Simulation System of Arrhythmia and HRV Analyzer

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Abstract

We aim to integrate our interactive simulation systems of arrhythmia and heart rate variability (HRV) analyzer by a Windows message to understand the theoretical mechanisms of arrhythmia and HRV. The arrhythmia simulator (250 kB, Visual Basic 6.0) was composed of 4 normal and 2 ectopic foci. The electrical activity of each cell was modeled by the conduction speed and the phase response curve. The ECG waves were graphically plotted with impulse conduction on a ladder diagram. An RR interval was sequentially messaged to the HRV analyzer (90 kB, Visual Basic 6.0), which automatically calculated power spectrum (PS) of HRV by Lomb's method and FFT. The power of VLF, LF and HF bands, mean, SD and range were listed. The HRV analyzer interactively showed the variation of PS influenced by a baseline trend of RR intervals, ectopic beats, sampling rate, the number of samples and window function.

http://info.ahs.kitasato-u.ac.jp/tkweb/tkp/tkp2005.html

1. Introduction

Heart rate variability (HRV) is a widely used quantitative marker of autonomic nervous system activity [1,2,3]. Many commercial devices now provide an automated measurement of HRV [1] and several free applications of HVR analysis are available [3,4]. The significance and the meaning of different measures of HRV are becoming more complex than generally appreciated, and there is a potential for incorrect conclusions and for excessive or unfounded extrapolations [1].

We have developed a virtual ECG simulation system for medical students, physicians and technicians [5]. The system shows various arrhythmias with a ladder diagram in real time along with the PR interval, conduction time and RR interval.

In this study, we made a Windows application of an HRV analyzer with an extended ECG simulation system to advance the understanding of the method of a frequency-domain analysis and HRV. These applications are to be used in research by physicians and other medical experts.

2. Methods

2.1. Simulation system for arrhythmias

The cardiac module consists of 6 cells, the sinus, atrium, A-V node, ventricle, and ectopic foci (Figure 1). The physiological properties of the cells, the automaticity and conduction delay, were modeled respectively by the phase response curve (PRC) and the excitability recovery curve (ERC). Each cell has a set of properties and visual properties such as ECG waveform and animations (at resting, activation and contraction). For a graphic presentation, each cell has data sets of the ECG waveform showing the sequence of the electrical potential. For example, an atrial cell has a P wave and a ventricular cell a QRS-T wave. The system interactively draws the ECG sequence as a ladder diagram in real time. The system generates diverse arrhythmias for various user settings of the cell function and conduction between cells. Users are able to make virtual experiments by setting up a protocol of electrophysiological stimulations.
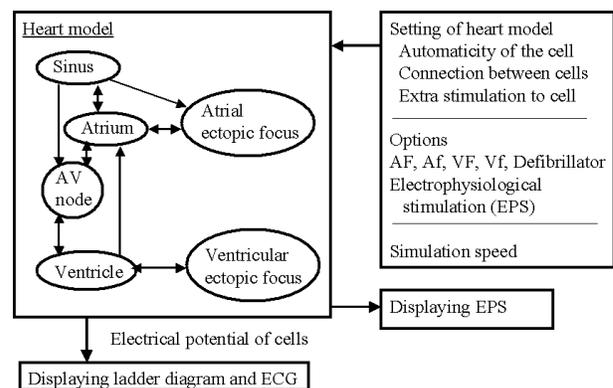
Figure 1. The system consists of the heart model that includes 6 autorhythmic cells. Arrow line between cells indicate the conduction pathway: antegrade, retrograde or bidirectional.

2.2. HRV analyzer

The HRV analyzer receives RR intervals from the ECG simulator, and analyzes HRV automatically and periodically in a time domain as well as in a frequency domain. The HRV analyzer consists of four submodules of (1) preparing RR data, (2) plotting the data sequentially, (3) analyzing the data, and (4) resynthesizing the original data. The data set module receives RR data via a Windows message from the arrhythmia simulator. The module transfers data from or to the clipboard, and converts the unit of data from millisecond to second if necessary. It automatically eliminates some special codes of CR, LF and Tab when the data are imported. The module generates virtual RR interval data with combination of sine waves, random numbers and extra beats. The generated test data is used not only to submit for learning HRV analysis, but also to forcibly fluctuate the sinus node in the ECG simulation system (external modulation of the sinus node presented in Figure 2).

Analyzing module analyzes the data by Lomb's method [6] and FFT. The module has an important option in accordance with a data type; if a sampling interval is irregular, such as RR interval, the data should be interpolated prior to FFT calculation with an appropriate sampling frequency. In case of a constant interval, information about the sampling frequency is required. Other basic options for FFT are the number of RR intervals, the type of window function (without window, Hamming or Hanning window) and the definition of the frequency bands. The power spectral density (PSD) of the RR intervals is analyzed for very low frequency (VLF 0.003—0.04 Hz), low frequency (LF, 0.04—0.15 Hz), and high frequency (HF, 0.15—0.4 Hz). The powers of VLF, LF and HF bands, and the LF to HF ratio, are calculated. Time-domain statistics include mean, standard deviation and range of RR intervals.

The resynthesizing module synthesizes new data by an inverse FFT method with a low-cut and high-cut filters defined by the user and plots them for comparison with the original graph.

3. Results

3.1. System architecture

The arrhythmia simulation system (tkp3.exe, 200 kB) and the HRV analyzer (variability.exe 90 kB) were developed in Visual Basic 6.0 and runs under MS-Windows. The simulation system models the electrical state and its conduction through the heart by 6 autorhythmic cells. The cell functions were implemented in an ActiveX control (tkpace.ocx, size 90 kB, developed in Visual C++ 6.0 with the Microsoft Foundation Classes (MFC) version 4.2) and incorporated into the cardiac
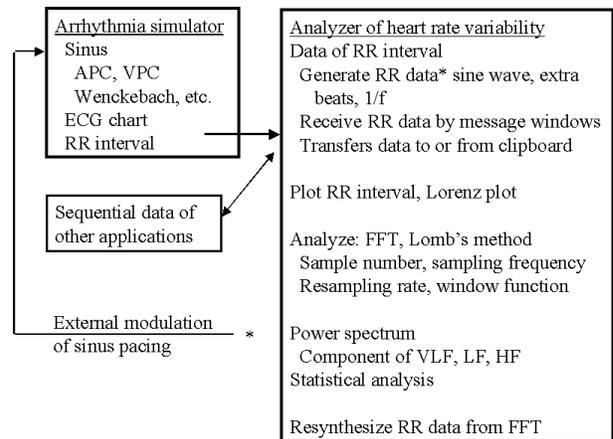
Figure 2. The arrhythmia simulator communicates with the HRV analyzer. The arrhythmia simulator sends an RR interval to the HRV analyzer by a Windows message.

module. The cell runs independently in each simulation step and calculates a new state due to an extra stimulation. After the cell is activated by its automaticity or an extra stimulation, and the conduction delay time elapses, the cell evokes an event message to the neighboring cells.

3.2. Sample run of arrhythmia simulator

Figure 3 shows an example of a phase response curve and a conduction recovery curve (excitation recovery curve) of the AV node. An ERC is represented by a decaying exponential function of the V1A2 interval.

Figure 4 shows an arrhythmia simulator including the "START" button, speed controller, reset button, and the checkboxes that are used to set the state of each cell to active or inactive. In the middle are 4 buttons to stimulate the cells and 2 checkboxes to control the atrial and ventricular ectopic foci. Antegrade and retrograde conduction between the cells are controlled by the user via the checkboxes in the window. The retrograde conduction and its delay times can be set in textboxes on the right side. It is possible to set 3 grades of AV blocks, and also the fibrillation and flutter of the atrium and the ventricle. The ladder diagram shows the relations between the P waves and QRS complexes. The slanted yellow lines show the spread of activation as transmitted. RR intervals are automatically measured in a unit of 2 milliseconds and labelled on the graph. These values are also transferred to the HRV analyzer.

The ladder diagram shows the mechanism of a re-entrant tachyarrhythmia with the capability of retrograde conduction (lower panel in Figure 4). The ECG waveforms were drawn in real time as a summation of the electrical potential of all active cells. The dynamic states of contraction and relaxation of the atrium and the ventricle were also presented graphically.
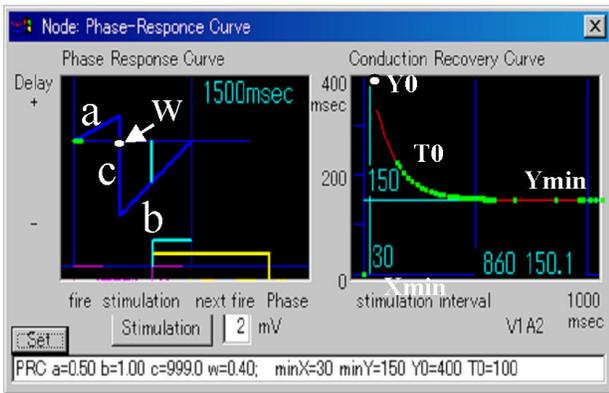
Figure 3. The phase response curve of an autorhythmic cell on the left panel is defined by the set of parameters (a, b, c and w). A horizontal magenta line on the abscissa denotes the refractory period of the cell. The yellow line at the bottom predicts the next firing time. Parameters of a conduction recovery curve can be displayed and changed in a textbox at the bottom of the window.

3.3. Sample run of a HRV analyzer

The HRV analyzer window is made up of 4 areas: data-set area at the top of the window, plot-area, analysis-option area in the middle and the results-view area at the bottom (Figure 5).

The data-set area receives the RR intervals into the textbox from the ECG application or a clipboard. The RR intervals are simultaneously plotted in a time chart and as a Lorenz plot. Each data segment analyzed is plotted with several colored lines in the lower part of the time chart. The time chart in the Figure 5 shows the data segment applied with Hamming window. A set of RR intervals is automatically and repeatedly analyzed when the length of RR data reaches the preset number of samples.

The power spectrum calculated without resampling (Lomb's method) is shown in the left panel, and the usual FFT with resampling in the right panel. The horizontal frequency range of the window is automatically adjusted to the resampling frequency / 2 (Nyquist frequency). The power of VLF, LF and HF bands, mean, SD and range of each segment are listed in the textbox below.

The analyzer generates a test series of RR intervals. At any given time, users are able to handle the amplitude and frequency of basic sine wave, 1/f noise wave and ectopic beats. The test data are immediately created and displayed in the textbox in the upper window. The analyser shows the power spectrum of the test data.

3.4. Communication between two systems

The virtual ECG simulator and the HRV analyzer are communicating with each other by the Windows message mechanism. The ECG simulator reports the RR
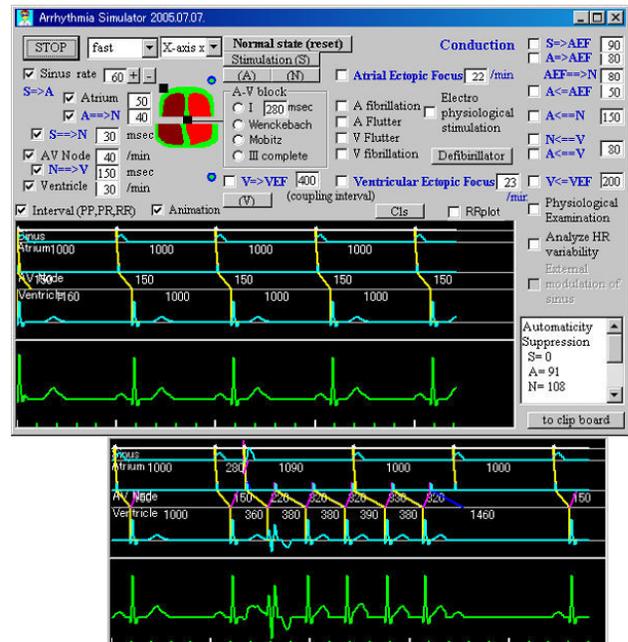
Figure 4. The upper panel shows a sinus rhythm. The lower panel shows a re-entrant tachycardia. Magenta diagonal lines in the AV node indicate retrograde conduction. A single external stimulus in the atrium initiates a micro re-entry in the AV node.

intervals to the HRV analyzer. The HRV analyzer receives the RR intervals beat-by-beat, and automatically analyzes the RR intervals under the preset condition. The user can interactively see how the arrhythmia, such as ectopic beats and Wenckebach rhythms, affects the HRV analysis.

Inversely, the HRV analyzer can optionally control the sinus node of the ECG simulator via a Windows message. The sinus node in the simulator has no fluctuation itself. To make the sinus arrhythmia, the HRV analyzer forcibly fluctuates the sinus node by the generated RR data via a Windows message (Figure 6).

4. Discussion and conclusions

HRV analysis has long been considered only as a "research toy," but nowadays it has gained growing interest in the clinical field as well [4]. Although the HRV software presents the power spectrum, the quality of the spectrum analysis depends on the sampling of the underlying continuous signals and noise content. To understand the basics of HRV analysis, it may be useful to analyze RR intervals composed of sine waves defined arbitrarily by an amplitude and a frequency. Our interactive HRV analysis with various settings, sampling rate, the number of samples, etc. will give more insights into a frequency-domain phenomenon. The HRV analyzer automatically receives virtual RR intervals and

periodically analyzes HRV. The users are able to see the effect of arrhythmias on an HRV analysis at any one given time. Sometimes the RR interval time series
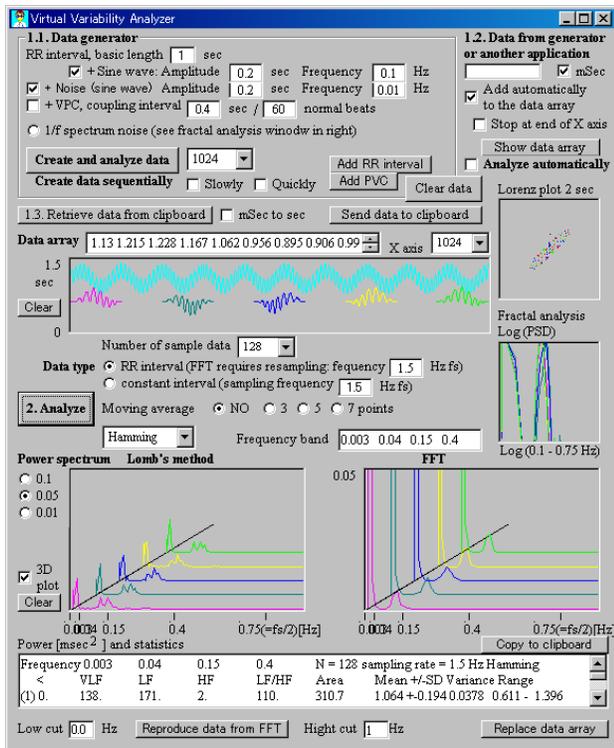
Figure 5. The HRV analyzer not only receives RR intervals from the ECG simulator, but also generates virtual RR data internally. A data-set area in the top of the window has 2 input textboxes to generate hypothetical data, a basic cycle length, 2 sets of amplitudes and frequency defining a sine wave, the number of extra beats, etc. Generated data can be modified manually in the data array textbox in the middle of the window.
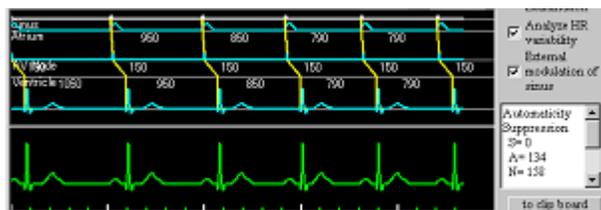
Figure 6. The HRV analyzer fluctuates the sinus rhythm of the ECG simulator via a Windows message.

includes a disturbing low-frequency, baseline trend component [4]. Our present HRV analyzer should be revised for detrending function.

Our system is unique in that the arrhythmia simulator and the HRV analyzer communicate via Windows message to analyze RR intervals or to externally control the sinus node of the ECG simulator. The HRV fluctuates the sinus node of the ECG simulator as an autonomic nervous system controls the sinus node in a living body. Although the handling of the Windows message require some additional coding in the programming, the modification of the original main codes was negligible. The communication method was proven effective to integrate or control the medical simulation systems independently developed.

Finally, the HRV analyzer showed the variation of power spectrum density influenced by a baseline trend of RR intervals, ectopic beats, sampling rate, the number of samples and window function. The interactive applications will help users in their understanding and interpretation of HRV.

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