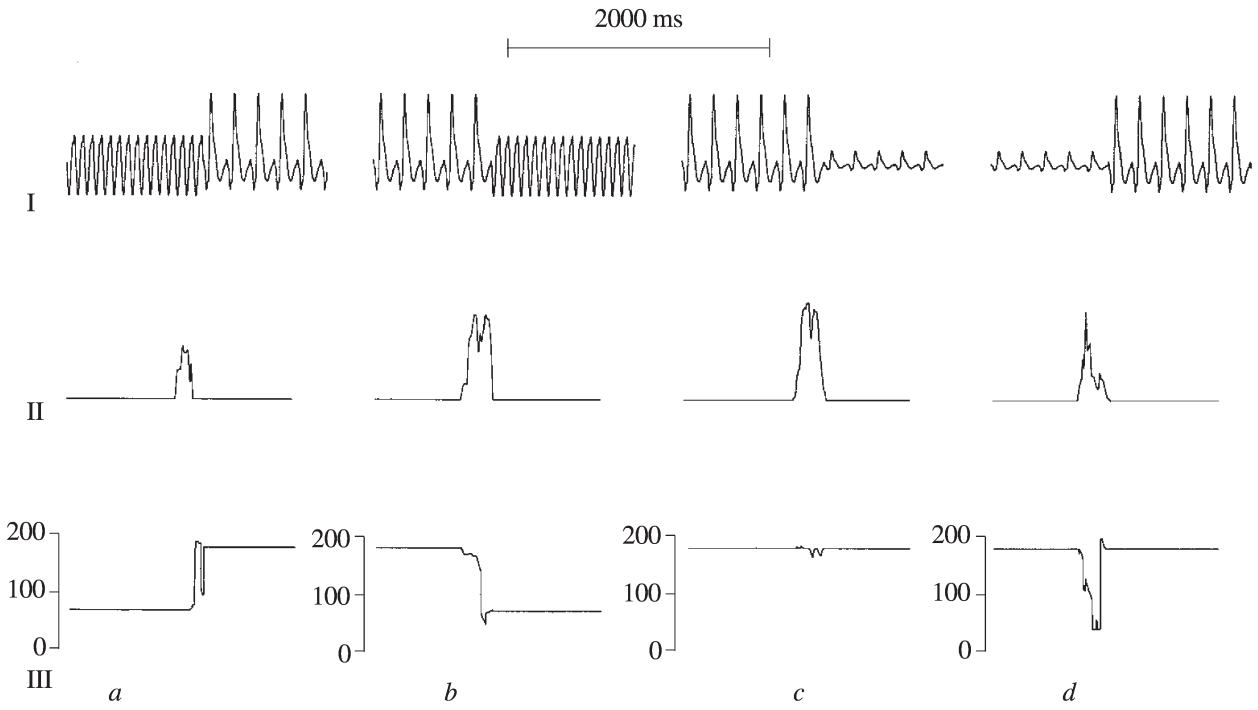

Fig. 2. (I) Simple pseudoelectrocardiograms (*a*–*d* from left to right) and the corresponding (II) I_i and (III) τ_i functions calculated using normalized-value analysis. Each pseudoelectrocardiogram includes two fragments composed of identical elements. By construction, the first and the second fragments in *a* (*c*) are the second and the first fragments, respectively, in *b* (*d*). Vertical axis is the same throughout. Time scale bar indicated at the top (2000 ms) applies to all rows.

validation procedure. Pseudoelectrocardiograms are the curves with known *V* values (by construction). Their elements were obtained when we processed the data of multielectrode mapping of excitation propagation in cardiac muscle during experimental ventricular arrhythmia (see [11] for more detail).

Panel I in Fig. 1 shows two types of QRS waveforms, one two-component and the other three-component (*a* and *b*, respectively), common in polymorphic ventricular tachycardia. These waveforms were the main elements of which pseudoelectrocardiograms were constructed to simulate polymorphic ventricular tachycardia. The width of the two-component element was T_a = 71 ms; the width of the three-component element was T_b = 182 ms. Hence, we had w_T = 2.56 and w_A = 1.56.

Figure 1-II shows a simple pseudoelectrocardiogram constructed of two fragments, one consisting of identical *a* elements and the other of identical *b* elements. Within each of the fragments, $w_i = 0$ (transition to an identical element). In the junction region (transition to a different element), $w_5 = 3$. As follows from (2), the overall variability index V = 0.16 in this case.

Figure 1-III depicts a more complex pseudoelectrocardiogram constructed of *a* and *b* elements, with one element varying in amplitude. In this case, the overall variability index V = 2.8.

The pseudoelectrocardiograms shown in Figs. 2-I and 3-I are used to demonstrate how our method of normalized-value analysis of electrocardiographic variability works. For each electrocardiogram, we determine the *V* index as described and then compare the calculated index with the results obtained using the proposed method.

3. Definition of the Index of Instant Electrocardiographic Variability within the Framework of Normalized-Value Analysis

To determine the local characteristics of electrocardiographic variability, we propose to compare some digitized segment of an electrocardiogram with another digitized segment, which is considered to be a reference sample. It is reasonable to choose its length (sampling window width) to be as short as the shortest QRS width in the biological species under study in the absence of arrhythmia. The procedure of comparison is implemented for each moment of time, yielding

the local characteristic of electrocardiographic variability (instant variability index I_i). This index is a tool for numerically comparing segment *i* corresponding to the current position of the sampling window with segment *j*, the first segment most closely resembling segment *i* (reference sample) in the subsequent recording.

Formally, the procedure of their comparison is as follows. For any segment of the electrocardiogram, vector $\boldsymbol{F}$ is defined:

$$\boldsymbol{F}_k = (f_{k,}\, f_{k+h}, \ldots f_{k+(p-1)h}),$$

where f_n is the signal amplitude at time *n*; *n* varies from *k* to $k + (p - 1)/h$, where *p* is the dimension of the so-called embedding space, and *h* is the embedding step (see, for example, [4, 5]). The distance between the *i*th and *j*th vectors is determined by the norm:

$$r_{ij} = \left|\boldsymbol{F}_i - \boldsymbol{F}_j\right|. \quad (3)$$

Note that, for periodic signals, $r_{ij} = 0$ if $|i - j| = mT$, where $m = 0, 1, 2, 3$, etc. For aperiodic signals, the smaller the difference between the *i*th and the *j*th segments, the smaller the r_{ij}.

Segments *i* and *j*, that is, the segment corresponding to the current position of the sampling window and the first segment most closely resembling that sample in the subsequent recording, respectively, are separated by a time interval τ_i: $\tau_i = j - i$, $j > i$. Seeking the *j*th segment and determining the τ_i value are based on the assumption that *j* is a unique function of *i*.

If τ_i were known, it would be possible to assess the similarity between the two segments using norm (3) in the *p*-dimensional embedding space. Therefore, we postulate:

$$I_i \equiv \frac{1}{S_i} r_{i(i+\tau_i)}, \quad (4)$$

where S_i is the peak-to-peak amplitude of the electrocardiographic signal in the sampling window corresponding to time *i*.

To automatically seek a segment most closely corresponding to the current sample and separated from it by the shortest interval, we systematically scan an electrocardiogram segment of length *L* (scanning window; ScW) using step size *h*. Every next segment within the scanning window is compared with the current sample by any technique (for example, a technique based on the use of an autocorrelation function or the norm in the embedding space).

In simple cases when the QRS complexes are identifiable, τ_i equals the inter-QRS interval, irrespective of the technique used. When the QRS complexes are difficult to identify, as in real polymorphic ventricular tachycardia, τ_i is formally set into correspondence with the position of the norm minimum. In other words, we assume that the r_{ij} minimum determines the segment *j* position in the scanning window. In this case, expression (4) reads

$$I_i = \frac{1}{S_i} \min_{k \in (i, i+L)} (r_{ik}). \quad (5)$$

This approach considerably saves the time for computing I_i by combining the search for a segment analogous to the current sample with their comparison. The scanning window width *L* is chosen to be as wide as the greatest QRS width in the biological species under study.

Note that a search for segments analogous to the current sample is, in general, a procedure independent of the comparison procedure. In fact, whereas the polymorphic properties of patient electrocardiograms make the basis for assessing their variability, there is no need to have search criteria also related to these properties.

4. Determining the Instant Variability Index for Pseudoelectrocardiograms

Normalized-value analysis was used to calculate the function I_i for simple pseudoelectrocardiograms (as those shown in Fig. 2) with a single transition for which w_i is nonzero and for relatively intricate pseudoelectrocardiograms (as those shown in Fig. 3). The elements used to construct these pseudoelectrocardiograms have the same width as the elements shown in Fig. 1-I; only the amplitude of element *b* varies.

The same pseudoelectrocardiograms (Fig. 3-I) were assessed by calculating the overall index of the electrocardiographic variability (*V*) described above and the I_i function. As evident from Fig. 3-II, the I_i values averaged over time tend to covary with *V* (table).

Contrary to expectation, the I_i function is not exactly the same across the transition regions for which the w_i values are equal. Figure 2 shows simple pseudoelectrocardiograms (panel I) along with the I_i functions calculated for them (panel II). The oscillation

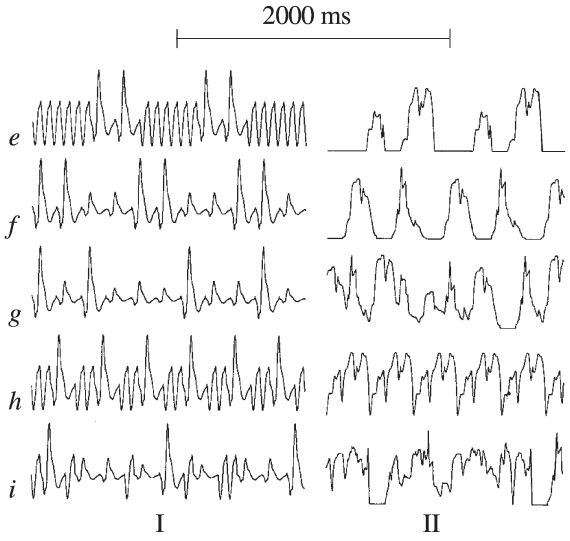

Fig. 3. (I) Intricate pseudoelectrocardiograms (*e–i* from top to bottom at the left) and (II) the corresponding I_i functions calculated using normalized-value analysis. Vertical axis is the same throughout. Time scale bar indicated at the top (2000 ms) applies to all rows.

period changes at the point of transition between nonidentical elements in pseudoelectrocardiograms *a* and *b*, but not *c* or *d*. Pseudoelectrocardiograms *b* and *d* are obtained from *a* and *c*, respectively, by transposition of their fragments; therefore, the electrocardiograms in each pair (*a* and *b*; *c* and *d*) do not differ in $w_i(1)$ at the point of junction of nonidentical elements. However, their I_i functions are different. In our opinion, some uncompensated error in recognizing and locating the segments analogous to the segment in the current sampling window is responsible for this difference.

Numerical characteristics of electrocardiographic variability in pseudoelectrocardiograms shown in Figs. 2-I and 3-I

Curve designation	Variability index V	Variability index $V_1 \cdot 10^3$	Index V_2 (coefficient of variation for I_i function)
a	0.2	0.4	0.27
b	0.2	1.1	0.36
c	0.3	1.2	0.35
d	0.3	0.5	0.32
e	0.6	3.0	0.73
f	1.0	3.7	0.91
g	1.8	6.1	1.52
h	2.0	7.5	2.43
i	2.8	6.2	1.78

The presence of such recognition errors may be suspected from the shape of τ_i function, as exemplified in Fig. 2-III. In electrocardiogram *d*, the interval between QRS complexes does not vary with time. Therefore, τ_i is expected to be constant. Contrary to expectation, τ_i changes dramatically at the transition from smaller to larger amplitudes, suggesting that there is an error in locating the segment-analog. Such an error is likely to arise when the neighboring complexes are very different, unlike those in electrocardiogram *a* (Fig. 2), which have comparable amplitudes. The characteristics may vary from complex to complex, but so great a difference between two consecutive complexes is rare to occur in experimental or clinical electrocardiograms.

The algorithm that we propose for seeking the segments analogous to that in the current sampling window may generate errors of two types. First, if the segment-analog is outside the sampling window, a segment for calculating the norm is necessarily at the end of the sampling window, which results in overestimating the I_i value. Second, if the scanning window contains several segments-analogs, and a segment most closely matching the segment in the sampling window is not the first in this series, the I_i value turns out underestimated. In our experience, when errors of both types are present, their effects on the I_i value are often offset, at least in part.

A long fragment of the electrocardiogram is usually analyzed to assess its polymorphism. Hence, it is desirable that the estimate of electrocardiographic variability obtained with the normalized-value method would be largely independent of the local characteristics of the signal and the errors in their determination. To overcome the shortcomings of the algorithm, we use the characteristics of electrocardiographic variability averaged over time.

5. Procedure for Averaging the Characteristics of Electrocardiographic Variability Obtained with the Normalized-Value Method

For further analysis of electrocardiograms or their fragments of arbitrary lengths, it is useful to construct some integral characteristics of electrographic variability. In our analysis, we use (i) the mean value of the I_i function, or the electrocardiographic variability index V_1, and (ii) the coefficient of variation of the

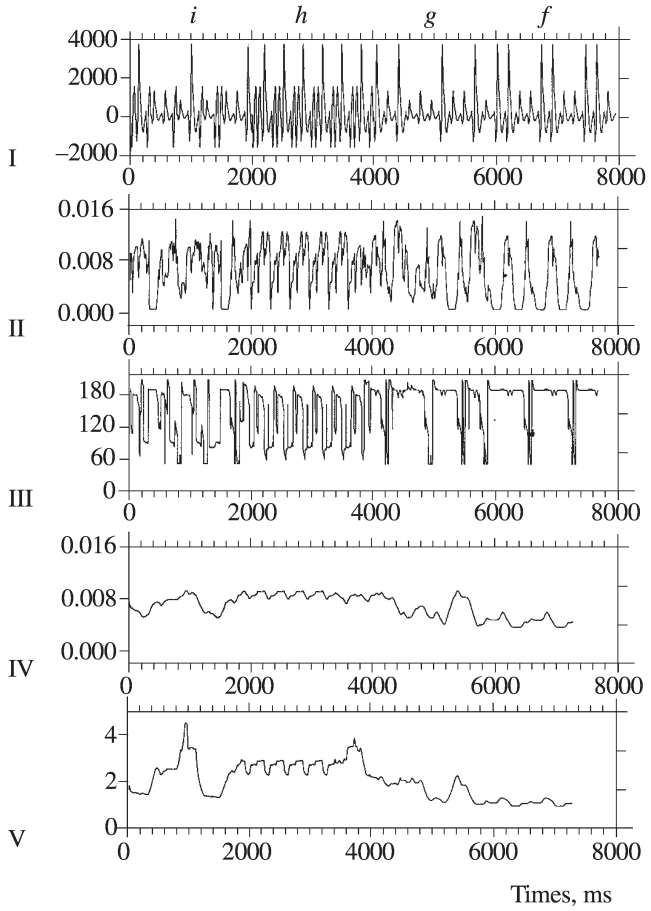

Fig. 4. (I) A pseudoelectrocardiogram composed of 2000-ms-long fragments of curves *i*, *h*, *g*, and *f* (Fig. 3) connected in series in the order of decreasing *V* values (see Section 2 for definition of the *V* index); and the corresponding (II) I_i, (III) τ_i, (IV) V_{1i}, and (V) V_{2i} functions.

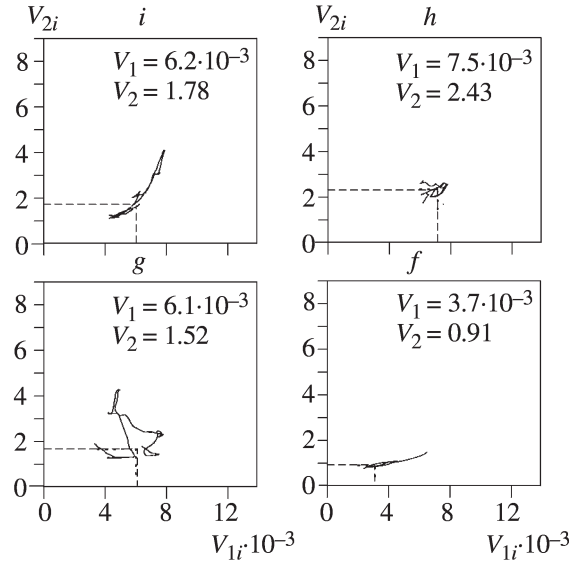

Fig. 5. Trajectories *i*, *h*, *g*, and *f* in the (V_{1i}, V_{2i}) parameter plane corresponding to the *i*, *h*, *g*, and *f* segments of the pseudoelectrocardiogram shown in Fig. 4-I. The V_1, and V_2 values are indicated at the top of each panel and are also plotted by dashed lines.

I_i function, V_2 [13]. Obviously (table), V_1 tends to increase as we go over to curves (pseudoelectrocardiograms) with higher values of the variability index *V*. Hence, the method proposed is sensitive to the variability of the signal. Recall that, unlike *V*, V_1 can be calculated without identifying the QRS complexes. The different procedures for their calculation may account for the fact that, from curve *f* to curve *i*, the changes in *V* and V_1 do not follow the same pattern (table).

6. Variability Indices in Monitoring the Dynamics of the Electrocardiogram

To monitor the electrocardiogram changes with time, we calculate the variability index V_{1i} and the coefficient V_{2i} for the segment in some fixed-width window, that is, the averaging window. Shifting it along the time axis, we obtain a trajectory in the (V_{1i}, V_{2i}) parameter plane, which reflects the dynamics of changes in the electrocardiogram. Note that the properties of the end segment of the electrocardiogram whose length is equal to the averaging window width are uncertain; therefore, the averaging window should not be too wide. Basing on the definition of ventricular tachycardia [9], we chose the width of the averaging window to be six QRS widths (about 400 ms in the electrocardiograms under study). Below, we assume that, unlike V_{1i} and V_{2i}, V_1 and V_2 (see Section 5 for their definitions) characterize segments that are considerably longer than the averaging window width.

Figure 4 shows an intricate pseudoelectrocardiogram and the temporal evolution of the corresponding I_i, V_{1i}, and V_{2i} functions. This pseudoelectrocardiogram (Fig. 4-I) was obtained by connecting in series 2000-ms-long fragments of curves *i*, *h*, *g*, and *f* (Fig. 3-I) in the order of decreasing *V* values (table). As can be seen, the I_i, V_{1i}, and V_{2i} functions (Figs. 4-II, 4-IV, and 4-V, respectively) reflect the changes in the pseudoelectrocardiogram.

Shifting the averaging window along the time axis of this electrocardiogram (Fig. 4-I), we obtain the trajectories in the (V_{1i}, V_{2i}) parameter plane (Fig. 5), which allow us to judge the dynamics of changes in the *i*, *h*, *g*, and *f* segments. Note that their projections onto

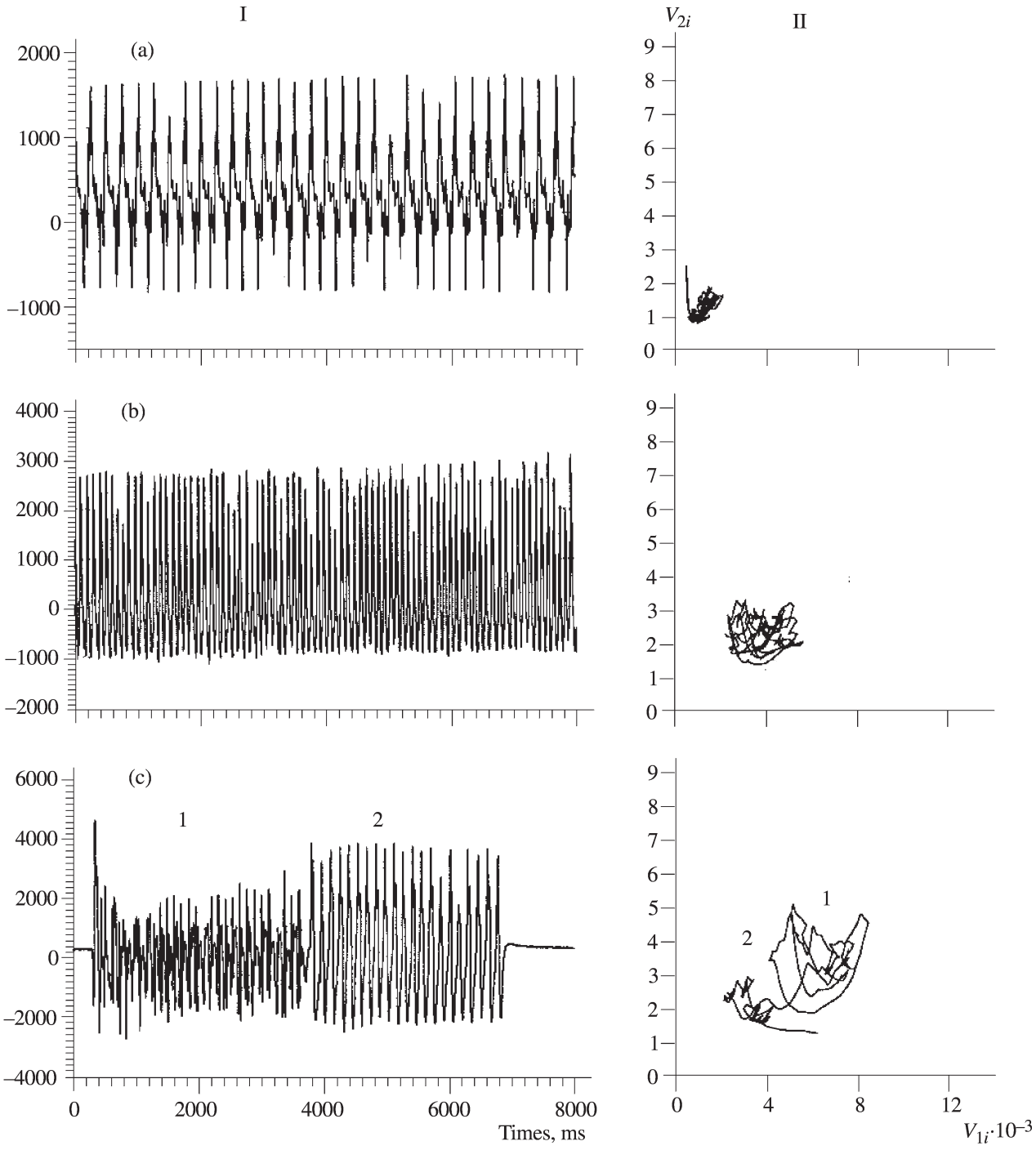

Fig. 6. (I) Experimental pseudoelectrocardiograms and (II) their trajectories in the (V_{1i}, V_{2i}) parameter plane as calculated by the normalized-value method.

the (V_{1i}, V_{2i}) parameter plane are narrow and are relatively far from one another. Importantly, these trajectories differ significantly even when the corresponding V_1 and V_2 are such (cf., for example, segments *i* and *g* in Fig. 5) that it is difficult to conclude whether the variability changes from segment to segment. In other words, constructing trajectories in the index space, we obtain an additional source of information concerning the electrocardiographic variability.

We emphasize that, with the normal-value method for assessing the dynamics of changes in pseudoelectrocardiograms (Fig. 5), there is no need to recognize individual peaks. Therefore, it is reasonable to expect that the variability index V_{1i} and the coefficient

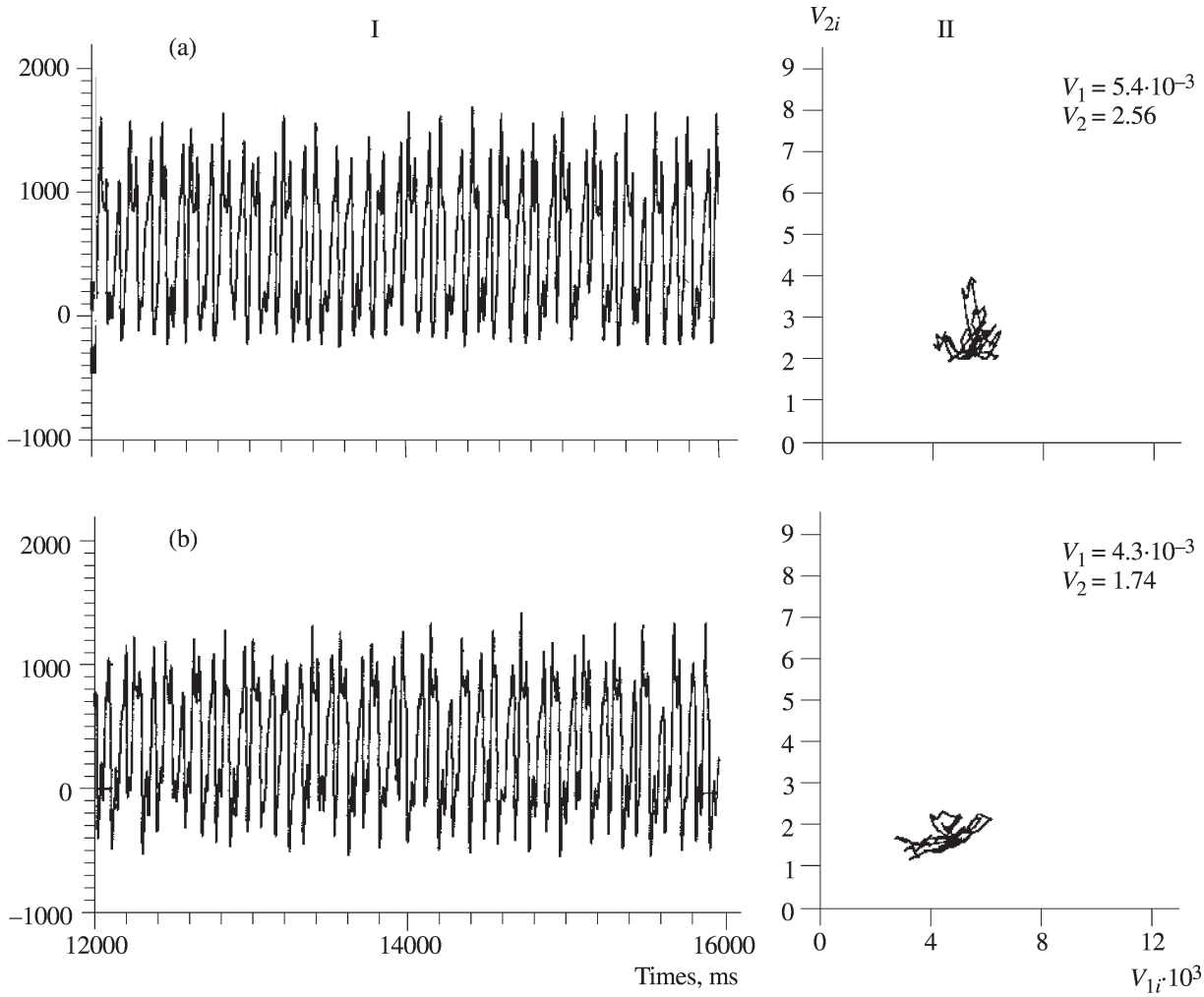

Fig. 7. (I) Two experimental pseudoelectrocardiograms in which no difference in variability can be detected by visual inspection and (II) their trajectories in the (V_{1i}, V_{2i}) parameter plane as calculated by the normalized-value method.

V_{2i} will be useful in assessing real polymorphic electrocardiograms, especially when individual QRS complexes are difficult or impossible to identify. As a first step to this goal, the normalized-value method proposed in this study is used to analyze the variability in pseudoelectrocardiograms constructed of the fragments recorded experimentally.

7. Analysis of Variability in Pseudoelectrocardiograms Constructed of the Fragments Recorded Experimentally

The pseudoelectrocardiograms to be studied represent time series constructed by weighted summation of separate electrocardiograms obtained by multielectrode mapping of excitation propagation during experimental arrhythmia in the isolated wall of the ground squirrel right ventricle. The experimental model and the procedure for constructing pseudoelectrocardiograms were described in detail elsewhere [11]. In this Section, we apply the normalized-value method to the analysis of variability in pseudoelectrocardiograms typical of polymorphic arrhythmia.

Figure 6 shows three such pseudoelectrocardiograms and their trajectories in the (V_{1i}, V_{2i}) parameter plane. One can see that, with an apparent increase in the variability (from Fig. 6a to Fig. 6b), the trajectory is shifted to larger V_{1i} and V_{2i} values. The corresponding integral parameters (variability index V_1 and coefficient V_2; not shown), which characterize the entire electrocardiogram, change similarly. It is easy to see (Fig. 6c) that the movement from more polymorphic segment *1* of the electrocardiogram to segment *2* where oscillations are relatively regular corresponds to the passage from one area in the (V_{1i}, V_{2i}) parameter plane to another. On average, both parameters are higher for the polymorphic segment than for the regular segment.

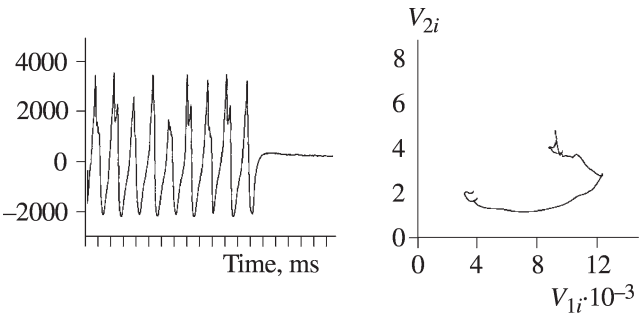

Fig. 8. Offset phenomenon, an artifact inherent in the normalized-value method: electrocardiogram recorded during end-stage arrhythmia (left) and its trajectory in the (V_{1i}, V_{2i}) parameter plane (right).

Figure 7 shows two pseudoelectrocardiograms in which no difference in variability can be detected by visual inspection. However, the types and locations of their trajectories in the (V_{1i}, V_{2i}) parameter plane clearly indicate that the two electrocardiograms differ in both V_1 and V_2 values and that the electrocardiogram in Fig. 7a corresponds to a more severe case of arrhythmia.

DISCUSSION

The method proposed in this study makes it possible to numerically analyze the electrocardiographic variability.

An essential result of this study is that the electrocardiographic variability is characterized by two parameters: the variability index V_1, defined as the mean value of the I_i function, and the coefficient of variation of the I_i function V_2. The latter parameter describes how the variability index varies with time, affording a possibility of distinguishing among arrhythmias that are similar in the variability index but differ in the temporal pattern of its variation. In other words, it comes to be possible to score polymorphism as "more stable" or "less stable." Note, however, that changes in V_1 are usually correlated fairly well with changes in V_2. Research into the nature of this fact will shed new light on the mechanisms of polymorphic arrhythmias. It is also important to address the issue of whether the changes in the myocardial excitation patterns are correlated with the changes in the trajectories in the (V_{1i}, V_{2i}) parameter plane.

Algorithm (5), which is a version of universal algorithm (4) for analysis of electrocardiographic variability in polymorphic arrhythmia, has some limitations. For example, the algorithm proposed sometimes select a segment-analog that does not coincide with the segment visually determined by an expert observer. In such cases (recognition errors), the I_i values are systematically over- or underestimated (see Section 4). Two other artifacts are also likely to occur with this algorithm. One of them is the onset phenomenon: a drop in I_i almost to zero in a segment preceding first fibrillations. The other is the reverse phenomenon: an abrupt rise in the I_i and V_{1i} values against a background of a relatively small change in the V_{2i}. The trajectory in the (V_{1i}, V_{2i}) parameter plane makes a kind of "smile" in this case, which does not reflect the actual changes in the electrocardiographic variability (Fig. 8). Both artifacts arise during the normalization for the peak-to-peak amplitude used in algorithm (5). Developing better algorithms for analysis of electrocardiographic polymorphism may become a goal of our future studies.

The normalized-value method or its modifications may be promising in classifying arrhythmias: the vague qualitative definition of polymorphism is replaced with its quantitative measure, the electrocardiographic variability index. The index allows the electrocardiographic variability to be assessed both for any moment of time and for arbitrarily long intervals.

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