ECGlab: User Friendly ECG/VCG Analysis Tool for Research Environments

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Abstract

We present ECGlab, a cross-platform, user friendly, graphical user interface for assessing results from automated analysis of ECGs in research environments. ECGlab allows visual inspection and adjudication of ECGs. It is part of our recently developed framework to automatically analyze ECGs from clinical studies, including those in the US Food and Drug Administration (FDA) ECG Warehouse. ECGlab is written in C++ using open-source libraries. Supported ECG formats include Physionet, ISHNE and FDA XML HL7. ECG processing and automated analysis is done with ECGlib (ECG analysis library). ECGs can be loaded individually or grouped using ECGlib index format and information such as demographics or signal quality metrics can be loaded from metafiles to navigate through the ECGs and guide their review. The user can graphically adjudicate the ECGs in a semi-automatic or manual fashion. Vectorcardiograms can be assessed as well. A prototype for automatic extraction, based on heart rate stability and signal quality, of 10 seconds ECGs from continuous Holter recordings is also available. ECGlab, which has been successfully tested in Linux and Microsoft Windows, is currently being used to assess ECGs from clinical studies. We are working on making ECGlab open-source in order to facilitate ECG research.

1. Introduction

Since 2005, the US Food and Drug Administration (FDA) and European regulatory agencies require almost all new drugs to undergo a Thorough-QT study [1] to assess the drug's proarrhythmic potential. The FDA ECG Warehouse [2] contains over 6 million digital ECGs from more than 200 Thorough-QT studies.

We recently developed an extensible framework for ECG automatic analysis (ECGlib [3]) in order to assess existing and new ECG biomarkers in clinical studies, including those from the FDA ECG Warehouse. While with ECGlib we were able to analyze hundreds of thousands of ECGs, we needed to be able to navigate through those ECGs and their corresponding analyses results in order to validate, review and improve our ECG analysis methods. We developed a graphical user interface (ECGlab) to perform these tasks. Although there are other ECG processing libraries and graphical user interfaces [4–7] available, we designed and developed ECGlib and ECGlab to be able to run in any operating system and without the need of any proprietary software (e.g. [5] and [6] require Matlab). We therefore developed a user friendly graphical user interface to enable graphical assessment of ECGs which we call ECGlab. ECGlab integrates with the ECGlib framework, which allows the user to process and automatically or semi-automatically adjudicate ECGs through its graphical user interface. ECGlab allows smart navigation, filtering, visual inspection and review of high volumes of previously analyzed ECGs using study protocol related information, such as demographics, subject, visit, study arm or time-point, but also additional information such as signal quality metrics. To address the need of extracting 10 seconds ECG strips from continuous Holter recordings, we are currently developing a separate tool (Holterlab), which allows ECG strips to be extracted either manually or using heart rate stability and signal quality criteria. These ECG strips can be automatically analyzed and grouped with ECGlib and the results can be reviewed with ECGlab.

2. Methods

We designed and developed ECGlab - a graphical user interface that employs ECGlib library - to be used as a viewer for visual inspection of one single ECG, either for semiautomatic processing of databases containing thousands ECGs. Figure 1 shows ECGlab's general layout and

its integration with ECGlib. ECG files are loaded form directories or from an ECGlib index into a list or tree view. An additional metadata file can be loaded into a table where ECGs can be filtered and ordered by different metrics. The selected ECG can be semi-automatically annotated. Annotations (such as offset of QRS complex and T wave) can be edited using the mouse or a text-based editor. Different measures of the ECG are displayed on screen. An optional workflow for reassessment can be specified to facilitate adjudication of multiple ECGs. ECGlab invokes ECGlibs application program interface (API) when loading ECGs and performing ECG processing tasks.

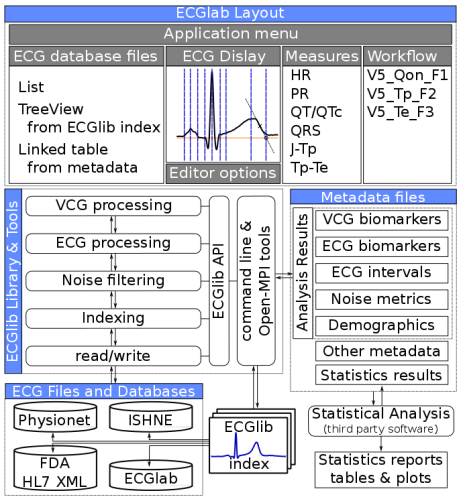

Figure 1. ECGlab's layout and integration with ECGlib.

2.1. ECG supported file formats

ECGlab supports the same ECG file formats as ECGlib, which include FDA XML HL7 [8], ISHNE [9] and Physionet [10]. Additionally, we defined the ECGlab XML file format to store the ECG analysis results produced by ECGlib. Briefly, a file contains a set of ECG waveforms and recording details (i.e. sampling frequency, recording time, etc.). Although longer recordings are supported, usually a waveform contains a 10 seconds strip with its corresponding beat-based annotations, and an optional derived waveform (e.g. a median beat) with its own annotations. The format supports storing annotations from multiple assessors in so-called annotation sets (e.g., from an automated algorithm or adjudicated annotations).

2.2. On-screen ECG/VCG assessment

We designed a graphical user interface to display ECGlab file format, which allowed us to visually assess the results of our automatic analysis in a 'file manager' fashion: list and tree views for navigation, table view with user defined ordering and a search text box.

We incorporated semiautomatic ECG adjudication features to the graphical user interface in two steps. First we added an on-screen fully manual annotation edition, which allowed us to correct wrong or missing automatic annotations either in global or in individual leads. Next, we included the automatic delineation by integrating the appropriate ECGlib calls to a wavelet-based delineator [11] and a least-squares tangent method [12] for T-wave offset assessment.

Finally, we incorporated a vectorcardiogram (VCG) display and integrated ECGlibs VCG methods into the user's menu, so the user can derive the Frank's VCG from any 12-lead ECG using inverse Dower [13], Kors [14] or Guldenring [15] transformation matrices. VCG from singular value decomposition can be computed and displayed too.

2.3. ECG database navigation assistant

When working with databases of ECGs, ECGlab can open a directory or a zip file, populate a list with the filenames in the graphical user interface, and then load and display each ECG as needed. Zip file support allows increasing speed and reducing network load in case of remotely stored databases.

Clinical study databases might contain thousands of ECGs, which are usually organized by subject, treatment arm, visit and time-point. When automatically analyzing a database, ECGlib builds an index pointing to the original raw signals, the pre-processing results (i.e. ECG signals after power-line noise removal and baseline wander correction) and the ECG processing results (i.e. QRS complexes in the 10 seconds strip, derived median beats and their corresponding annotations). To facilitate the review of large amount of ECGs from a clinical study database, ECGlab can load ECGlib index files and display them in a tree view organized by subject, visit and time-point, which facilitates the review tasks.

To facilitate the evaluation of outliers, we incorporated a sortable table view that allows loading metadata information from comma separated value (CSV) files. The first column of the CSV file contains the ECGlib index path of the corresponding ECG file, while the following columns can contain any arbitrary variables such us demographics, individual or global lead interval durations, noise metrics or any other statistical values. These files can be generated during automatic ECG analysis or using external tools for data analysis (such as R, MATLAB or EXCEL). The table can be sorted by specific variable, filtered and specific ECGs can be opened with a mouse double-click.

2.4. Semiautomatic assessment workflow

When semi-automatically adjudicating ECG databases, the user has to repeat the same operations for each ECG.

ECGlab can load a workflow file which allows assigning keyboard short-cuts to specific actions. For example, if the user is assessing Q-onset and T-end in V5 in the median beat of all the ECGs, the actions of i) selecting lead V5, ii) selecting or creating the Q-onset and iii) waiting for user validation or correction can be assigned to F8 so when user presses F8 he only needs to confirm or correct. T-end related actions can be assigned to F9 in a similar fashion. The tangent used by the least-square method [12] can be displayed to assist the user to determine the end of the T wave (Figure 2).

2.5. ECG extraction tool for Holters

A separate tool (Holterlab) to perform ECG extractions from long term Holter recordings was also required. The tool had to be able to load and display long 12-lead recordings (e.g. >24 hours long), support protocol event based navigation and help the user to select and extract 10 seconds ECG strips based on heart rate stability (e.g. Badilini, et al. [16]) and signal quality criteria.

Holterlab uses ECGlibs QRS detector to compute and display RR time series, which are then combined with signal quality metrics by ECGlib extraction methods. Extractions can be performed either manually or in a semi-automatic or fully automatic fashion.

3. Results

Two different graphical user interfaces were developed using Qt GUI toolkit [17]. Both are written in C++ using open-source libraries, while core ECG signal processing is performed by ECGlib library.

3.1. ECGlab graphical user interface

The ECGlab graphical user interface (Figure 2) is organized on three panels. On the left, the ECG Database Navigation Assistant panel allows browsing and navigating through the ECGs, also using the additional controls: search/filtering text box, navigation buttons, tree view and metadata table. The metafile tab shows a sortable table populated with the ECGlib index path and variables from any CSV file as described in 2.3 above. The user can sort the ECGs, either ascending or descending, by any variable just clicking on the column of the variable. By double clicking a row, the selected ECG is shown in the display and automatically selected in the tree view, which facilitates its comparison with other ECGs around the same time-point.

The central panel can display ECG signals in different modalities selecting the corresponding tab: ECG (superimposed of single lead), 4x3 ECG view, VCG (Figure 3). Semi-automatic annotations can be done either on the ECG display view or through the annotations editor control below the ECG display.

The right panels show current ECG measurements and the currently loaded workflow (optional).

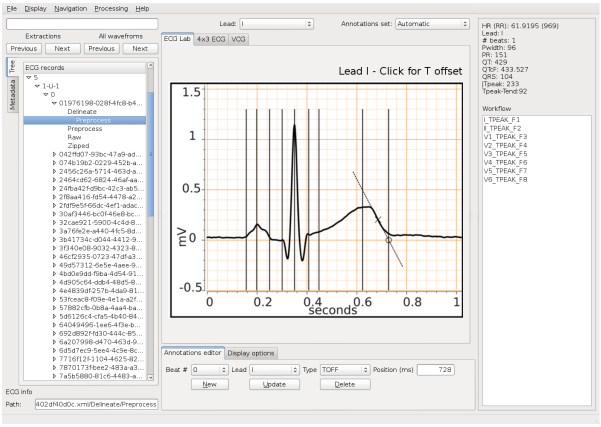

Figure 2. Screenshot of ECGlab user interface.

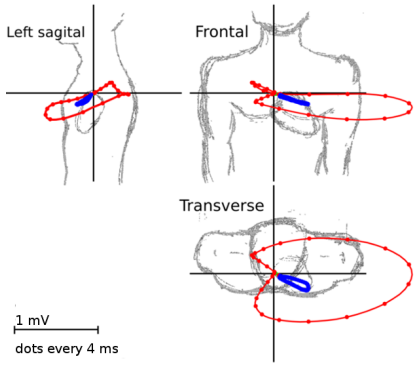

Figure 3. VCG detail from ECGlab's VCG view.

3.2. Holterlab graphical user interface

Figure 4 shows a screenshot of the Holterlab graphical user interface while reviewing a 10 minutes 12-lead ECG Holter.

On the left, the view panel shows a section of the ECG in the upper part and the heart rate (RR series) in the lower part. The leads are displayed in sequence from top to bottom (lead I-III, augmented leads and V1-V6). The user can select the length of the displayed ECG (default is 10 seconds).

On the right, the information and event panel shows the available patient information and displays the recorded events, loaded from a CSV file. The ECG time window relative to a certain event is automatically selected when double clicking on an event.

The user can perform 10 seconds extractions manually or using the automatic method. Extractions are saved in ECGlab file format to allow further comprehensive analysis with ECGlab or other ECGlib tools.

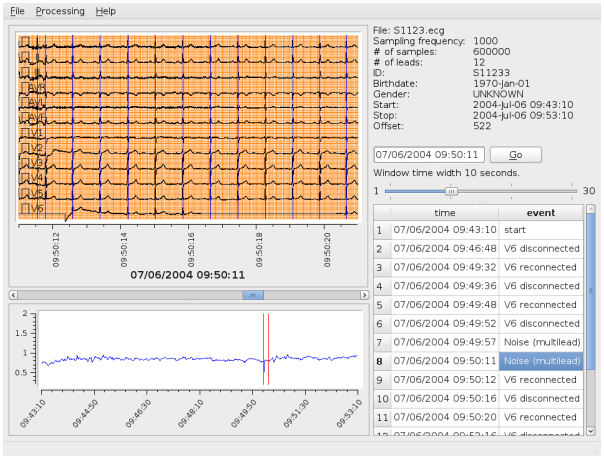

Figure 4. Screenshot of Holterlab.

4. Discussion

ECGlab has been tested successfully in Linux and Microsoft Windows. Currently it is being used to assess automatic measurements obtained from Thorough-QT studies and other clinical studies [18].

We are currently working on making ECGlab and ECGlib open-source in order to facilitate ECG research.

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