

# MATLAB: AN EXTENSIBLE SOFTWARE PACKAGE FOR ANALYSIS OF MULTICHANNEL ECG RECORDINGS

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**Abstract**—Analysis of multichannel ECG recordings (body surface maps and endocardial maps) requires special software. Both interactive usage of a fast and robust user interface and batch job processing for the analysis of large amounts of data is necessary. In addition, the package should be user-extensible, because new techniques for the analysis of multichannel ECGs are continuously under development, and it should not take very much time to develop.

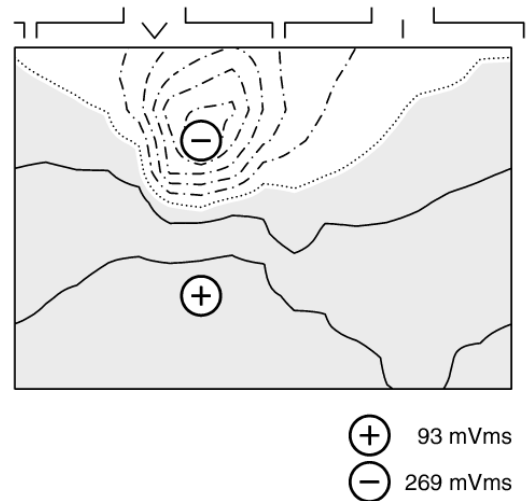
We wrote a package using an interactive computational program (MATLAB). The package includes routines for both common and experimental data processing tasks, as well as an extensive user interface. Sources are well documented using the WEB system, and available to the users. Any part of the package can be changed by the user, and new parts can be added. The package is used by its authors and several researchers from associated research groups.

## INTRODUCTION

Electrocardiographic Body Surface Map (BSM) recordings and high-resolution endocardial maps typically consist of many leads sampled at a high frequency. Our group uses recordings of 64 upto 256 channels sampled with frequencies ranging from 0.5 upto 4 kHz, 8, 14, and 16-bit resolution at bit steps of 0.73–2.0  $\mu\text{V}$ , and containing either BSM or endocardial leads, or both (see, for example, Grimbergen or Metting van Rijn[1][2]). The way these recordings are processed differs much from the way single-lead or standard 12-lead ECG's usually are processed. The multitude of channels makes visual inspection of waveforms almost impossible, but enables the spatial representation using, for example, pseudocolor maps or contour lines as shown in figure 1.

Often these recordings must be processed quickly. For example, if a BSM recording is used for localization of paced beats during catheterization, an estimate of the pacing site must be produced within seconds. In cases like this, and also if small amounts of recordings are pro-

cessed in a way that requires input from a human expert, an interactive system is necessary that can perform all common tasks easily. For example, it must be able to apply baseline corrections, integrate over time, produce pseudocolor maps of potential and integral values, detect activations in endocardial recordings, and detect QRS complexes in BSMs. Also, it would be useful if new algorithms can—with little effort—be incorporated in a user interface package, so they can be tested interactively.



**Figure 1.** Example of a Body Surface Map. The front of the subject is displayed left, the back right. Shoulders, sternum, and spine are indicated above the map. The top of the map is at the level of the superior sternal notch and the bottom is at the level of the umbilicus. Potential values are indicated with isopotential lines. The area with positive potentials is coloured grey. Maximum and minimum are indicated.

There are also cases where batch processing of data is more appropriate. For example, to create and test a new algorithm, it is often desirable to repeat the cycle of changing and testing—on a large amount of recordings—several times. Both the preprocessing of data and new algorithms often require standard routines to perform, e.g., loading of recordings from file, baseline correction, and activation detection. A toolbox of standard routines, that can be extended with newly developed methods, is then desir-

able. The presence of a library of simpler functions, to do even more common things like searching, sorting, differentiation, principal components analysis, etc. can make experimenting even easier.

Data processing routines often present their results in a graphical way, such as a pseudocolor map, a scalar tracing, histogram, or contour chart. Programs can be much easier developed if standard routines for these tasks are available.

## METHODS

We chose to create our software as a MATLAB toolbox: MATLAB (The Mathworks inc., Natick MA, USA) is a command interpreter (strictly speaking: a 'just-in-time compiler') that can apply mathematical operations to matrices, has commands for low level graphics and the creation of user interfaces built-in, and includes large libraries of computational and high-level graphical routines. It can interpret script files and dynamically link functions written in C or Fortran if a special interface library is used.

The use of an interactive programming environment makes it possible to view internal data structures at any time. In this respect, it is like running the software under an extremely versatile debugging program. Whenever the developer wishes, data can be displayed either numerically or graphically, values can be changed, and test programs can be run that verify the consistency of data structures. If an error occurs, parts of the software can be changed and operations can be repeated to check if the error disappears.

MATLAB's graphical capabilities and functions for building user interfaces made it easy for us to create a graphical user interface and graphical data displays. Our programs make extensive use of pseudocolor maps, contours, and line drawings for display of potential maps, isochrone maps, and ECG waveforms.

A drawback of an interactive programming environment is the time the program interpreter takes to operate. However, MATLAB needs to compile a program only once in a session to run it several times, and modern computers are capable to run the precompiled code fast enough for a user interface or small computations. Bottleneck operations, such as baseline correction of a multilead ECG were programmed in C, compiled, and placed in files that MATLAB can link dynamically, and then behave like any ordinary MATLAB script or built-in function, except that they are much faster than a script.

If a program contains interesting algorithms, or for any other reason needs to be understood by many people, program documentation is important. We chose the "literate programming" technique[3][4] for this purpose. A 'literate' program is written in the style of a small book. It consists of small chunks of code, that come with a de-

scription of what the code does. The code is written in the programming language of choice; the documentation is written in L<sup>A</sup>T<sub>E</sub>X (in our case), which means that it can come with mathematical formulae, graphics, references, indexes, etc. Filter programs extract the program part for the sake of the compiler and translate the program into something that L<sup>A</sup>T<sub>E</sub>X (the text processing program) can typeset. Our C-language functions were documented with CWEB[5]; For the MATLAB programs we created a literate programming system, called MWEB, ourselves.

The documentation could be printed (but it takes hundreds of pages) and was also made available on-line, by putting it on our WWW page as a set of fully cross-referenced PDF documents.

The MATLAB system runs on several platforms (we use UNIX (Linux) and Windows '95) and behaves exactly the same on all platforms, except for the look-and-feel. This makes our package platform-independent, save that the C-language routines must be compiled for each platform independently.

To accommodate both interactive use and batch processing we created in fact two packages: a low level toolbox and a separate user interface that builds on the toolbox. The toolbox can also be used independently for batch jobs, and for user-created additions.

## RESULTS

The package creates several windows on the screen; each window displays (a part of) the data in a different way, and contains user interface controls to perform tasks that are connected with the kind of display. Some of the windows are:

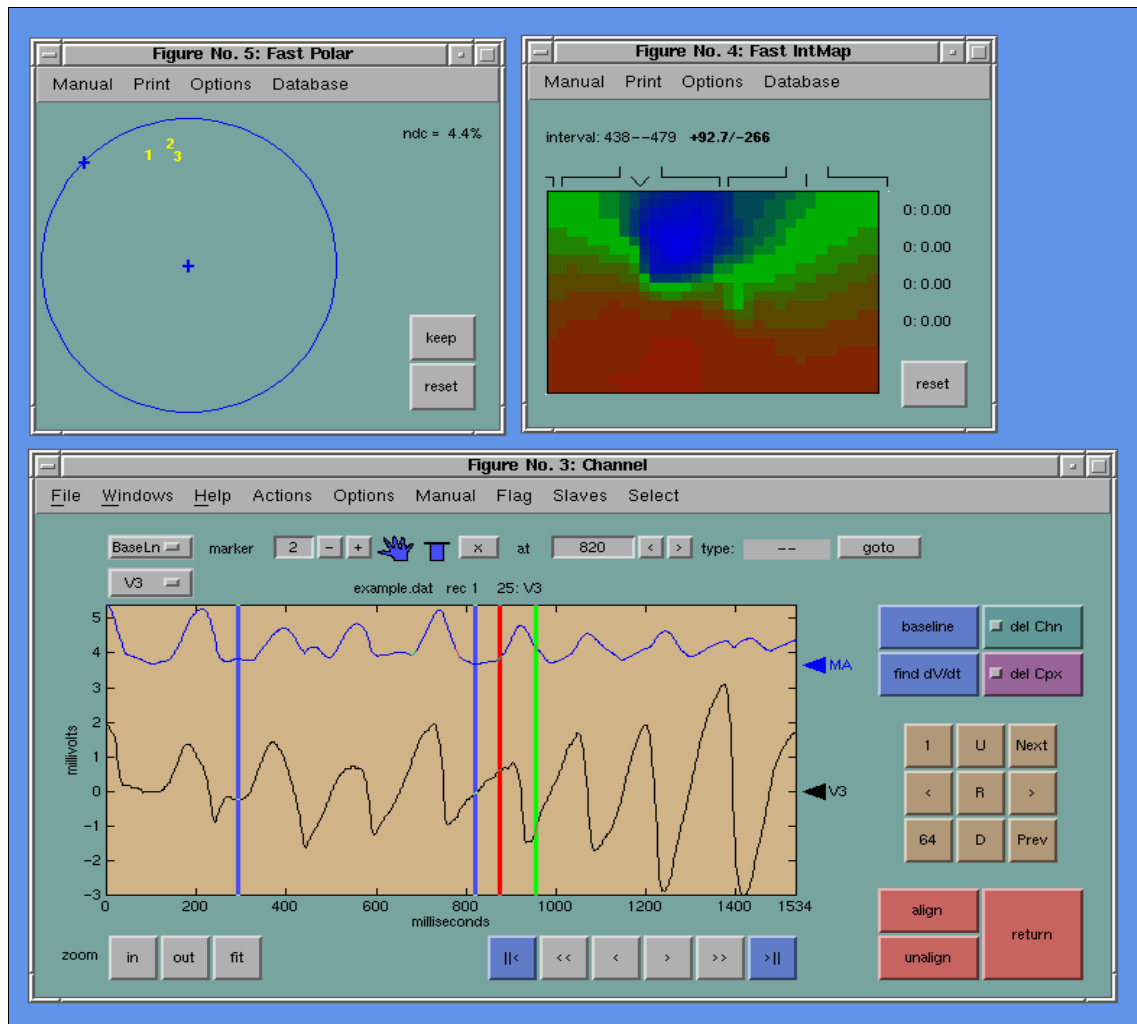
*The Recording window* shows all ECG waveforms, positioned like the underlying electrode configuration.

*The Channel window* shows an ECG plus optionally one or more other channels or derived signals that can be used as a reference. This window supports selection of time instants (such as begin and end of a QRS complex), baseline correction, filtering, etc. This window is illustrated in the bottom part of figure 2.

*The Map windows* display potential maps and integral maps, used in the analysis of multichannel surface ECGs. A Map window is illustrated in the top right of figure 2. Time instants for maps are selected in the ECG window.

*The Activation Map window* displays endocardial activation maps and isochrone charts. This window is illustrated in figure 3.

To each window correspond one or more programs that create and maintain their window. We tried to make the windows and their programs as independent as possible, but some interrelations were inevitable. Most relations, however, are hierarchical; for example, a button in one

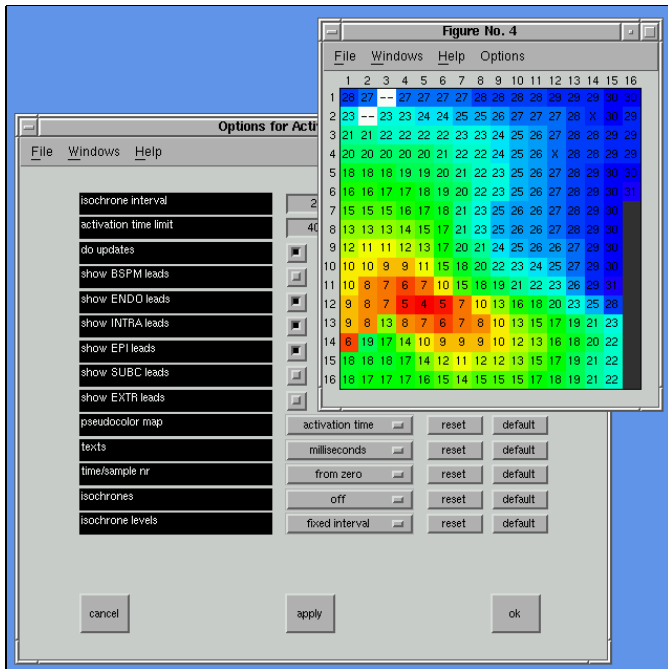


**Figure 2.** Channel window (bottom), Map window (top right), and localization window (top left). The Channel window displays two signals showing a polymorphic ventricular tachycardia sequence: precordial lead V3 (lower trace) and the mean absolute value of all channels (upper trace, labelled “MA”). The vertical bars in the ECG are called “markers.” The markers can be dragged with the mouse, and serve to indicate time instants to be used for baseline correction (left two markers), and begin and end of, for example, a QRS complex (right two markers). The Map window shows the QRS integral map thus indicated. The localization window shows a polar view of the left ventricle where three subsequent complexes of a polymorphic VT are localized.

window makes a call to a function that creates another window.

Some of the capabilities of the package are:

- loading of body surface, endocardial, and combined recordings, with configurable electrode grids, and any scale, resolution, and sampling interval
- (piecewise linear) baseline correction of ECG waveforms
- display of single-channel and multichannel ECGs (any subset of leads can be shown simultaneously)
- detection of QRS complexes as described by Kemmelings et al.[6]
- generation of potential maps and integral maps using pseudocolor plots and isopotential lines
- automatic creation of sequences of maps for the creation of movies
- comparing QRS integral maps to database maps for localization of ectopic beats[7]
- continuous localization of ectopic beats using the surface ECG and presentation in a polar projection of the ventricle, as described by Potse et al.[8] (see figure 2 top left)
- computation of ‘nondipolar content’ [9][10]
- detection of endocardial activations
- display of isochrone charts and pseudocolor activation maps
- display of colour data on three-dimensional surfaces[11]



**Figure 3.** Activation Map window and its associated options window. For every window there are one or more options windows where parameters can be changed. Using the controls in this options window the user can, e.g., switch isochrones on or off, set the isochrone interval, specify how activation times must be displayed, and select what data must be shown using pseudocolors.

- signal-alignment and signal-averaging

Some routines create high-quality graphical output, suitable for publication. An example is shown in figure 1.

## DISCUSSION

Software for multichannel ECG analysis must be fast, flexible, extensible, and easy to use. These requirements are in part contradictory. Our approach is flexible because an interactive mathematics program is used, although slower than if directly implemented in e.g. C. If a modern computer is used, the system is fast enough for our purposes. In principle the open and flexible interface allows the user to corrupt internal data. However, inexperienced users will not corrupt data because we chose variable names that are unlikely to be used by accident, and experienced users who do change the data may be assumed to know what they are doing.

On several occasions, we have implemented new methods first as MATLAB scripts, then improved them, and finally re-implemented them in C for a better performance.

The software is used by its authors, as well as by several medical and biomedical researchers, in clinical as well as experimental research groups. The fact that we use it ourselves, and the close contact with other users, have been helpful in debugging and improving the system quickly.

## CONCLUSION

The software described here makes it easier for us to implement data processing methods for multichannel ECGs and allows biomedical researchers to use them interactively. Researchers with some programmings skills can also use it for batch processing. It has been of great help in several projects, and its importance is expected to grow in the near future.

## ACKNOWLEDGEMENT

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