Temporal evolution for the phase histogram of ECG during human ventricular fibrillation

Ming-Chya Wu[*,†], Zbigniew R. Struzik[**], Eiichi Watanabe[‡], Yoshiharu Yamamoto[**] and Chin-Kun Hu[†,§]

[*]*Research Center for Adaptive Data Analysis, National Central University, Chungli 32001, Taiwan*
[†]*Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan*
[**]*Graduate School of Education, The University of Tokyo, Tokyo 113-0033, Japan*
[‡]*Division of Cardiology, Department of Internal Medicine, Fujita Health University School of Medicine, Toyoake, Aichi-Ken 470-1192, Japan*
[§]*Center for Nonlinear and Complex Systems and Department of Physics, Chung Yuan Christian University, Chungli 32023, Taiwan*

Abstract. A novel approach to momentary/instantaneous morphological assessment of phase histograms, extending phase statistics analysis, is used to investigate electrocardiograms during ventricular fibrillation (VF) in humans. By using empirical mode decomposition (EMD) and the Hilbert transform, we calculate the instantaneous phase of intrinsic mode functions (IMFs) in Holter data from 16 individuals, and construct the corresponding momentary phase histograms, enabling us to inspect the evolution of the waveform of the time series. A measure defined as the difference between the integrals of the probability distribution density of phase in different regions is then used to characterize the morphology of the momentary histograms and their temporal evolution. We find that the measure of morphology difference allows near perfect classification of the VF data into survivor and non-survivor groups. The technique offers a new possibility to improve the effectiveness of intervention in defibrillation treatment and limit the negative side effects of unnecessary interventions. The approach can be implemented in real time and should provide a useful method for early evaluation of (fatal) VF.

Keywords: Ventricular Fibrillation; Empirical mode decomposition
PACS: 87.19.Hh, 05.45.Tp

INTRODUCTION

Cardiac arrhythmias are disturbances in the normal rhythm, and fibrillation is manifested as irregular electrical activity of the heart. During fibrillation the coordinated contraction of the cardiac muscle is lost and the mechanical pumping effectiveness of the heart fails. Therefore, the prediction of ventricular fibrillation (VF), which can lead to sudden cardiac death, is an important issue in cardiology. Yet to date, there exists no effective measure capable of predicting fatal VF. Since short-term VF can also occur in the electrocardiogram (ECG) of healthy people, the first task in this issue is to distinguish fatal VF from non-fatal VF.

From the viewpoint of cellular eletrophysiology, the appearance of ventricular tachycardia (VT) is due to the formation of a reentrant wave in cardiac tissue, driving the ventricle at a rate much faster than the normal sinus rhythm. VF is a spatially and temporally disorganized state arising from the subsequent breakdown of the reentrant wave into multiple drifting and meandering spiral waves [1, 2]. Therefore, the detection of

CP922, *Noise and Fluctuations, 19th International Conference*, edited by M. Tacano, Y. Yamamoto, and M. Nakao

the characteristic features corresponding to the disordered state in electrocardiograms (ECG) is likely a path toward the early evaluation of VF.

Here we address the issue by employing phase statistics analysis [3, 4, 5, 6] to investigate ECG data during VF. Phase statistics analysis is in principle an extension of the Hilbert-Huang transform (HHT) [7], consisting of empirical mode decomposition (EMD) and the Hilbert transform. The HHT is an algorithm designed for nonlinear and non-stationary time series analysis, and phase statistics analysis is an approach capable of describing morphologies of a wave in a statistical sense [4]. In the following sections, we will introduce phase statistics analysis and the construction of a measure for inspecting the temporal evolution of momentary phase histograms.

METHOD

The phase statistics approach consists of the calculation of the instantaneous phase of a time series and the statistics of the calculated phases. In order faithfully to calculate the phase, we decompose empirical data into a number of well-defined IMFs by EMD. All IMFs obtained by EMD enjoy a good Hilbert transform, and one can calculate the instantaneous phase of resultant IMFs directly by the Hilbert transform.

The EMD method is developed around the assumption that any time series consists of simple intrinsic modes of oscillation. The essence of the method is empirically to identify the intrinsic oscillatory modes by their characteristic time scales in the data and then decompose the data into these modes [7]. The details of procedures of the EMD can be found in Ref. [4, 7]. After decomposition, a time series $x(t)$ is decomposed into n IMFs c_i's and a residue r_n, *i.e.*

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t), \tag{1}$$

$$c_i(t) = r_{i-1}(t) - r_i(t). \tag{2}$$

The numbers of IMFs decomposed from different time series by the EMD are generally different, and essentially depend on the structures and length of the time series. Among the resultant IMFs, the first-IMF c_1 has the highest frequency, c_2 is the second, and c_3 follows. In Ref. [8], we have found that the first three modes c_1, c_2, and c_3 are essential components sufficient for describing the (detail) structures of the original VF time series used in the present study.

The instantaneous phase of the resultant IMFs can then be calculated by the Hilbert transform. For the kth mode, this can be done by first calculating the conjugate pair of $c_k(t)$, *i.e.*,

$$y_k(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{c_k(t')}{t - t'} dt', \tag{3}$$

where P indicates the Cauchy principal value. With this definition, the two functions $c_k(t)$ and $y_k(t)$ forming a complex conjugate pair define an analytic signal, and one can

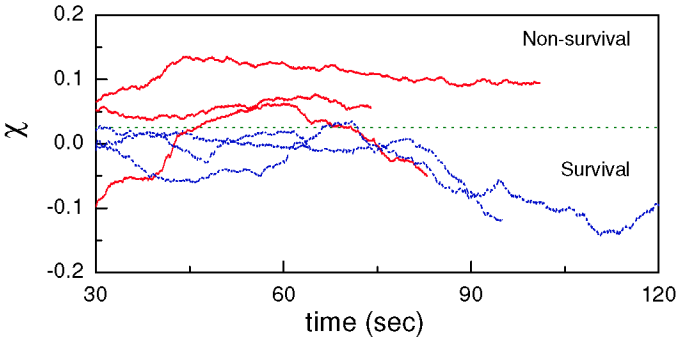

FIGURE 1. χ as a function of time for typical VFs of survivals (dashed line/blue color) and non-survivals (solid line/red color). Dotted line is the threshold which separates regimes of survival and non-survival.

calculate the instantaneous phase $\phi_k(t)$ of the function $c_k(t)$ by

$$\phi_k(t) = \tan^{-1}\left(\frac{y_k(t)}{c_k(t)}\right). \tag{4}$$

The value of $\phi_k(t)$ ranges from $-\pi$ to π.

TEMPORAL EVOLUTION OF THE PHASE HISTOGRAM

Next, we define the histogram of instantaneous phase satisfying the following normalization condition $\int_{-\pi}^{\pi} P(\phi_k)\,d\phi_k = 1$, where $P(\cdots)$ stands for the probability density function (PDF). We have found that the PDF of instantaneous phase can be classified into three types of patterns, CV (convex), UF (uniform), and CC (concave), according to the morphologies of the histograms [8]. To quantify the phase distribution patterns, we define a measure χ,

$$\chi = \langle P_1(\phi_1)\rangle - \langle P_2(\phi_1)\rangle, \tag{5}$$

where $\langle\cdots\rangle$ denotes an average, P_1 is the PDF of ϕ_1 in the range $-0.5\pi \le \phi_1 \le 0.5\pi$, and P_2 is for the phase in the range $-\pi \le \phi_1 < -0.5\pi$ or $0.5\pi < \phi_1 \le \pi$. More specifically, χ is a measure of the difference between the average of the PDFs of the phases located in the range $-0.5\pi \le \phi_1 \le 0.5\pi$ and the average of those not in this range. According to this definition, we have $\chi > \varepsilon$ for the CV type, $|\chi| \le \varepsilon$ for the UF type, and $\chi < -\varepsilon$ for the CC type. The value of ε is determined by the properties of statistics. Ref. [8] reports that the CV type VF is likely to be the fatal VF. It is better to establish a proper threshold of χ such that there is a clear separation for the CV type pattern from the UF and CC types. From the analysis of Holter data from 16 individuals, we find that taking $\varepsilon = 0.025$ gives reasonable results which are consistent with direct visual inspection. Note that $\varepsilon = 0.025$ corresponds to a tolerance of 5% from the probability $P = 0.5$. Consequently, we can describe the temporal evolution of the phase histogram by measuring $\chi(t)$ with a fixed window. As $\chi(t)$ enters into the regime of the CV type pattern $\chi(t) > \varepsilon$, it is

considered as an indication of the occurrence of fatal VF. For practical purposes, here we take a window of 30 sec. Figure 1 shows χ as a function of time for typical VFs of three survivals and three non-survivals. The threshold ε of χ can substantially separate the survival and non-survival groups into survival and non-survival regimes.

CONCLUSION

In conclusion, we have introduced an approach for inspecting the temporal evolution of the phase histogram of ECG during VF. In this approach, the ECG time series of VF is decomposed by the EMD [7] into a number of IMFs, and the instantaneous phase of these IMFs are calculated by the Hilbert transform. The phase distribution patterns of the first-IMFs can be classified into the UF, CC and CV types. The CV type VF time series is likely to be the fatal VF [8], as indicated by the statistics of the phase distribution patterns of VFs from 16 subjects. We define a measure χ as the difference between the integrals of the probability distribution density of phase in different regions to characterize the morphology of the momentary histograms and their temporal evolution. We find that the measure of morphology difference allows near perfect classification of the VF data into survivor and non-survivor groups. The technique offers a new possibility to improve the effectiveness of intervention in defibrillation treatment and limit the negative side effects of unnecessary interventions. Furthermore, the temporal evolution of the measure with a window of 30 sec is used to inspect the evolution of the phase histogram of ECG during VF. We find that a threshold of the measure separates survival and non-survival groups. This suggests that the measure of χ with a proper window may be implemented as a real-time monitor for the early evaluation of fatal VF.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of the Republic of China (Taiwan) under Grant No. NSC 95-2112-M-001-008 and National Center for Theoretical Sciences in Taiwan (M.-C. Wu, C.-K. Hu), and (in part) by grants from the Medical and Welfare Equipment Laboratory, Japan (Y. Yamamoto).

REFERENCES

1. D.J. Christini and L. Glass, *Chaos* **12**, 732-739 (2002).
2. N. Bursac, F. Aguel and L. Tung, *Proc. Nat. Acad. Sci. USA* **101**, 15530-15534 (2004).
3. M.-C. Wu, M.-C. Huang, H.-C. Yu and T. C. Chiang, *Phys. Rev. E* **73**, 016118 (2006).
4. M.-C. Wu and C.-K. Hu, *Phys. Rev. E* **73**, 051917 (2006).
5. M.-C. Wu, *Physica A* **375**, 633-642 (2007).
6. M.-C. Wu, *J. Korean Phys. Soc.* **50**, 304-312 (2007).
   phase statistics of human ECG data, manuscript submitted (2007).
7. N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung and H. H. Liu, *Proc. R. Soc. Lond. A* **454**, 903-995 (1998).
8. M.-C. Wu, E. Watanabe, Z. R. Struzik, C.-K. Hu and Y. Yamamoto, Identification of fatal ventricular fibrillation patterns from