Beats: An Interactive Research Oriented ECG Analysis System

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Abstract

We developed BEATS (Beat Editing And Tracking Software), an interactive program to extract beat-to-beat information about the QRST complex. It is aimed at recordings of intermediate length, typically 20 minutes, corresponding to an average exercise ECG.

BEATS accepts any 8-channel ECG recording which is then converted into a 3-channel vectorcardiographic X, Y, Z representation and the spatial velocity. After beat detection the user aids the program in determining the global positions of the onset QRS, J point and T apex at several different heart rates. From the global T apices the local T apex, the steepest slope in the descending limb of the T wave and the end of the T wave are determined.

BEATS produces a file with baseline corrected signals and a file with the parameters for each QRST complex. These files can be used as input for other programs that run unattended and extract QRST features like QRS- and T- integrals, QRST angle, etc.

1.   Introduction

Although the electrocardiogram (ECG) is over 100 years old, its ease of use and its value in the clinic is still unsurpassed. With the introduction of the digital ECG, many analysis programs became available, mainly with a commercial background and designed to robustly perform in the clinic. Most of these commercial programs do not offer options for the user to interfere with the detection and analysis of the ECG. While this may be preferable in a clinical setting, it may hamper research in case key values (e.g. QT interval, QRS duration) are incorrectly calculated. Also, many values of interest may be missing (e.g. the spatial angle between the QRS and T axes). To that purpose the LEADS program was developed in our department [1]. Briefly, this VCG (vector cardiogram) based program takes a 10-60 s 8-channel representation of a standard 12-lead recording, constructs one averaged beat from beats selected by the user and calculates a large number of parameters for this averaged beat. LEADS has been used extensively in our department and by cooperating groups and has been the basis of a number of publications [e.g. 2, 3]. One of the restrictions of LEADS, however, is that only parameters form averaged beats are calculated and no beat-to-beat changes can be measured, like in T wave alternans (TWA). In order to address these limitations we have developed a sister program, BEATS (Beat Editing And Tracking Software) that will perform a beat-by-beat analysis of recordings of up to 1 hour.

2.   Methods

2.1.   Design

Focus and approach: BEATS focuses on the determination of features of the individual QRST complexes in recordings of considerable length, with emphasis on the T wave. BEATS does not attempt to discriminate between different morphologies nor does it perform any (rhythm) diagnostics.

Programming language: MATLAB (The MathWorks, Natick, MA, USA, release R2007b). BEATS runs equally well on Windows PC and Apple Macintosh computers.

Input: BEATS accepts 8 channel (I, II, V1-V6) recordings sampled at 500 Hz in ASCII Comma Separated Values (CSV) format. The length of the recording is but limited by the computer's memory. On a typical PC with the Windows XP operating system and 2 GB of memory, recordings of up to 45 minutes have been routinely analyzed without problems. Currently, conversion modules to the CSV input format have been developed for Siemens®, Philips®, Physio Control® and Mortara® 12 lead 10 s resting ECGs and Case8000® (GE Medical Systems) exercise ECGs. Before BEATS processing, we use a preprocessing program with adaptive high-pass filtering, to correct for coarse baseline drift, according to the method developed by Shusterman et al. [4], although BEATS also accepts uncorrected ECGs.

Output: Measured ECG landmarks as Tab Separated Values (TSV); a (coarse plus fine) baseline corrected ECG (8 channel CSV); a complete history of all user actions (for debugging purposes); and an auto save file to minimize data loss in case of an abnormal program termination.

2.2.   Processing stages

Initialization: Initially, a VCG is synthesized from the 8-channel ECG data by using the conversion matrix by Kors [5].

Beat detection: Fully automated; detects QRS complexes when spatial velocities of the VCG rise above the default threshold. Detection can be influenced by changing the threshold, which may be necessary when, e.g., the morphology of the QRS complex changes during the recording.

Baseline correction: The baseline is adjusted by piecewise linear interpolation through the isoelectric points preceding each QRS complex (according to the baseline correction method developed by Shusterman et. al. [4].

Viewing: The recording is presented as baseline corrected X, Y and Z signals and, selectable, 1) the spatial velocity, 2) the vector magnitude or 3) the first derivative of the vector magnitude. All signals can be magnified (amplitude, time scale, or both). The instantaneous heart rate is given and 2 horizontal lines mark the 95 and 110 bpm positions throughout the display (see Figure 1). The latter is usually considered the heart rate range of interest for TWA analysis.

Interaction: Each individual complex or a range of complexes can be selected or deselected for parameter calculation. Falsely identified QRS complexes can be deleted and the exact position of undetected QRS complexes can be inserted. The user also provides BEATS with initial guesses for the global position of the key landmarks in time in and around the QRST complex (the isoelectric point, the onset QRS, the J point, and the T apex) at the highest, lowest and 3 intermediate heart rates.
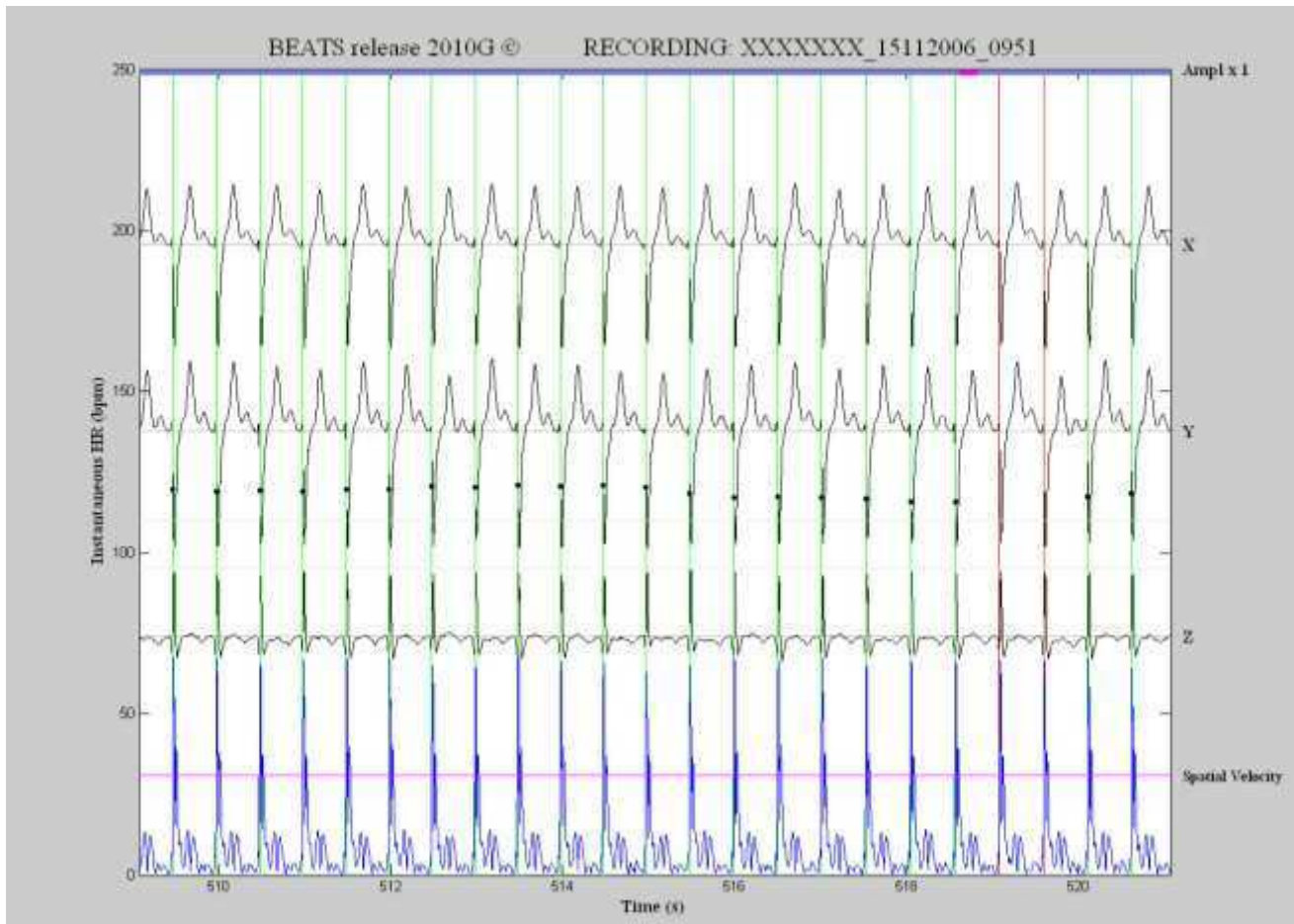

Figure 1: Early processing stage. The upper 3 signals represent the X, Y and Z components of the VCG, each with their isoelectric lines (grey), the lower signal represents the spatial velocity with the threshold (horizontal magenta line) used for beat detection. Vertical green lines denote selected beats, red lines denote rejected, deselected beats. The two horizontal grey lines mark the 95 and 110 bpm heart rate band, the small black dots represent the instantaneous heart rate.

Calculations: In order to compensate for varying positions of the landmarks at different heart rates, the positions marked by the user are used to calculate the global positions at all intermediate heart rates using a second order fit. After each recalculation, the positions of the isoelectric points are used to perform a new baseline correction. T-wave landmarks are determined in the vector magnitude signal. For each T apex, a second order fit is performed to precisely localize the apex. The steepest slope following the T apex is then determined by linear regression of 10 samples in a moving window of 60 ms after the apex. The end of the T wave is finally determined as the intersection of the steepest slope and the abscissa.

Parameter visualization: The fiducial points of all beats are given with a vertical line, green for selected beats, red for deselected beats. Optionally, the positions of the globally calculated parameters can be viewed as dotted lines, those of the individually calculated T apex, steepest slope and end of T as solid lines. For each marker line the distance to the corresponding fiducial point may displayed in ms (see Figure 2).

Consistency check: A typical recording of 20 minutes may consist of over 2500 QRST complexes. Correct detection and/or parameter calculation of each individual complex may not be possible due to noise or other confounders. The following inconsistencies can be brought to the user's attention with a yellow square, upon request: large differences in consecutive instantaneous heart rate, QT values or positions of the steepest slope and parameters that are out-of-sequence. If necessary, the corresponding QRST complexes can be deselected and thus be excluded from the analysis.
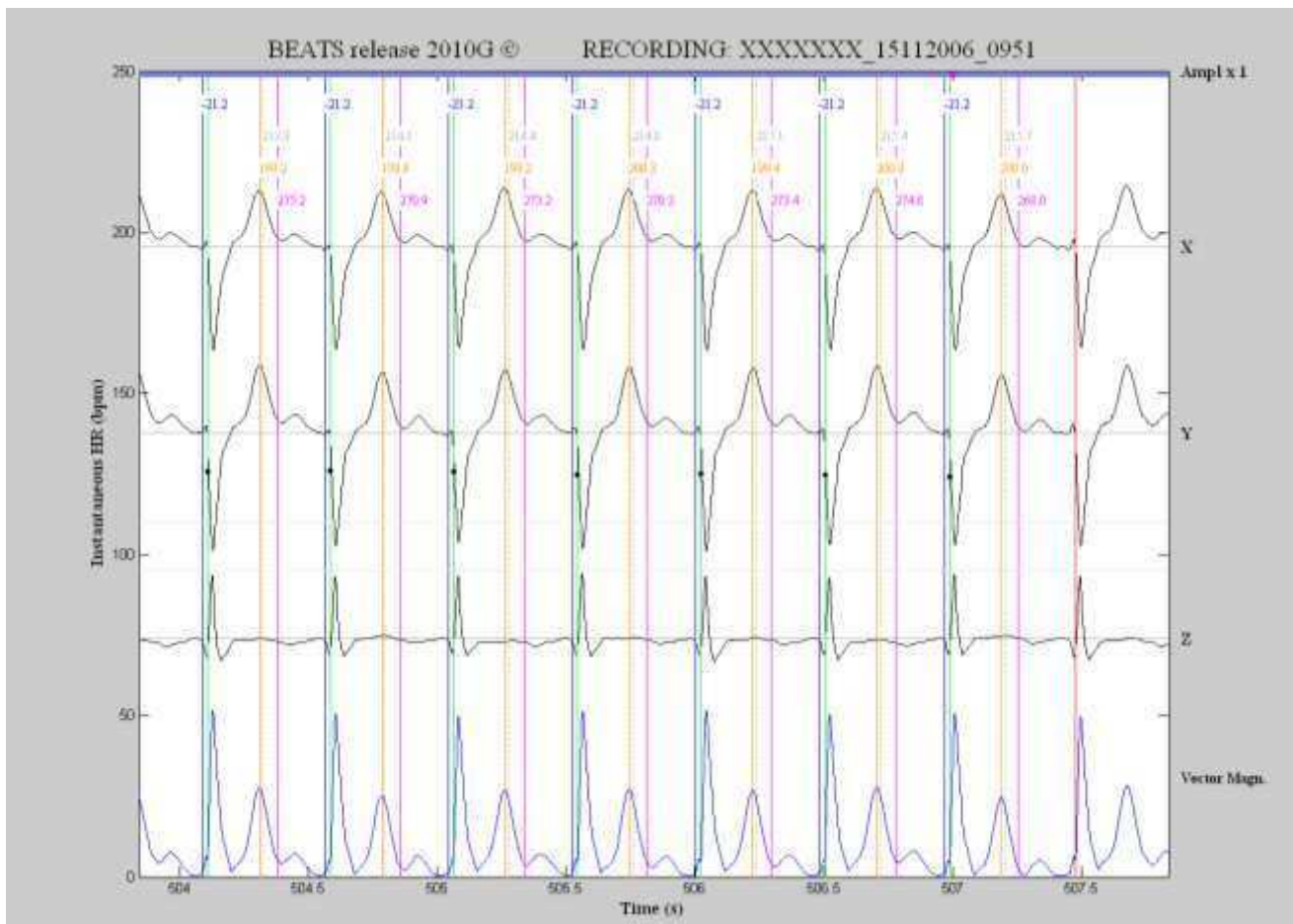

Figure 2: Example of a nearly finished analysis with the position of the global T apices (dotted), local T apices (orange), end of the T wave (magenta) and onset QRS (blue). Positions are displayed as vertical lines and numerically in the upper part of the figure. All values are in ms and are relative to the fiducial point. Additional parameters, not shown in this example, are: isoelectric point, J point and steepest slope. Note that the lower tracing represents the vector magnitude rather than the spatial velocity.

Saving: 1) The parameters are saved in consecutively numbered files in order to enable the user to continue analysis later, or to experiment with different detection levels and be able to revert to previous settings. Automatic loading of the most recent parameter file at the beginning of a session will skip the beat detection and calculation routines described above. 2) The complete 8 channel signal with the corrected baseline is saved as a CSV file, as input for other programs. It is not used as input for BEATS again: when a subsequent BEATS analysis of the same recording is done, the original input signal is used again. 3) Each minute an autosave file with all parameters is updated, only to be used in case of an abnormal prorgam termination.

3.   Results

The number of recordings currently processed by BEATS is now around 500. Ca. 100 of these analyses were recorded during various forms of mental stress tests, and performed, with its main purpose, to accurately determine the onset QRS to facilitate Heart Rate Variability (HRV) analysis of these recordings (to be published). Most of the remaining recordings were analysed to calculate TWA in exercise ECGs of patients with an implantable cardiac defibrillator (ICD) (to be published). Ca. 35 recordings were analysed to calculate the ventricular gradient in ICD patients [6].

The average time needed to perform a complete analysis on an uncomplicated 20 min recording with good signal quality requires no more than 5 min. For more complicated and/or noisy signals a complete analysis may take over 30 min to complete.

4.   Discussion

BEATS has proven to be a reliable tool for extracting a number of landmarks from ECG recordings of up to 45 minutes.

In our experience, inaccurate initial guesses, especially with respect to the isoelectric point, the onset QRS and the J point could lead to inaccurate results. We therefore adopted the strategy that initial guesses be made in high-quality areas of the recording. The T apex is less affected by a slightly erroneous guess because the each apex is robustly determined by a second order best fit. However, we are confident that with a little training the user will be able to make the initial guesses for the most a difficult parameter, the isoelectric point, to within 5 ms of each other and within 2 ms for the other parameters.

We have chosen not to give the user the option of individually marking the end of each T wave since this will result in a mix of machine determined and human determined values, thus introducing a bias.

For researchers interested in cooperation we can provide BEATS in executable format (PC or Macintosh computers).

A feature extraction program (FEATS) is also available to calculate, beat-to-beat, over 35 features. These features include, but are not limited to, the azimuths, the elevations and the magnitudes of the QRS vector, the T vector and the ventricular gradient. Also, the QRS axis and T axis azimuths and elevations, and the QRS-T spatial angle and the angle in the frontal plane are calculated.

We feel that this description of our approach to the design of this research-oriented ECG analysis program might be helpful to others who are planning to create comparable software.

References

[1] Draisma HHM, Swenne CA, van de Vooren H, Maan AC, Hooft van Huysduynen B, van der Wall EE, Schalij MJ. LEADS: An Interactive Research Oriented ECG/VCG Analysis System. Computers in Cardiology 2005;32:515-8.

[2] Hooft van Huysduynen B, van Straten A, Swenne CA, Maan AC, van Eck HJ, Schalij MJ et al. Reduction of QRS duration after pulmonary valve replacement in adult Fallot patients is related to reduction of right ventricular volume. Eur Heart J 2005;26(9):928-932.

[3] Hooft van Huysduynen B, Swenne CA, Draisma HHM, Antoni ML, Van de Vooren H, Van der Wall EE et al. Validation of ECG indices of ventricular repolarization heterogeneity: a computer simulation study. J Cardiovasc Electrophysiol 2005;16:1-7.

[4] Shusterman V, Shah SI, Beigel A, Anderson KP. Enhancing the Precision of ECG Baseline Correction: Selective Filtering and Removal of Residual Error. Computers and Biomedical Research 2000;33:144–160.

[5] Kors JA, van Herpen G, Sittig AC, van Bemmel JH. Reconstruction of the Frank vectorcardiogram from standard electrocardiographic leads: diagnostic comparison of different methods. Eur Heart J 1990;11(12):1083-1092.

[6] Man S, de Winter PV, Thijssen J, Maan AC, van Meerwijk WPM, van der Wall EE, Schalij MJ, Swenne, CA. Changes in The Ventricular Gradient Measured During Exercise Tests Predict Antiarrhythmic Therapy in Primary Prevention ICD Patients. Computers in Cardiology 2010;37 (in press).

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