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# Graphical User Interface for Calculating Wave Intensity from Cardiac Catheterization Measurements

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*Abstract*— **Wave intensity analysis (WIA) as a framework to assess cardiovascular hemodynamics has been successfully used in many clinical applications. Typically, wave intensity calculations require the simultaneous acquisition of blood velocity and blood pressure at the same vascular site. Unfortunately, many hemodynamic parameters that are used to monitor pre-operative patient hemodynamic state use both invasively acquired blood pressure measurements in catheterization laboratory and non-invasively acquired blood velocity measurements. To utilize wave intensity analysis to assess patients undergoing cardiac interventional procedures, we have developed a graphical user interface (GUI) that uses standard clinical measurements which include invasive blood pressure waveforms and Doppler echocardiography images to calculate wave intensity parameters. The GUI consists of three main subroutines that allow clinicians to import raw data and extract and analyze the blood pressure and blood velocity signals separately. Using the electrocardiogram signals as an alignment marker, the re-formatted signals are aligned, and wave intensity is calculated. Wave intensity features such as forward compression wave (FCW), forward expansion wave (FEW) and wave speed are calculated and output in a table for statistical analysis. The GUI represents the first attempt to create a program that encourages clinicians to use WIA for hemodynamic assessment in patients undergoing cardiac catheterization procedures with the data they have already procured.**

*Clinical relevance*— **The graphical user interface developed encourages the use of wave intensity calculations in patients who undergo cardiac catheterization and for whom routine pulsed Doppler echocardiography and invasive pressures are collected.**

## I. INTRODUCTION

Cardiac catheterizations are common procedures used as diagnostic and therapeutic options in patients suffering from coronary artery blockages, for patients needing an assessment of ventricular performance, and in the pediatric population for diagnosis of congenital heart defects [1]. During these procedures, clinicians measure hemodynamic variables, such as vascular and ventricular pressure, cardiac output, blood velocity, and valvular function. These variables give interventional cardiologist a multidimensional snapshot of patient hemodynamic status. Recently, wave intensity has been used to quantify ventricular performance in various clinical scenarios [2-7]

Wave intensity, WI, provides a time-domain decomposition of pressure and blood velocity in the vasculature. Namely, the contributions of forward-travelling and backward-travelling (i.e., reflected) energy waves initiated by the ventricle during the cardiac cycle are analyzed and compared across various patient disease states. While WI has been measured using non-invasive techniques such as magnetic resonance imaging [8] and with asynchronous doppler echocardiography and tonometry techniques, the use of wave intensity has not been widely adopted by cardiologists. Part of this lack of utilization stems from the use of modalities that are not standard of care and need for simultaneous measurement of blood velocity and blood pressure signals, which is challenging. In this paper, we address the first challenge of utilizing commonly procured hemodynamic measurements to estimate wave intensity.

In this paper, we outline the development of a GUI that uses raw measurements of blood pressure during cardiac catheterization and Doppler echocardiography images of blood velocity in the ascending aorta. The GUI consists of three subroutines that separately process blood pressure waveforms, convert blood velocity images to data elements, and calculate wave intensity and associated parameters from derived and aligned hemodynamic signals.

## II. GRAPHICAL USER INTERFACE

The GUI, shown in Figure 1a, consists of three functional tabs: the import data tab, the Doppler echocardiography image tab, and the pressure signal tab. The user procedure, shown as a block diagram in Figure 1b, requires importing data files and Doppler images, extracting electrocardiogram (ECG) data from both signal formats, extracting one-dimensional signals from pressure and blood velocity images, detecting QRS peaks from ECG signals for pressure and blood velocity signal alignment, time scaling signals to match heart rate, and calculation of wave intensity. In the subsequent sections, we detail the function and components of each functional tab and GUI subroutine.

### A. Data Import

Prior to utilizing the import file tab, data files must be formatted for data extraction. The data import tab accepts text files (.txt) which are tab or comma-delimited and with the naming conventions: patientType_patientID_doppler and patientType_patientID_pressuresite. Multiple files can be imported if the doppler and pressure files for the same

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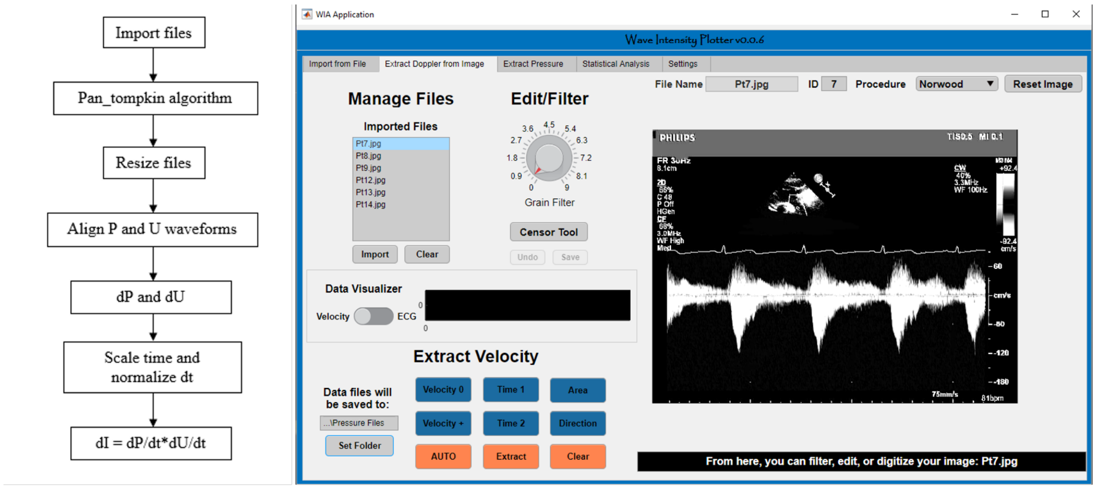



(A) (B)

Fig. 1. (A) block diagram of the GUI and the (B) GUI tabs to import files, process Doppler echocardiographic images, and pressure waveforms

patient ID are imported together. Subsequently, a list is created to allow the user to select a specific patient of interest and to perform wave intensity calculations on the specified patient data. The blood velocity and pressure waveforms are also displayed for the patient that is chosen. The wave intensity subroutine then calculates various WI parameters such as early systolic energy and late systolic energy and the values for the maximum forward compression wave (FCW) and forward expansion wave (FEW).

## B. Blood Velocity Extraction

The Doppler Extraction tab extracts one-dimensional blood velocity data values from a two-dimensional Doppler echocardiogram image. This is achieved by digitally analyzing and converting the image into arrays of discrete data points. The tab includes features to prevent misuse or improper usage such as input validation, sequence constraining or flexibility, redundancy removal, and copious reminders for the user to correctly complete the intended task. A block diagram of the blood velocity data extraction tab is shown in Figure 2.

Within this tab, the user may push buttons to select multiple image files (i.e., .jpg, .png., .tiff file formats) to be imported into the main register. The program will verify that the selected files are not duplicates or do not exist in the register. The user has the option to then delete sections of the image, which is practical for redacting personally identifiable information. This deleting function is easily achieved by drawing the desired area as a rectangle on the image and verifying its position to be to specification, allowing the program to replace the image pixels with pure black pixels. Furthermore, the program allows for filtering of the image as a common unwanted feature of Doppler images is graininess that can cause unwanted and inaccurate velocity readings in the future. This is achieved using a simple twist dial with different levels of filter intensity.

Aside from editing the image, users are required to input a patient ID number and the type of surgery (if any) the patient underwent (Fontan, bidirectional Glenn, control, etc.) The imported Doppler images display velocity as a continuous filled area of white color stemming from the horizontal time axis. To digitize this data, the algorithm developed employs user-defined locators, calibration points, and outlines to find the area of interest. The algorithm will systematically determine the peak of each pixel column and assign this a value of velocity in cm $s^{-1}$, a timestamp in seconds, and a corresponding ECG trace value, which is unitless as it is only used in further algorithms as a relative time marker.

Once the entire image is digitized, the data is available for plotting and visualization within the same tab in a section where the user can specify which variable to plot versus time. The data is written to a text (.txt file) and saved in a predetermined location, unless such a location is not yet specified. Before this happens however, the program will ensure the user has not given incorrect inputs such as velocity calibrations that are imprecise or impossible, a blank or zero patient ID number, or invalid numerical inputs for either velocity or time calibrations (negative or alphabetical). This maximizes the chance that user created mistakes do not propagate into further usage of the extracted data, further enhancing the robustness of this application.

## C. Blood Pressure Data Formatting

Typical data files from the cardiac catheterization laboratory contain many columns of data from a single catheter. These data consist of pressure along various

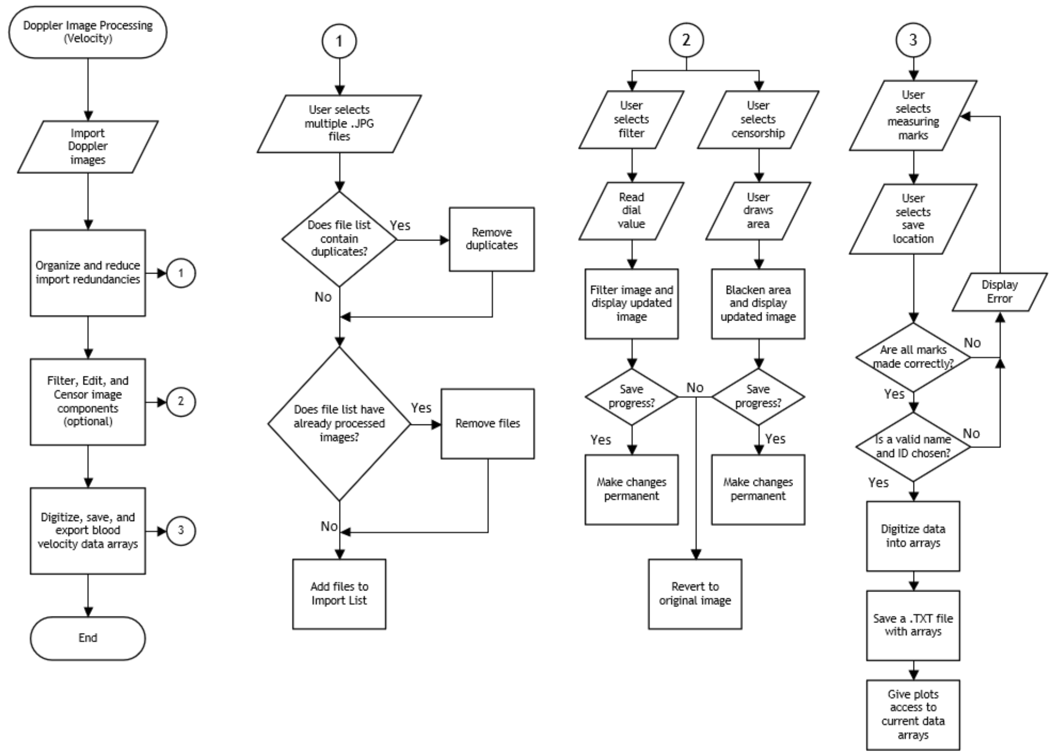



Fig. 2. (A) block diagram of the GUI and the (B) GUI tabs to import files, process Doppler echocardiographic images, and pressure waveforms

locations in the blood vessel, ECG traces, and miscelaneous pressure measurements. The blood pressure data allows the user to visually identify the relevant blood pressure data sets that need to be exported for WIA. The pressure subroutine is used to extract the relevant data that is used for WIA.

Once the files have been imported, a list populates underneath the export button. The list contains the imported pressure files which allows the user to select and initiate the reformatting of the chosen file. Clicking the imported pressure file will plot all columns of data located in that file as shown in Figure 3. The top window titled Pressure Data graph, plots all of the columns of data located in the file while the bottom window titled Selected Pressure Data graph displays the desired column data to be used for WIA calculations. On the left side of the GUI, below the reset button, a table that has the chosen file's column data. The Plot Selected column in the table shows that all the values are currently '0', signifying off or not plotted, while a '1', signifying on, means the data is plotted.

By default, the data is plotted with indices on the x-axis and data values on the y-axis. If sampling rate is chosen, a sampling rate input is required from the user to allow the system to create the time variable, which replaces the indices on the x-axis. When exporting data, two-column data must be selected from the data selection table. If two-column data are not selected, the program will give an error message. The GUI program allows the user to choose the directory and location of where the reformatting pressure data file is saved.

### D. Wave Intensity Calculations

Wave intensity analysis was carried out using a background subroutine which is not displayed for the user. All functions and the GUI are developed in MATLAB (Mathworks, Danvers MA). The main algorithm takes the reformatted pressure and blood velocity signals and parses them on a beat-by-beat basis using the QRS complex of the associated ECG trace for each. The QRS peaks are labeled using the Pan-Tompkin algorithm.The separated pressure waveforms were then ensemble averaged for each patient individually and smoothed using built in smoothing filters. Wave intensity during one averaged cardiac cycle was calculated and normalized to the sampling rate using equation 1.

$$dI = \frac{dP}{dt}\frac{dU}{dt} \tag{1}$$

Where dI is the normalized wave intensity with units of W $m^{-2}$ $s^{-2}$, dP is the change in aortic pressure, dU is the change in aortic blood velocity, and dt is the sampling interval for pressure and velocity respectively.

From the wave intensity signal, the wave energy flux was calculated by integrating over the time span of interest

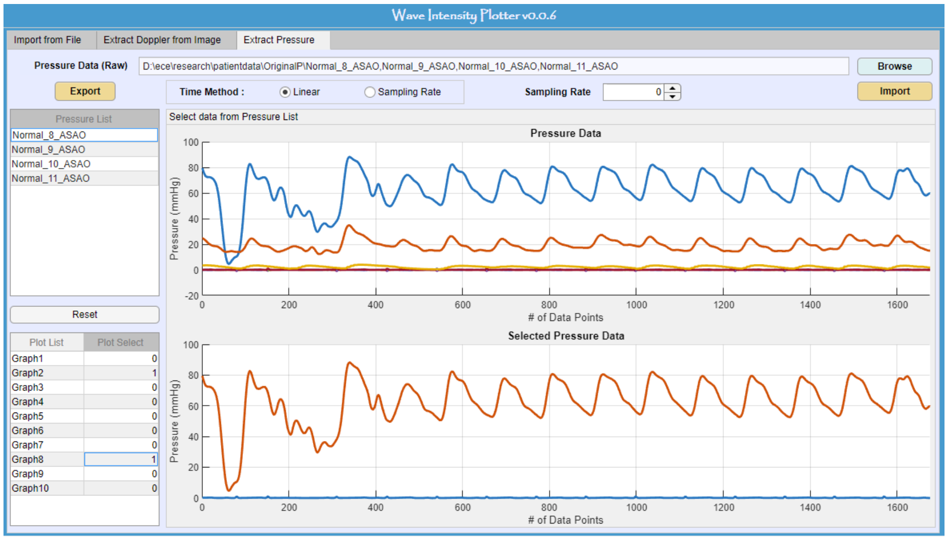



Fig. 3. Process to extract the signals of interest from the pressure waveform file

as defined by equation 2. This was done for the time span corresponding to early systole and for the time span corresponding to late systole.

$$E = \int_{t_1}^{t_2} dI dt \tag{2}$$

The units of energy flux in this study has units of J m$^{-2}$ s$^{-2}$. Wave speed was calculated using the sum of squares method [9] shown in equation 3.

$$c = \frac{1}{\rho}\sqrt{\frac{\sum dP^2}{\sum dU^2}} \tag{3}$$

where $\rho$ is blood density and is taken to have a value of 1050 kg m$^{-3}$.

## III. Wave Intensity on Fontan Patient Data

We calculated the wave intensity patterns for a cohort of single ventricle patients known as the Fontan population. Analysis of the results are published [10]. The GUI was used to calculate the wave intensity parameters for Fontan patients and controls to quantify the degree of ventricular impairment in single ventricle patients. The ensemble averaged pressure data and flow velocity data are shown in Figure 4a. Diastolic and systolic pressure points are labeled on the pressure trace.

Wave intensity plots and parameters for the same patient are also shown in Figure 4. As can be seen, the GUI labels the forward compression wave (FCW) and forward expansion wave (FEW). It also shades in the early systolic energy, ESE, (in red) and late systolic energy, LSE, (in grey). Values of FCW, FEW, ESE, LSE, and wave speed are saved in a structure format with specified patient ID. The time, ECG, ensembled pressure, and ensembled blood velocity waveforms are also saved in the same file.

### A. GUI Limitations

Even though the GUI represents first attempt to create an application to encourage WIA in clinical scenarios, there are some limitations. First, the current GUI application cannot calculate the values for backward compression wave (BCW) and backward expansion wave (BEW) because these parameters require simultaneous acquisition of the blood velocity and blood pressure. In addition, the GUI does not currently allow the importation of patient characteristics. This is important for normalizing functional hemodynamic variables in patients with different sizes (i.e., normalizing to body surface area, BSA). This normalization was done in previous studies but had to be done manually to compare patients of different size.

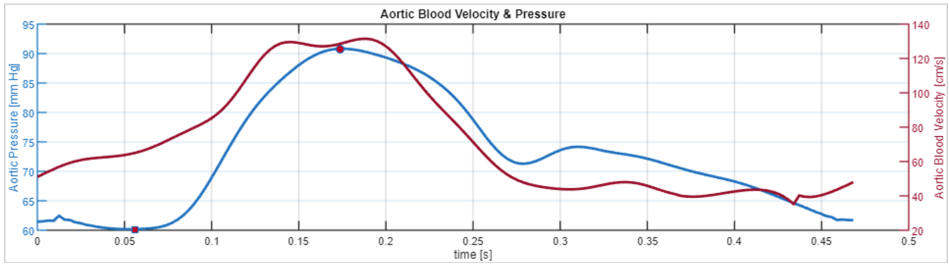
Another limitation of the GUI is the need to reformat the pressure files due to lack of consistent formats from clinicians. While this adds to the manual work prior to WIA calculations, it is necessary to ensure accurate readings. The need to reformat the pressure plots may be eliminated if clinicians are told a priori to save only desired data.

### B. Future Improvements

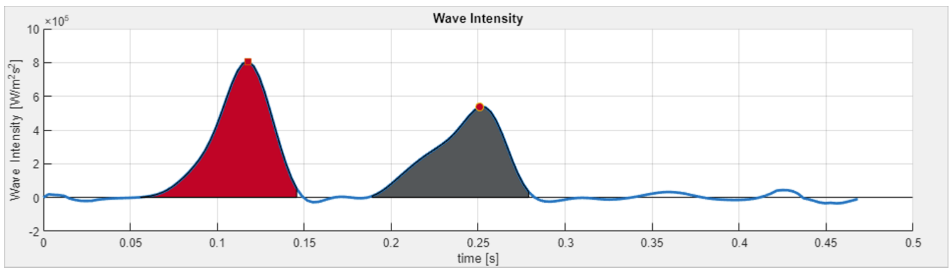
Future iterations of the GUI will implement more functions for clinical presentation. For instance, a section to import patient characteristics such as BSA, body mass index (BMI), and other hemodynamic measurements like ejection fraction, will be included. A basic statistical analysis tab will be incorporated to find correlations and compare two different groups. Normality checks on the dataset will be carried out to ensure the appropriate statistical test is utilized.

## IV. Conclusion

The development of a graphical user interface that calculates wave intensity parameters from standard of




(A)




(B)

Fig. 4. (A) ensemble-averaged pressure (in blue) and blood velocity (in red) waveforms and (B) resulting wave intensity profile with FCW and FEW marked

care catheterization measurements is presented. The GUI utilizes three subroutines and are held together by a main algorithm that calculates wave intensity variables. A pressure data tab allows the user to sift through relevant data from a file that contains invasive pressure and ECG data measured in the cardiac catheterization laboratory. A Doppler echocardiography tab allows the user to import a Dopper echo image and converts it to a one-dimensional waveform for further analysis. These two signals are then aligned using their respective ECG signals and wave intensity is calculated. All WIA parameters are saved in a structure file for processing with statistical software. The GUI has been tested and validated on data analysis on pediatric controls and single ventricle patients. The GUI represents a tool to test the feasibility and usefulness of WIA in various cardiovascular assessments.

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