

LEADS: An Interactive Research Oriented ECG/VCG Analysis System

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Abstract

We recently developed a MATLAB program, LEADS (Leiden ECG Analysis and Decomposition Software), for research oriented ECG/VCG analysis. Any eight-channel recording in Comma-Separated Values format (CSV) can be input. After detection of QRST complexes in the spatial velocity signal and baseline correction, LEADS generates a default selection of beats for subsequent averaging. The analyst may then adjust this selection, after which the selected beats are averaged to generate a representative and low-noise averaged beat (ECG and VCG). In this beat, LEADS computes default onset-QRS, end-QRS and end-T instants, which may be subsequently reviewed/edited. Finally, several conventional and advanced ECG and VCG parameters are automatically computed, and the results are output in the form of a CSV file. By virtue of the combination of adjustable configuration settings and interactive procedures, LEADS has provided us with the ability to reliably analyze ECGs ranging from normal to highly pathological.

1. Introduction

More than 100 years after its conception, the electrocardiogram (ECG) remains vivid and alive; as a popular clinical diagnostic procedure and also as the subject of scientific research. Computerized signal processing became an option several decades ago, and since that time a multitude of programs for ECG analysis have become available.

Regarding the standard 12-lead ECG, clinical programs have always focussed on automated parameter measurement and on the reliable generation of diagnostic statements. These programs are essentially designed to perform part of the work of the ECG analyst and of the cardiologist, who may subsequently concentrate on reviewing the measurement results and the generated diagnosis. Nearly all of these programs have a commercial background, their performance has been validated with databases such as the CSE database, and in many cases they are built-in to the electrocardiograph.

When doing research, such commercial facilities can

be of help, however, there are severe limitations. Due to the fact that they are designed to perform robustly in the clinic, commercial programs are not very flexible. When, for example, such a program incorrectly measures QRS duration, it is in most cases impossible to get the correct value other than by estimating it from the printed ECG or from the computer screen. Furthermore, in the rare case where there is access to the measured ECG characteristics, this set of parameters is often not what is needed. E.g., the electrical axes of the QRS complex and of the T wave are often available only in the frontal plane, and not in three dimensions. This means that a simple but essential ECG parameter, the spatial angle between the QRS axis and the T axis, cannot be determined.

To our knowledge, there is currently no software on the market for experimental standard 12-lead ECG processing that includes the option to add one's own algorithms (the exception might be the new CardioSoft[®] system, introduced during the Computers in Cardiology 2005 conference). Existing systems with experimental possibilities are bound to a specific center. This prompted us to develop our own ECG processing program which we have named LEADS (Leiden ECG Analysis & Decomposition Software). In the following we describe the design philosophy and the major algorithms and interactive procedures of LEADS.

2. Methods

2.1. Design philosophy

Based on the experiences with the first version of LEADS in 2003, the current 2005 version was developed. The main considerations that underlie LEADS are listed in the following paragraphs.

Focus and approach: LEADS focuses on the determination of a low-noise representative averaged beat (QRST complex), in which multiple parameters can be measured, paying special attention to the T wave. LEADS combines the standard 12-lead ECG approach with the vectorcardiographic (VCG) approach. No diagnostic options or rhythm detection are built in. Only parameters that cannot easily be derived from others are output, e.g. end-T instants in each ECG lead are output but not QT

dispersion.

Programming language: MATLAB (The MathWorks, Natick, MA, USA, release 14). The MATLAB environment was chosen due to its universal nature and widespread use in research and scientific computing.

Input: LEADS accepts any eight-channel (leads I, II, V1-V6), 500 Hz sampled ECG with a resolution of 5 μ V/bit and duration between 10 seconds and 1 minute. Currently, conversion modules to the ASCII Comma-Separated Values (CSV) LEADS input format exist for Marquette[®], Mortara[®] and Siemens[®] ECGs.

Output: Measured ECG parameters in CSV format; ECG plots in portable document format (PDF). Temporary graphs generated during processing may be saved at will in one of the MATLAB supported figure export formats.

Reliability of the results: High reliability of the results is achieved through combining automated processing (to accomplish at least a reasonable quality initial analysis) with interactive review/edit procedures to fine-tune the analysis results.

Default analysis: Fully automated; should analyze any ECG waveform. Correct performance in the case of bizarre QRST waveforms and extreme heart rates can be achieved by editing the processing-parameter file.

Interaction: Review/edit procedures allow for correction of the beats that were automatically accepted/rejected for computation of the averaged beat, and for correction of the default settings of the onset-QRS, end-QRS and end-T instants. Full use of the MATLAB zooming option during interaction. Where useful (e.g., in end-QRS setting), graphs are displayed with ECG leads superimposed.

Reprocessing with next LEADS versions: When an ECG is processed for the first time, the processing parameters of the default analysis results and the user corrections are all stored in a history file. When new versions of LEADS are released which compute more ECG parameters, ECGs which have been previously processed can now be processed automatically, in batch, by accessing their history files.

2.2. Computed parameters

LEADS computes conventional and advanced ECG and VCG parameters. Parameters output are as follows:

Administrative:

- ▶ LEADS version
- ▶ Recording ID
- ▶ Analysis date and time
- ▶ VCG reconstruction matrix used

Beats:

- ▶ # of accepted beats; # of rejected beats
- ▶ Mean interbeat interval preceding accepted beats

QRS complex:

- ▶ QRS axis azimuth and elevation
- ▶ Maximal vector (instant and magnitude)
- ▶ End-QRS instant
- ▶ QRS integral for 12 leads
- ▶ Spatial QRS integral magnitude

T wave:

- ▶ T axis azimuth and elevation
- ▶ Maximal vector (instant and magnitude)
- ▶ 'Global' end-T instant, determined in vector magnitude signal
- ▶ T integral for 12 leads
- ▶ Spatial T integral magnitude
- ▶ Area end-QRS – apex-T in vector magnitude
- ▶ Area apex-T – global end-T in vector magnitude
- ▶ Apex-T instants and amplitudes for 12 leads
- ▶ End-T instants for 12 leads
- ▶ Area end-QRS – apex-T for 12 leads
- ▶ Area apex-T – global end-T for 12 leads
- ▶ T singular values σ_1 - σ_8
- ▶ J, J+60 and J+80 amplitudes for 12 leads

QRS complex & T wave:

- ▶ QRS-T spatial angle
- ▶ QRS-T angle in frontal plane
- ▶ Ventricular gradient azimuth, elevation and magnitude

User actions:

- ▶ Shifts by user of onset-QRS, end-QRS, end-T instants
- ▶ User comments.

2.3. Processing stages

In this section, we aim to give a general overview of the LEADS processing stages. Obviously, many details that may become very relevant under certain conditions, had to be omitted.

Initialization. After reading of the processing-parameter file, and (when existing) the processing history file the ECG file is read. ECG leads III, aVL, aVF and aVR are computed and the VCG is generated using either the inverse Dower matrix or the Kors matrix [1].

Beat detection. Beats are detected in the spatial velocity signal derived from the VCG. Rough beat detection is conducted with a default threshold of 15% of the maximal spatial velocity value. This parameter and processing parameters that follow can all be modified in the processing-parameter file. Fine detection is achieved by a back search until the point is reached where the spatial velocity is under a default threshold of 5% of the maximal spatial velocity value. This yields the fiducial points for later averaging.

Paced beats. If the paced beats detector is set to ON in the processing-parameter file, the fiducial points for

averaging are detected in the pacing pulses rather than in the upstroke of the following QRS complexes. Thereby the morphology of the pacing pulse will be retained in the coherently averaged beat.

Baseline correction. The amplitude of all ECG and VCG leads is averaged between -30 and -10 ms before every fiducial point. We suppose that (these parts of) the PR-segments are isoelectric. The baseline is assessed by a cubic splines interpolation between these average amplitudes which are -20 ms before the fiducial points. Subsequently, the ECG and VCG are baseline corrected. Beats with more than default $10 \mu\text{V}$ baseline sway are excluded from the default set of beats to be averaged.

Interbeat intervals. Next the interbeat intervals are computed. Beats with preceding intervals that are default $<20\%$ premature or $>20\%$ postmature are excluded from the default set of beats to be averaged.

Noise estimation. In every beat, skipping the first 200 ms, the high-frequent noise content is determined. When the noise level is above a default threshold of $90 \mu\text{V}$, the beat is excluded from the default set of beats to be averaged (skipped mean average, see also [2]).

Review/edit beat selection; beat averaging. The complete ECG is presented to the LEADS analyst, together with the default beat selection for averaging. The user may freely change this selection. The final selection of beats is used to compute the averaged beat (ECG and VCG). In addition, the mean interval preceding the selected beats is computed.

Onset-QRS, end-QRS, end-T. Further computations are conducted on the averaged beat. Default onset-QRS, end-QRS and end-T instants are computed in the vector magnitude signal (see Figure 1).

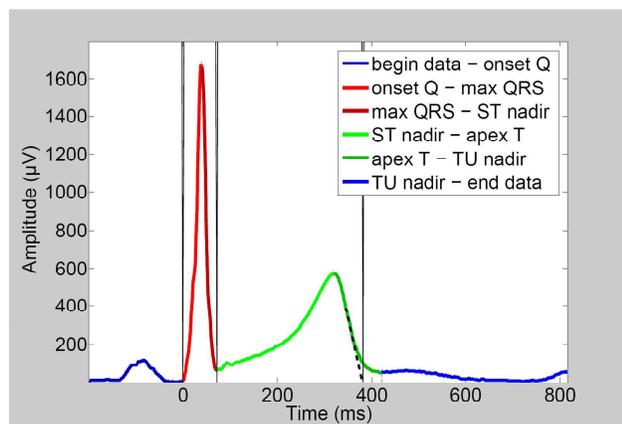


Figure 1. Plot to inspect the automatically determined onset-QRS, end-QRS and end-T instants. Complex ECGs (e.g., congenital heart disease) sometimes require searching interval adjustment.

Onset-QRS is found with a parabolic fit method at the

lower left leg of the QRS complex. End-QRS is at the smallest vector magnitude between QRS and T.

Global end-T is at the intersection of the steepest tangent to the descending leg of the T wave with the baseline; an analogous method is used to find the end-T instants in the 12 ECG leads.

Also, the peak-T and TU-nadir are determined in H.

Review/edit onset-QRS, end-QRS, and end-T instants. The user may shift these points with the aid of a crosshair cursor (see Figure 2 and Acknowledgements).

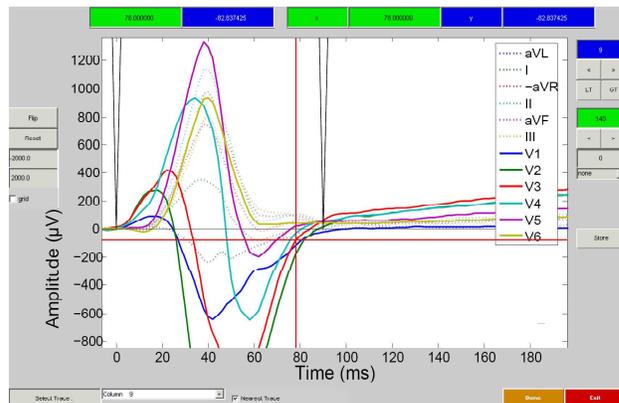


Figure 2. Crosshair adjustment of automatically determined onset-QRS, end-QRS and end-T. Often, the end-QRS determination is critical. The superimposed zoomable display helps to identify the lead with the latest J point in keeping with the Minnesota code.

Parameter calculation and output. Given a low-noise averaged beat that is representative for the recording and in which the user may or may not have corrected the onset-QRS, end-QRS and end-T instants, all variables as listed in section 2.2 can now directly be computed and output. Graphical output consists of two PDF format files with a standard ECG and the average beat, respectively (see Figure 3).

3. Results

To date, we have processed approximately 3000 ECGs with LEADS. About one third of these ECGs were pathological: heart failure (including right ventricular, left ventricular and biventricular pacing); congenital heart disease (Tetralogy of Fallot) [3-5]. Another third was relatively noisy, due to the fact that they were made during maximal exercise tests [6]. Signal quality permitting (if a 10-s ECG is very noisy, averaging does not help much due to the limited amount of noise-free beats) we have always succeeded to adjust the processing-parameter file in such a way, and to perform the interactive procedures in such a way that a reliable result was attained.

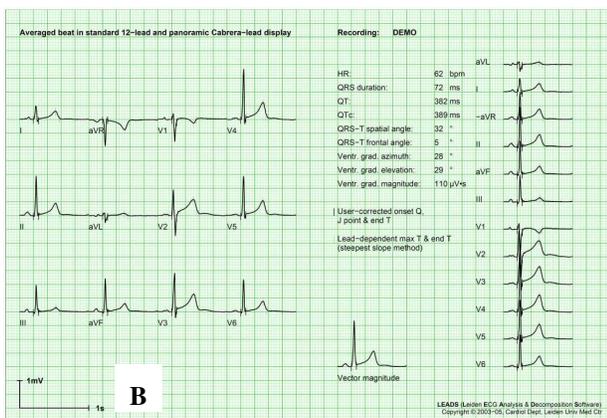
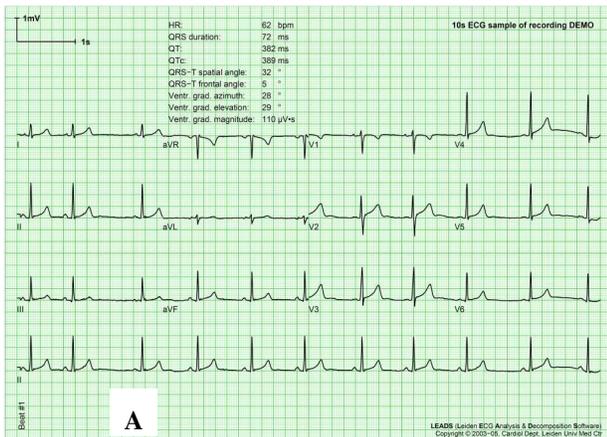


Figure 3. When an ECG has been analyzed using LEADS, both a 10-s sample (in standard 12-lead display; panel A) and the averaged beat (in standard 12-lead as well as in Cabrera-lead display; panel B), together with a selection of analysis results are output in PDF format.

4. Discussion and conclusions

In our approach, the human observer decides about what is correct and not correct in ECG analysis. It is the human observer who reviews and corrects the computer decisions if necessary. This is accepted practice in biological signal processing, but it is also considered essential to compare the decisions of multiple observers and to compare multiple decisions by the same observer about the same ECG, to ensure the inter- and intra-observer consistency. This will be accomplished for LEADS in the near future. We will also test how effectively the default onset-QRS and end-QRS landmarks perform (the tangent method for end-T determination is generally accepted).

In summary, we have developed a computer assisted ECG/VCG measurement program that may be used in conjunction with routine clinical electrocardiography for research purposes. Processing remains fully under the

control of the ECG analyst, and it is relatively easy to implement the computation of new ECG or VCG parameters.

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

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