ACTS: Automated Calculation of Tachograms and Systograms

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Summary

We present a software program, ACTS (Automated Calculation of Tachograms and Systograms), written in a graphical language that performs fast QRS-peak detection in electrocardiogram (ECG) signals and recognizes the systolic blood pressure values (SBP) in blood pressure curves. After peak detection, the consecutive peak-to-peak intervals are calculated and stored for later processing of heart rate variability (HRV) and blood pressure variability (BPV). The program we developed has been tested for speed and effectiveness and compared with a commercially available program, Windaq data analysis. We found that ACTS performed 5 times faster in detecting QRS complexes and SBP values. ACTS also made incorrect annotations about 10 times less than the Windaq program. Because correct QRS detection is a must for the calculation of HRV, visual inspection and correction of the tachograms used to be very time-consuming. With the aid of ACTS this job is performed much faster.

Key Words

ECG, HRV, DSP, peak detection

Introduction

Heart rate (HR) and (systolic) blood pressure (SBP) are characterized by continuous fluctuations, which can be quantified by heart rate variability (HRV) or blood pressure variability (BPV) techniques, respectively. These HRV and BPV measurements are used as markers of cardiovascular autonomic modulation [1]. Time domain analysis of HRV and BPV uses statistical methods to quantify the variation of the standard deviation or the differences between successive intervals. Frequency domain spectral analysis allows calculating the respiratory rate dependent high-frequency power, which is mediated purely by vagal activity, and low-frequency power, which has been suggested to represent predominantly sympathetic modulation [2]. Currently, the most important clinical applications are post-myocardial infarction risk stratification and detection of diabetic neuropathy [1].

The correct detection of QRS peaks in the electrocardiogram (ECG) and of the systolic maxima in the blood pressure curve is a step of paramount importance in determining tachograms and systograms, respectively. Tachograms and systograms are then used to calculate HRV and BPV. Erroneously detected or missed peaks introduce significant artifacts, especially in spectral analysis, and have been a source of misinterpretation. Commercially available algorithms frequently fail to detect the R peaks in ECG signals adequately. These failures can mostly be attributed to 50 Hz interference, artifacts, or large P or T waves. Quality control, including manual correction of these incorrect annotations, is often very time-consuming.

The purpose of this project was to develop a software program in LabVIEW (Laboratory Virtual Instrument Engineering Workbench, National Instruments, Austin, TX, USA). This program should, firstly, import the digital signal from an acquisition system, which we chose to be Windaq with Advanced Codas (Keitley Instruments, Cleveland, OH, USA), into LabVIEW, and, secondly, calculate the tachogram and systogram. Finally, based on these signals, advanced signal processing has to be performed, such as the calculation of HRV, BPV, and baroreflex sensitivity. Thus, the program was supposed to accelerate and automate most of the, to date very time-consuming, processing of ECGs and blood pressure curves.

Materials and Methods

Digital data input into LabVIEW

The analog ECG and blood pressure signals were recorded in humans and in rats for at least 10 min with the Windaq data acquisition system (Dataq DI220PGH, 8 channels, 12-bit precision, 82.9 kHz maximum sampling rate on all channels [3], DATAQ Instruments Inc., Akron, OH, USA). At least two channels were recorded, each at a sampling rate of 1000 Hz, providing a temporal resolution of 1 ms. The signals were stored in the binary format CODAS, proper for Windaq, that can be read with Windaq Playback (DATAQ Instruments Inc., Akron, OH, USA). Restricted calculations can be performed with Advanced Codas. A normal procedure (using Windaq Playback) to detect QRS peaks on an ECG signal uses the following steps: 1) calculation of the sliding average, using a negative smoothing factor to remove baseline drift, 2) subtraction of the noise level, 3) positive rectification of the ECG signal, and 4) peak detection. Finally, after a visual inspection of the detected peaks, a point file is generated in spreadsheet format (ASYST or Lotus), containing the consecutive RR or SBP intervals exported as an ASCII file.

The new program that performs import and peak detection on the Windaq files with the ECG and blood pressure signals has been written in LabVIEW 4.0.1 (National Instruments, Austin, TX, USA), a graphical programming language with many visualization options. The binary Windaq file consists of three parts: a header, the data, and a trailer. The header contains 35 elements of various byte sizes [4], describing every

data acquisition parameter, as well as various relative references to the data and trailer elements. Header element 1 describes the total number of channels contained in the file and the sample rate denominator. Header element 1 is a 2-byte, unsigned integer. The total length of the header is 1156 bytes. The number of channels is coded in the bits T0 to T4 in bytes 0 and 1. In LabVIEW, these 2 bytes are configured differently, as can be seen in Figure 1.

The data element of the file contains, for each enabled channel, the A/D converted data of the ECG and SBP recordings. In each sample, coded into 2 bytes, 12 bits contain the actual information of the recorded data. The other 4 bits contain additional channel information. The channels are multiplexed, which means, if 3 channels are enabled during acquisition, the format of the data element looks like this:

Data array = $[A_0] + [B_0] + [C_0] + [A_1] + [B_1] + [C_1] + [A_2] + [B_2] + ...$

A_i = samples of channel 1, B_i = samples of channel 2, C_i = samples of channel 3.

The trailer element contains information related to event markers created during acquisition, event marker annotations, and time and date stamping information. To decode the number of channels recorded during acquisition, a special subVI (equivalent to a subroutine in conventional languages) in LabVIEW (Figure 2) converts the bits T0 to T4 to a decimal number. This number is used to de-multiplex the data array in the correct number of channels. The data array is read at an offset of 1156 bytes from the beginning of the file, because the header section for the standard Windaq version has a length of 1156 bytes. In this way, each channel is reconstructed without loss of information.

ECG peak detection algorithm

To obtain the tachogram, we first need to calculate the intervals between the consecutive heartbeats or RR intervals. The program we developed detects the peak-to-peak intervals between consecutive QRS complexes, based on a level-triggered peak detection, and calculates the time intervals between them. In an ECG signal, we can mark peaks (the top of the R wave) or valleys, depending on the lead used. A peak detection level higher than the T waves but smaller than the R peaks has to be set by the user (Figure 3). The user also
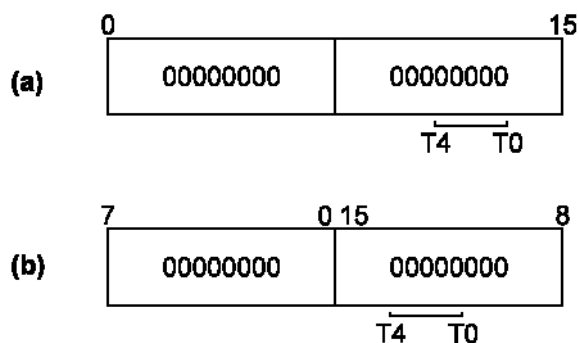

Figure 1. Configuration of bytes 0 and 1 (a) in the Windaq binary file and (b) in LabVIEW.
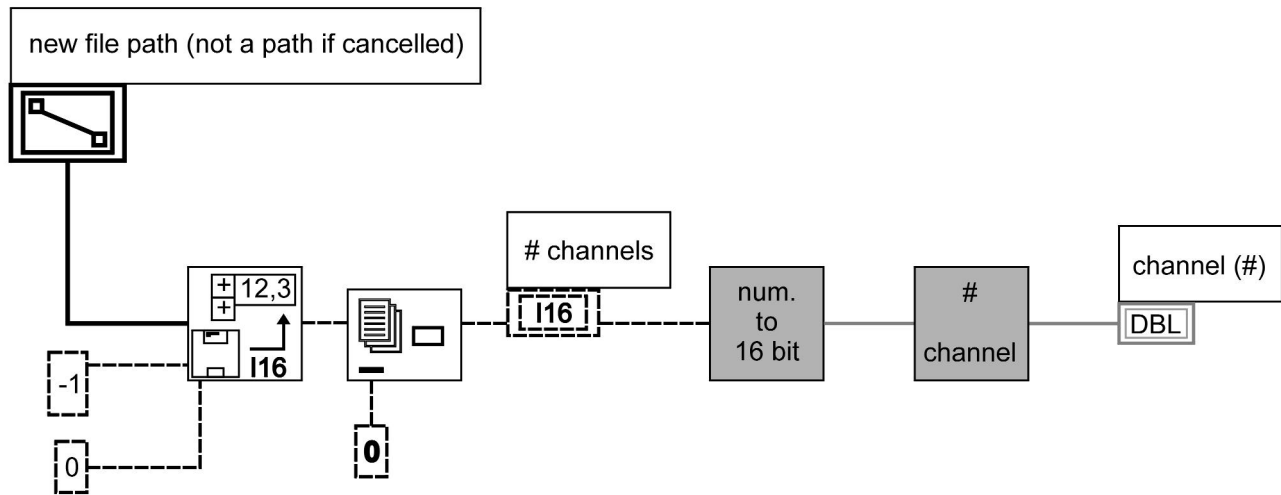
Figure 2. LabVIEW subVI to decode the number of channels enabled during acquisition.

has to mark one RR interval on the signal tracing. This interval will be used in the peak detection algorithm as an offset from one detected peak to the next peak.

The R peaks will be detected as indicated in Figure 4. Because of the baseline drift of the ECG signal, a high-pass filter (cut-off frequency 1.0 Hz) is applied prior to calculation of the peaks or valleys. This removes the low-frequency baseline drift but does not alter the shape of the QRS complex (maximum peak in power spectrum: f_{QRS}=4.1 Hz).

The moment the ECG signal exceeds the threshold level, the maximum value (or the minimum when detecting a valley) of the signal is calculated in a window of half the length of the user-indicated RR interval. To avoid double peak detection on broad QRS complexes with RR' configuration, an offset (blanking period) of 1/3 the window length from the detected peak or valley is applied. Figure 5 illustrates this algorithm.
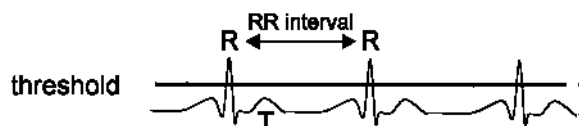
Peak detection on blood pressure signals

The tachogram only needs a single input: the RR interval. The time base can be reconstructed by simple accumulation. In contrast, the systogram requires two inputs: the consecutive SBPs at their maximal value and the corresponding timing. Because the amplitude of the SBP is needed, a high-pass filter cannot be applied to the blood pressure signal. This also implies that a fixed threshold algorithm can no longer be used. The blood pressure samples are first converted to mmHg units. Then, SBP peak detection is performed, based on the Automatic Baseline Control (ABC) algorithm [5]. ABC has also been used in some pacemaker algorithms. The ABC algorithm is represented in the flow chart of Figure 6.

To avoid loss of an adequate threshold when an artifact or erroneous annotation is encountered, the threshold variation can only be 50% of the difference between the previous and the present peak amplitude. The user

Figure 3. Example of a correct setting for the threshold level.
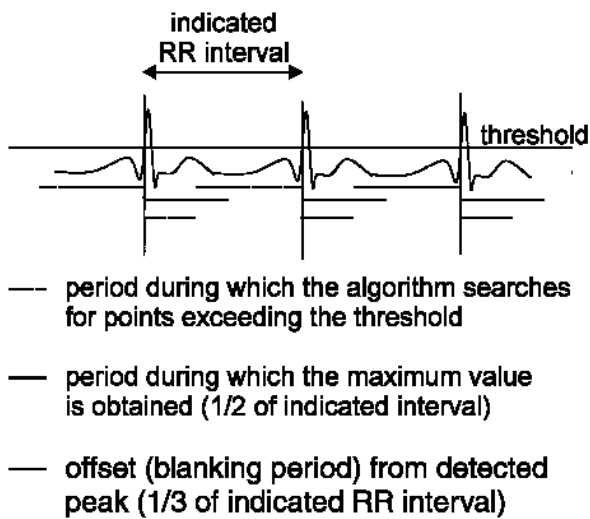

Figure 4. Detection of QRS peaks.

Fig. 5. Illustration of the peak detection algorithm on an ECG signal.

has to set the threshold of the first SBP wave. When the blood pressure signal exceeds the threshold level, the point where the signal drops below the threshold is detected. In this window, the maximum SBP value is then marked as a peak.

Power line interference (50 Hz) sometimes causes (small) spikes that cross the threshold level. As a necessary condition for implementing our program, at least 20 consecutive samples have to be above or

below the threshold level before the next peak can be detected. If there are less than 20 samples satisfying the threshold criterion, no mark is placed.

In Figure 7, an SBP curve with smooth transition and one with a transition in which a spike crosses the threshold level are shown. With the 20-sample criterion, this spike does not cause an erroneous annotation.

The LabVIEW program: ACTS

When running ACTS (Automated Calculation of Tachograms and Systograms), it prompts the user to indicate which Windaq file (filename.WDQ) has to be processed. Immediately, all recorded channels are displayed. The user now sets the detection level for every channel separately and indicates whether peak or valley detection is desired. The user also marks one RR interval that will be used to calculate the offset, as described above. After calculation of the peaks or valleys, a window appears that allows correction of erroneous annotations. In this window, a graph is generated with the consecutive RR intervals and/or systolic pressure against a time base (the tachogram or systogram), and a short period of the ECG or SBP signal is displayed. The ECG/SBP signal displayed corresponds to the RR or PP interval marked on the tachogram/systogram and is controlled by a cursor. After inspection of the tachogram/systogram, a simple button-click brings the user back to the main program.
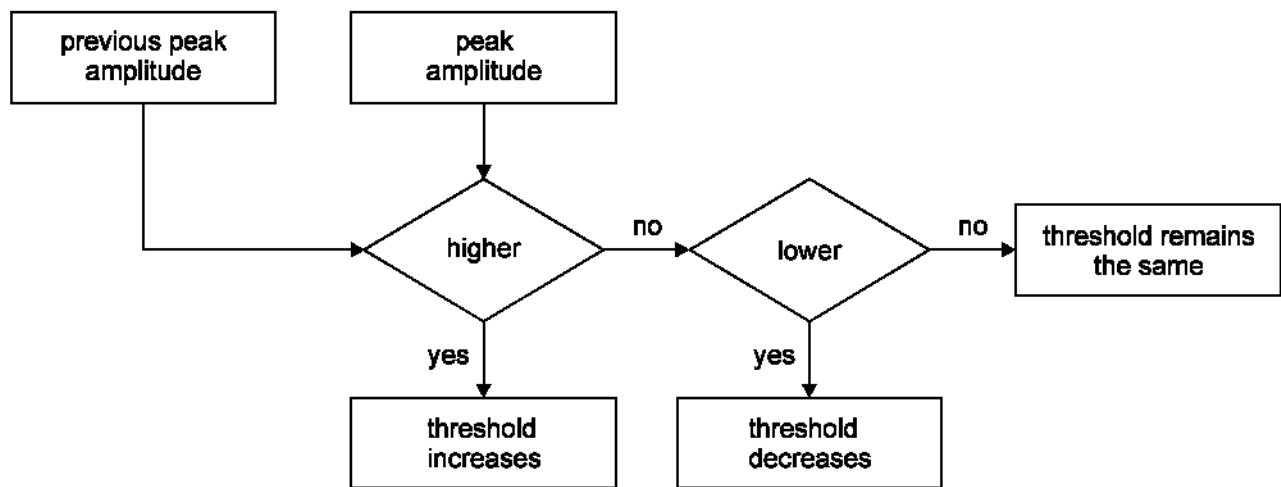

Figure 6. Flow chart of the ABC algorithm used for peak detection on blood pressure signals.
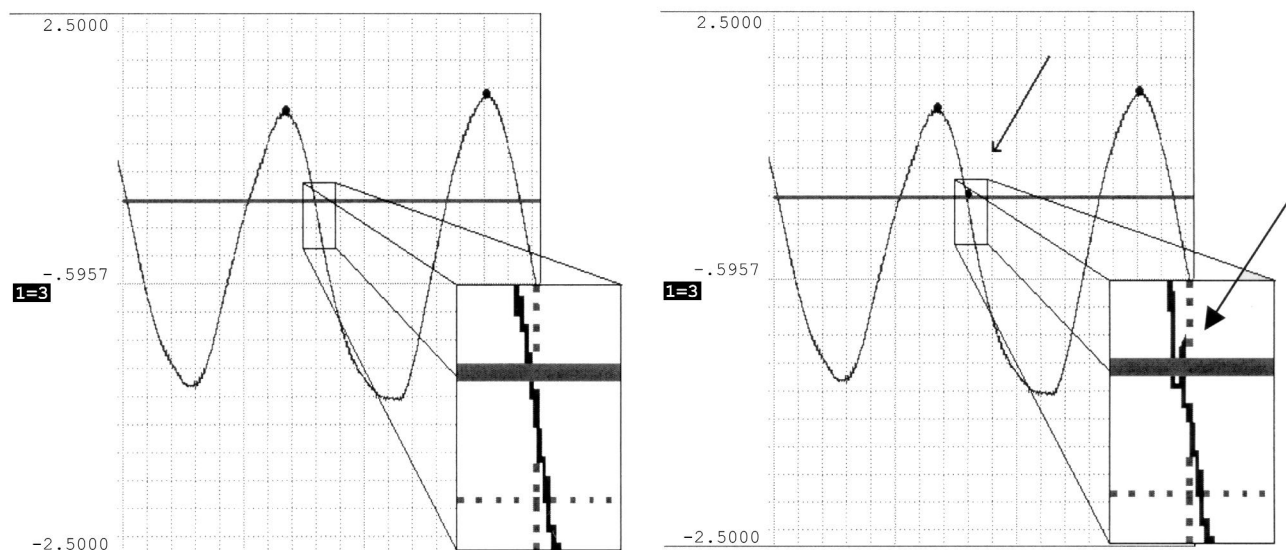
Figure 7. A blood pressure curve with smooth transition (left) and a blood pressure curve with a spike (right). Without the 20-sample criterion, this spike would cause an erroneous annotation.

Visual inspection is facilitated, because one can simultaneously view the original ECG/SBP signal and the tachogram/systogram. In the main program, an enlarged signal display with marked peaks is presented to the user. The user is able to switch between ECG and tachogram plot or SBP curve and systogram. The instantaneous link between the tachogram/systogram mode and the original ECG/SBP tracing mode allows immediate identification of any abnormality. A text file that contains the consecutive RR or SBP intervals for each channel separately can then be generated. Depending on the nature of the signal (ECG or blood pressure signal), the filename receives the extension RR or BP.

Results

The ACTS program has been tested for speed and effectiveness, and the results were compared to commercially available software for peak detection, Windaq Advanced Codas.
Ten files from a 10-minute 2-channel recording of human ECG signals and ten files from an ECG and SBP recording of a rat were tested. Time recording started at the opening of the file and stopped when the text file containing the RR or SBP intervals was saved in a correct format. ACTS needed an average of 7 min and 46 s (SD 0 min 29 s) to process a 10-minute recording of a 2-channel ECG tracing, whereas the Windaq algorithm needed an average of 35 min and 21 s (SD: 7 min 18 s).
Counting the number of incorrect annotations tested the effectiveness of the programs. ACTS had a mean of 9.4 incorrect annotations per file, while Windaq performed worse with a mean of 86.5 incorrect annotations per file. The main reason for the ACTS program to falsely detect a peak was a low signal-to-noise ratio. The Windaq algorithm performed less effectively because it fails to recognize 50-Hz interference or (high-frequency) muscular potentials in the signal. Furthermore, it frequently failed when the QRS complex was broad and double-spiked (RR' pattern).
The tachogram/systogram files that ACTS produced were also processed with another LabVIEW program that calculates HRV and BPV. The results were compared with the results obtained from the processing of the text file created with the Windaq software. There were no significant differences.

Conclusion

The ACTS program in LabVIEW has been thoroughly tested with both ECG and blood pressure signals. Speed and efficiency were compared with the results obtained from a commercially available peak-detection software program. ACTS provides a large speed gain by automatically calculating the tachogram or systogram from an ECG signal or SBP signal, respectively. Its ease of use and its speed advantage make ACTS definitely superior to the Windaq peak-detection software.

The ACTS program is available from the authors at shipping cost.

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