VizCOM: A Novel Tool for Advanced Visualization and Analysis of Cardiac Optical Mapping Data

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Abstract

Cardiac optical mapping is the state of the art used for quantifying cardiac spatiotemporal dynamics, with recent advances enabling high-quality recordings from high-resolution CMOS cameras at relatively low prices ($500). Analyzing the large data sets to extract quantitative information is now a bottleneck. We developed VizCOM, a highly interactive feature-rich Python-based tool for visualizing and analyzing cardiac optical mapping data that works on Windows and MacOS. VizCOM can process very long (minutes) voltage or simultaneous voltage-calcium recordings from various cameras. A mask can be drawn to isolate a region of interest, and the signal from any pixel can be displayed by moving the mouse over the image. Filtering methods available include stacking and baseline drift removal. Activation maps (colors/isochrones) for wave fronts/backs can be displayed. Plots of action potential duration (APD) vs. diastolic interval for all pixels and of APD dispersion across the whole tissue can be shown for each beat, as well as ΔAPD plots for alternans. APD also can be calculated for a line drawn across the tissue to analyze alternans. All values can be saved, including histograms of APD spatial distributions, APD restitutions, and movies of activation sequences. Overall, VizCOM provides comprehensive high-level support for visualization and analysis of cardiac optical-mapping signals.

1. Introduction

Over the past 30 years, optical mapping has become one of the most important tools for studying cardiac electrophysiology at high spatiotemporal resolution of voltage and calcium in *ex vivo* [1] and recently even using *in vivo* [2] hearts. Among many other discoveries, optical mapping has been instrumental in confirming the existence of reentrant spiral waves in animals [3] and in human hearts [4], 3D scroll waves [5] and discordant alternans in cardiac tissue [6, 7].

The high resolution of optical mapping allows for the collection of large amounts of spatiotemporal data, which then must be processed and analyzed. While this task initially was performed primarily with custom-written software, in recent years, several software packages have been developed to aid in the analysis of optical-mapping data.

The RHYTHM open-source toolkit [8] was developed in particular to facilitate multi-camera panoramic optical-mapping setups, including processing and analyzing data. The software, which runs in MATLAB, can perform manipulations such as averaging in time and space and has been used to construct spatial maps of activation during ventricular fibrillation.

Another option, ElectroMap [9], was designed as a high-throughout open-source toolkit that can work with datasets obtained through optical-mapping as well as other recording modalities. Running in MATLAB or as a stand-alone executable file for Windows or MacOS using the MATLAB runtime, software can be used to calculate activation and repolarization, perform ensemble averaging, identify arrhythmias, and quantify beat-to-beat heterogeneity.

A third toolkit, COSMAS [10], is provided in both MATLAB and Python and is based on scripting for user input to facilitate batch processing. COSMAS can be used to create spatial maps of activation and conduction velocity and to calculate and visualize other quantities including action potential duration (APD), calcium transient duration, and alternans.

All of these toolkits provide valuable methods, but space exists for the development of a tool independent of commercial software that supports a broad range of analysis methods. In this paper, we present our new comprehensive Python-based tool, VizCOM, which provides an expanded set of interactive offerings to visualize and analyze cardiac optical-mapping data.

2. Methods

VizCOM is an open-source software suite for the visualization and analysis of cardiac optical mapping data, developed in Python. It updates and extends a custom-written Fortran and then Java code previously developed by some

of the authors to analyze optical-mapping data [7, 11].

The graphical user interface (GUI) is built upon the PySide6 framework, a Python binding for the Qt cross-platform application toolkit (available from `https://www.qt.io`). All data visualization and plotting functionalities are handled by *pyqtgraph*, a graphics library built on top of Qt. Other core libraries used in VizCOM include NumPy, SciPy, matplotlib, and scikit-image.

The core data structure of VizCOM is a *CardiacSignal* object that contains the raw signal, metadata, and history of transformations. Upon ingestion, optical-mapping data is stored as three-dimensional arrays with dimensions corresponding to time, height, and width (T, H, W), and stored with `float32` precision. VizCOM is designed for interoperability and supports data from Cascade and SciMedia cameras, for example.

3. Results

VizCOM provides a suite of basic transformations and advanced functionalities for signal processing, and customization options to support user preferences. Upon opening, the user can select the camera type and data mode (voltage or voltage–calcium) to load the recording. The display then presents the tissue structure in one panel alongside a signal-versus-time panel. By moving the mouse over the structural image, the corresponding voltage signal for that pixel is immediately plotted in the time-series window. The main functionalities can be undone at any time and include the following:

- **Mask Generation:** It is easy to generate irregular regions of interest (masks) to restrict analysis to selected sections of the tissue (see Fig. 1). Masks can be interactively modified at any time using the mouse (adding or removing points), and brightness adjustments can be performed to better identify edges. Masks can also be saved and reloaded for use with other recordings that share the same field of view.

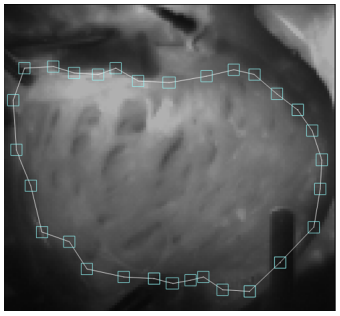

Figure 1. Example of the right ventricular endocardial structure of a mammalian heart imaged by the camera. The points indicate the interactively created mask used to restrict analysis to the region inside it.

- **Signal Conditioning** The voltage-versus-time window includes buttons and sliders for signal processing, allowing signal inversion, temporal trimming (selection of shorter time segments), and normalization of signals either pixel-wise, globally across the entire spatial domain, or within specified time sections.
- **Signal Zooming and Display:** Time signals and other graphs from the advanced analysis can be zoomed in and out using the mouse (right-clicking on the window provides options for mouse button optimization). Additional options allow adjustment of line thickness and signal and background colors, as illustrated in Fig. 2 and Fig. 4.
- **Filtering:** Spatial and temporal averaging are implemented using convolution with either Gaussian or uniform kernels, with adjustable radius and weights to suit the noise level in the recording. An additional option allows stacking of spatiotemporal signals in cases where noise is high but the signal is in steady state (i.e., periodic). The algorithm aligns action potentials based on the timing of their maximum upstroke velocity (estimated from the signal's first time derivative) and performs ensemble averaging [12], thereby greatly improving signals by increasing the signal-to-noise ratio.

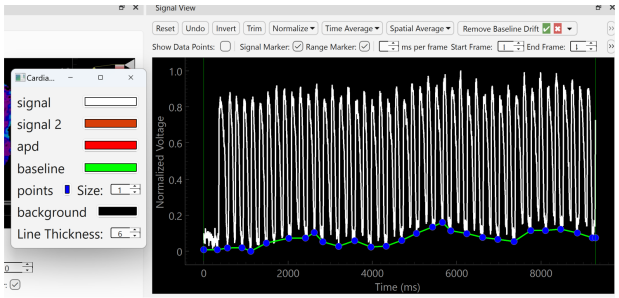

Figure 2. Example of drift removal for the voltage signal over time. Different methods are available to correct drift in the time signals. The blue line shows the calculated values that would be applied for drift removal if accepted; alternatively, parameters can be adjusted until the user is satisfied with the correction across all signals in space. The right panel illustrates how all elements of the graphs, such as signal colors, thickness, and background, can be modified. Moving the mouse across the structure image as in (Fig. 1) automatically plots the voltage signal and corresponding drift removal line for the selected pixel, allowing exploration of the entire tissue.

- **Drift Removal:** A drift correction algorithm is included, which identifies diastolic intervals (DIs) by detecting maxima and/or minima in the signals. The drift is then removed by reconstructing the signal using adjustable parameters and linear interpolation between the detected values, as illustrated in Fig. 2.
- **Time Visualization and Movies:** On the structure

panel, after processing the spatiotemporal signals, animations of the voltage or calcium signals can be played with adjustable speed (frames per second) and frame skipping. A moving line on the signal-versus-time window indicates the current position of the animation relative to the time signal. Users can also step forward or backward by any number of frames with single clicks. In addition, animations can be saved as movie files. Fig. 3A-D shows examples of snapshots of a wave propagating through tissue from the top to the bottom.

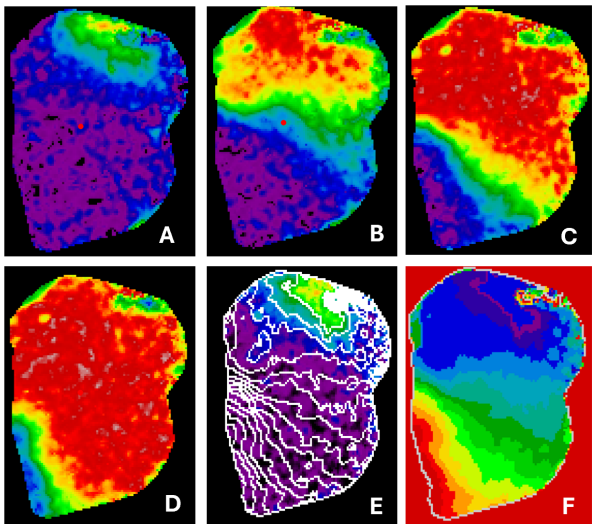

Figure 3. A-D: Examples of the voltage signal propagating from the top to the bottom from a movie generated with the data, with excited tissue in red and unexcited tissue in blue. E: Automatic contour plots generated for the propagating signal, after selecting beginning and final times to plot. F: Same as E, but as a spatial map of activation time.

VizCOM also provides several advanced analysis functionalities for extracting electrophysiological parameters.

- **Activation Mapping:** Isochrone maps of activation wavefronts and repolarization wavebacks are generated by identifying contour lines at a user-defined threshold for each time step. Fig. 3E and F show example activation maps as isochrones and a spatial map, respectively. Colormaps as well as contour line color, thickness and spacing can also be easily modified using menu options.
- **APD and DI Analysis:** APDs and DIs are calculated (or re-calculated as desired) by finding the temporal intersections of the signal with a user-defined percentage of the action potential amplitude, as shown in Fig. 4. This procedure allows for the pixel-level analysis of cardiac alternans, including the generation of APD restitution plots (APD vs. DI). Fig. 5 shows an example of an APD restitution plot generated from a single pixel across multiple beats during alternans. Once the APDs and DIs are calculated, they can be displayed on the voltage signals and restitution graphs for all pixels within the mask by moving the mouse across the structure.

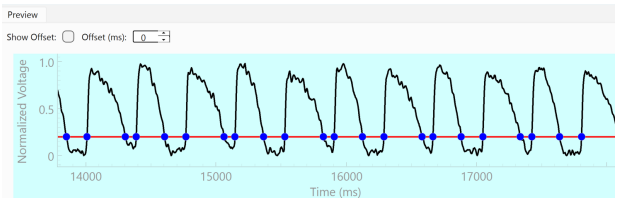

Figure 4. Example of APD alternans in the voltage signal after applying small time and space averaging together with drift removal. Moving the mouse across the structure (as in Fig. 1) automatically displays the signal for that pixel. The background, colors, and line thickness have been changed compared to Fig. 2.

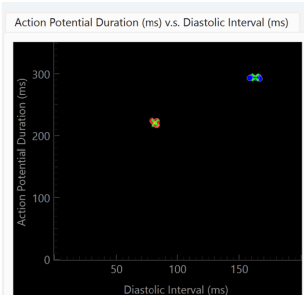

Figure 5. Calculated APD vs. DI for a point in the tissue, in this case appearing as two sets of points due to alternans. Moving the mouse across the structure (as in Fig. 1) plots the corresponding APD-DI pairs for the selected pixel.

- **Spatial APD and DI Analysis:** After APD and DI values are calculated everywhere in the tissue, spatial maps of APD and DI can be generated to quantify APD dispersion and spatiotemporal alternans patterns. Fig. 6A-B shows the dispersion of APD in space during alternans for two successive beats, with the alternation in color between the upper and lower regions demonstrating the switch between long- and short-APD regions. The difference in APD between consecutive beats can be calculated directly, as shown in Fig. 6C, which clearly shows the out-of-phase alternating regions in contrasting colors and the nodal region with near-zero difference in APD in white. The map can also be used to draw lines for use in plots of APD over space calculated across the lines for consecutive beats, as shown in Fig. 6D-E to display, for example, discordant alternans or concordant alternans along those lines.
- **Frequency Analysis:** Dominant frequency maps are computed via Fast Fourier Transform on a pixel-wise basis, enabling the localization of high-frequency sources during arrhythmia recordings.
- **Saving Data:** In addition to saving animations, all analyzed data can be exported. This includes the full fil-

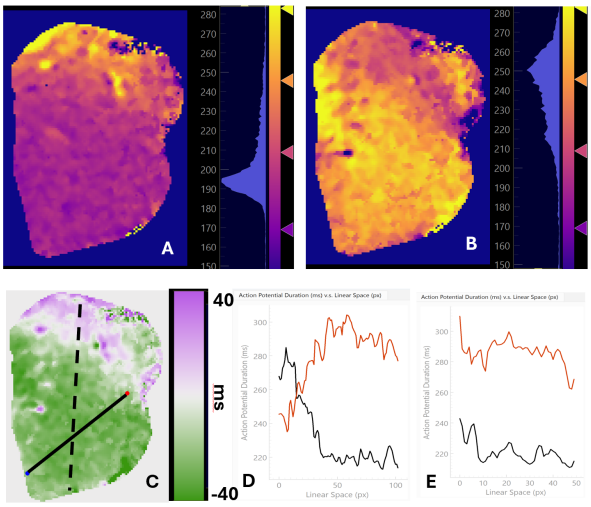

Figure 6. A-B: Calculation of dispersion in APD across the tissue for two consecutive beats during alternans. The histograms indicate how many pixels have a given APD for each beat. C: Difference in APD between consecutive beats calculated by VizCOM. D: Plot of APD across space, when selecting a line from top to bottom (dashed line in C) indicating discordant alternans going from long-short and short-long across the 1D line shown by the black and red lines. E: Same as in D but taken from the solid line in C, displaying only concordant alternans.

tered and de-drifted spatiotemporal dataset, single-pixel time signals, and spatiotemporal APD or DI dispersion values per beat, as well as spatiotemporal alternans data for further analysis or figure generation.

4. Discussion

VizCOM provides an integrated and highly interactive platform for the visualization and quantitative analysis of cardiac optical mapping data. Compared with other existing toolkits, VizCOM is open-source, Python-based, and independent of commercial software, while offering a broader range of interactive features such as drift removal, spatiotemporal filtering, and real-time exploration of pixel-level dynamics. These capabilities make it accessible to research groups without extensive computational expertise, while still providing advanced analysis for experienced users. By facilitating both basic processing and in-depth electrophysiological quantification, VizCOM can accelerate discovery in cardiac arrhythmia research and broaden the adoption of optical mapping across laboratories.

Acknowledgments

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