An Interactive Digital Platform for Arterial Wave Intensity Analysis

John L Tassone, Ashraf W Khir

Brunel University, London, UK

Abstract

Background: Wave intensity analysis (WIA) is a technique that is used for the evaluation of the working condition of the heart and the arterial system. Simultaneous measurements of blood pressure (P) and velocity (U) are required for calculating wave intensity (dI), which can also be determined non-invasively using U and diameter (D) of the vessel at the measurement site. The technique allows for the separation of P, U, D and WI into their forward and backward directions.

Aim: This paper describes the development of an interactive digital platform that can be used to analyse arterial waves, determine WI, providing a range of cardiac and arterial indices.

Methods and results: The platform is developed in Matlab, and operates interactively by allowing the user to select the data and the type of analysis based on the availability of the acquired signals. The user chooses to visualise the analysis of the raw signals or part of, and decide which set of results would be saved either in excel or '.txt' files, together with all the automatically generated graphs and tables.

The wave speed is calculated using the PU-Loop or lnDU-Loop techniques, automatically taking into consideration the possible lag between the velocity and pressure, or diameter using linear regression techniques. Also, the platform shows the separation of the forward and backward waves, whose meaningful indices are tabulated interactively with variations of wave speed. The platform is designed for batch analysis of large data-sets, and has been used for investigating signals taken in vivo of dogs which have undergone different hemodynamic manipulations. The results are in good agreement with those processed manually.

Conclusion: The proposed platform is easy to use, saves computational time and effort for the assessment of a cardiac performance and arterial stiffness.

1. Introduction

Wave intensity analysis is based on the solution of 1-D conservation of momentum and mass equations of flow in flexible tubes [1]. It is a time domain analysis that considers the waves travelling in the vessels as the summation of wavefronts. The net wave intensity is defined as the product of the change in pressure (dP) times the change in velocity (dU), dI=dPdU and represents the flux of energy per unit area carried by the wavefronts. With the knowledge of wave speed (c) WIA allows the separation of measured pressure (P), velocity (U) and diameter (D) waveforms in their forward (P_+, U_+, D_+) and backward (P-, U-, D_-) components [2,3].

1.1. Platform description

The platform consists of two windows. The first one (Figure 1) is used to load the files containing the data to be analysed and set some analysis preferences.

Button (A): The "Load Files" opens a dialog box that allows for finding the source files. The "multi-selection" mode is available so that several files can be loaded at the same time avoiding the need to look for each file singularly. All the loaded files are listed in the interactive *panel (B)*. The selection of a file leads to the visualization of its header (if available) in the central *table (C),* to allow the user to specify the signals under consideration in *panel (D)*. If the file is in excel format the names of its sheets are visualized in the central *list (E)*. The user can also select the units of measurements in *table (F),* set the cardiac cycle subdivision options in **(G)** and set the filtering preferences in **(H)**. The user can choose to perform WIA following different approach **(I)** according to which signals are available: P and U or D and U. In the case of P and U it is also provided the possibility of using the windkessel model theory to perform the separation of the pressure waveforms in the reservoir and excess components [4].

When all the preferences are set, pressing the "OK" button opens the second window (Figure 2). An interactive *list (J)* allows for selecting the file to be analyzed. *Panel (K)* is dedicated to the visualization of PU, lnDU or PexU –Loop according to the selected type of analysis. *Panel (L)* consists of three graphs in which wave separation is plotted. *Buttons (M)* toggles between the visualization of the input signal (ECG, P, D and U), the separation of waves (ECG, P and $P_\pm$, D and $D_\pm$, U and $U_\pm$) and the computation and separation of wave intensity (dI, dI_+, dI). *Tool (N)* is used for solving the time lag between the input signals, *tool (O)* is used to evaluate the
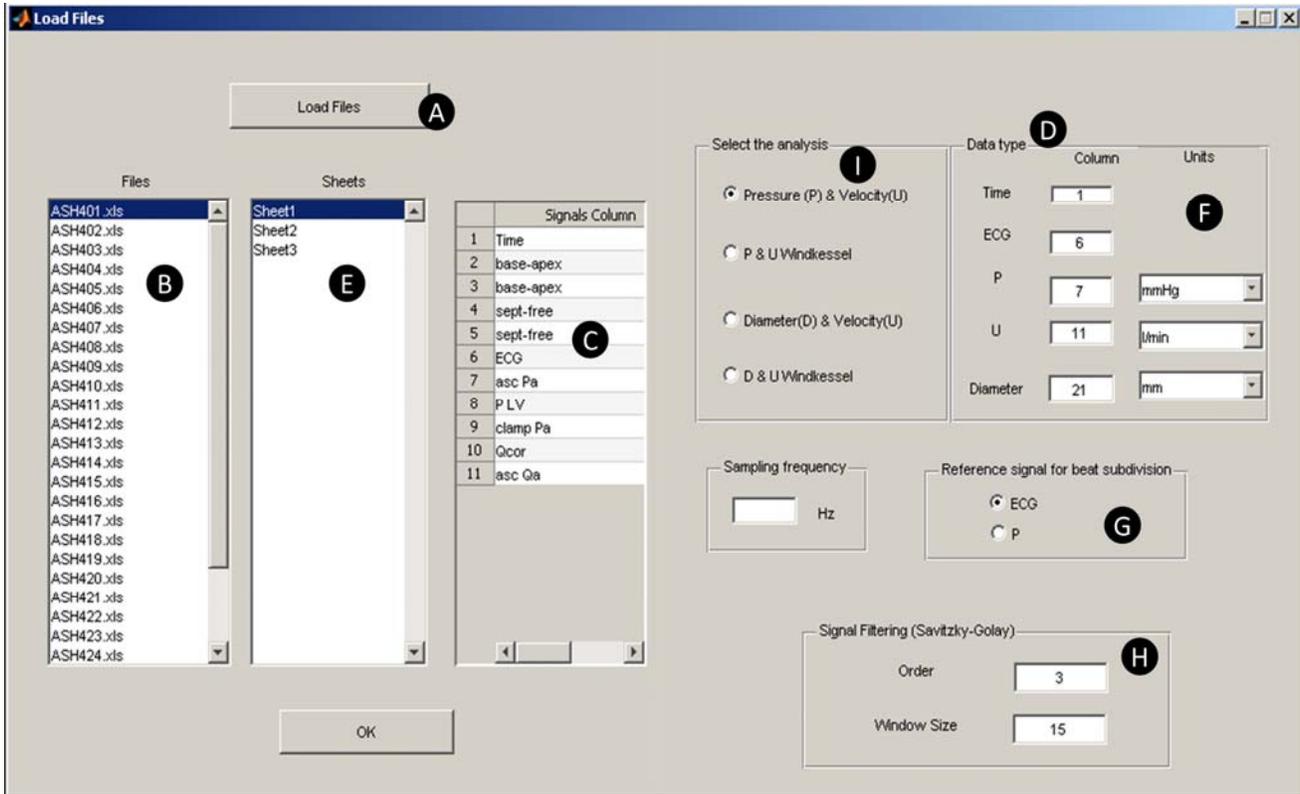
Figure 1. Screenshot of the first window for loading files and set the analysis parameters.

effects that changes in wave speed have on the separated waves and wave intensity. *Table (P)* contains the numeric values that characterize the separated P, U, D waves or the WIA according to which modality has been chosen. In particular, performing the WIA the table shows: (1) Peak intensity of the forward compression wave (FCW), forward expansion wave (FEW), backward compression wave (BCW) and time of their peaks with respect to the onset of ventricular ejection; (2) Onset of the FEW and the BCW with respect to the ventricular ejection time; (3) Energy of the FCW, the FEW and the BCW.

While performing the wave separation, the table shows: (1) Peak and minimum of $P_\pm$, and $U_\pm$; (2) The onset and peak times of P, $P_\pm$, U and $U_\pm$ all with respect to ventricular ejection time.

Once the analysis is finished the results can be saved with the possibility to choose all the beats or only a selected portion. According to the analysis mode the output files are figures containing: (1) PU-Loop, lnDU-Loop or PexU-Loop; (2) U, with its separated $U_\pm$ components; (3) P, with its separated Pex, Pr / $P_\pm$ components or D, with its separated $D_\pm$ components; (4) Net WI (dI) with its forward (dI_+) and backward (dI_-) components. The figures are saved both in "png" and "fig" format. The data in the table are saved in two excel files one for WIA the other for the separation.

2. Subroutines

The platform consists of a subroutine for each block shown in the flow chart of Figure 3.

2.1. Load files

The data source files can be in three different formats: text (txt), Matlab (mat) and Excel (xls or xlsx) opened using TEXTSCAN, IMPORTDATA and XLSREAD respectively. Once the files have been loaded the software shows a preview of the header (for text and Excel format only) allowing the user to select the column containing the signals needed for the analysis.

The software is designed to deal with different measure units: pressure can be measured in Pa or mmHg, velocity in m/s. Instead of velocity the user can provide flow measurements and in this case an average value of the diameter of the vessel is required in order to convert flow into velocity. The default input signals are four vectors containing sampling time (t), ECG, P or D and U. In case the t vector is not provided the sampling frequency will be requested and a fictitious time vector will be created.
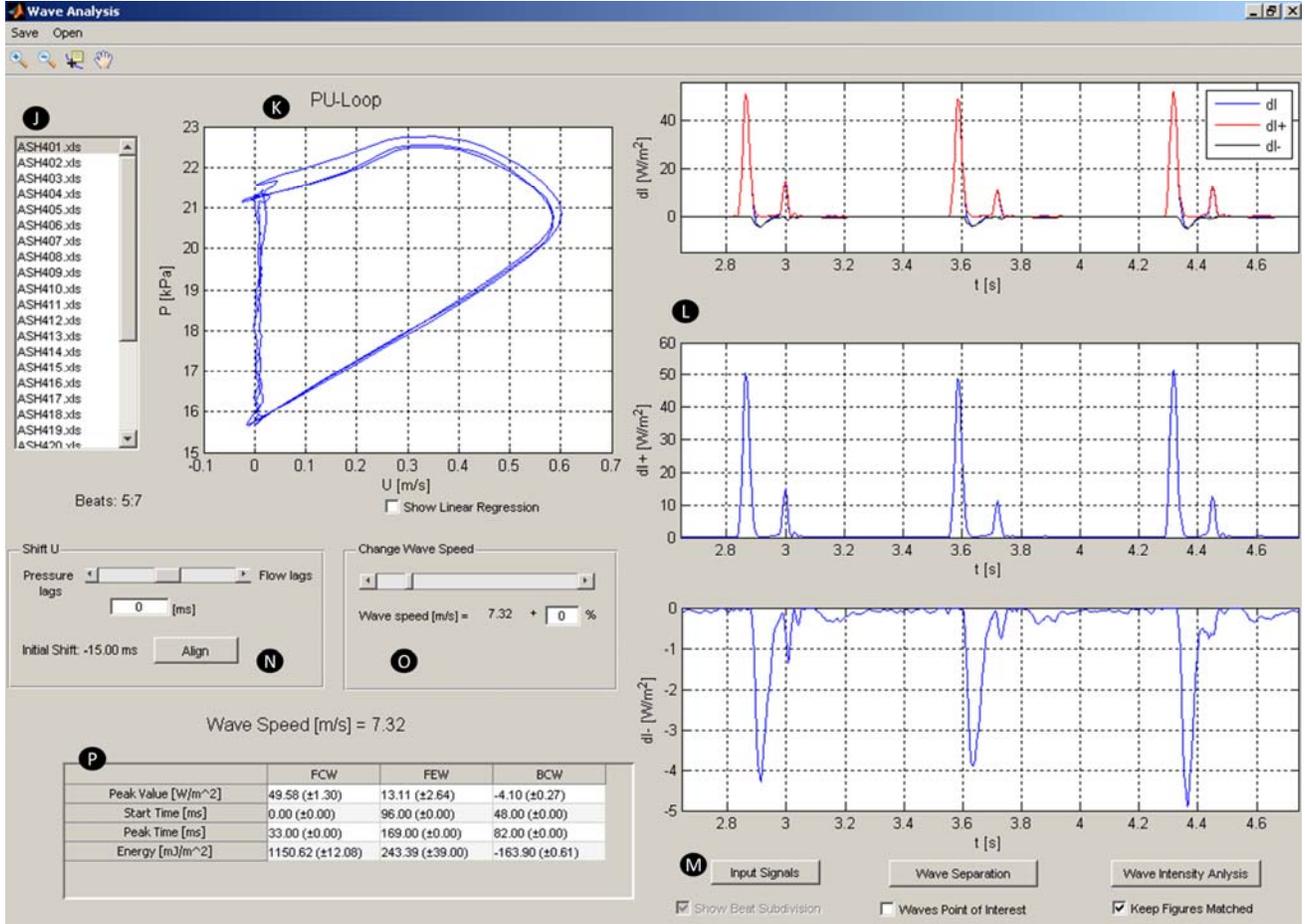
Figure 2. Screenshot of the main window that shoes the disposition of buttons and tools.

2.2. Filtering

The user has the possibility to set a Savitzky-Golay filter for smoothing the signals [5]. The filter coefficients are computed with the SGOLAY function. Two parameters are required by this function: the polynomial order and the window size. If not specified no filter is applied to the input signals

2.3. Cardiac cycles subdivision

The platform performs the analysis independently for each cardiac cycle. If the ECG signal is available the R-peak is taken as reference for the subdivision that is carried out using the ECG processing package [6]. If the ECG is not available the user can choose to divide the beats using the foot of P waveform.

2.4. Signal alignment

Simultaneous pressure or diameter and velocity measurements are required to calculate wave speed [2,3]. Because of the different frequency response of the instrumentation, the acquired signals can be asynchronous and lead to error in the estimation of the wave speed. The alignment is carried out shifting the U signal automatically or by eye. In the automatic case the global lag is obtained by computing the lag for each cardiac cycle and then rounding the average of the lags to the nearest integer. The delay for each cycle is determined by the highest correlation method [7].

2.5. Wave speed determination

Wave speed is determined using the PU-Loop [2] or lnDU-Loop [3]. For the analysis that includes the windkessel model wave speed is computing using P_{ex} instead of P. These techniques are based on the assumption that the relationship between P and U, or the logarithm D and U is linear in the absence of reflections, and c can be determined as:

$$c = \pm \frac{1}{\rho} \frac{dP_{\pm}}{dU_{\pm}} \tag{1}$$

$$c = \pm \frac{1}{2} \frac{dU_{\pm}}{d\ln D_{\pm}} \tag{2}$$

2.6. Wave intensity computation

Once the wave speed is known the forward and backward separation can be computed according to [1]:

$$dI_{\pm} = \pm \frac{1}{4\rho c}(dP \pm \rho c dU)^2 \tag{3}$$

$$_n dI_{\pm} = \pm \frac{1}{4(D/2c)}(dD \pm \frac{D}{2c}dU)^2 \tag{4}$$

for pressure and velocity and diameter and velocity respectively. In the case with windkessel the wave intensity analysis is carried out using P_{ex} instead of the measured P.
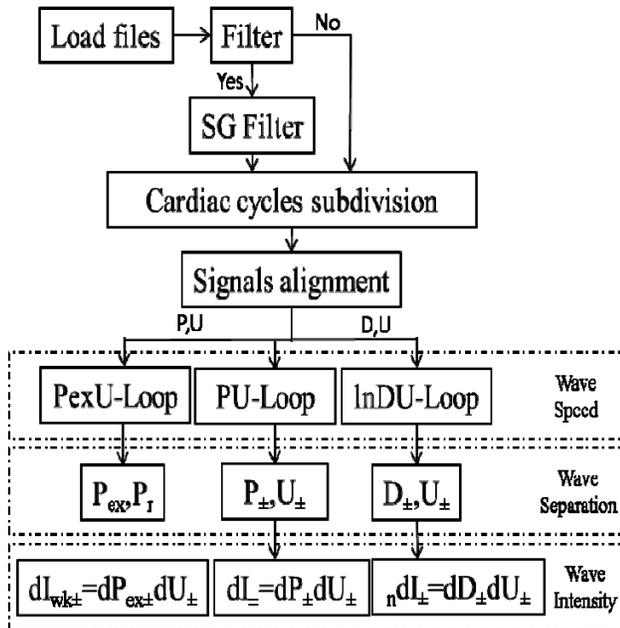

Figure 3. Flow chart of the platform showing the different mode in which the analysis can be carried out.

2.7. Wave separation

The wave separation is computed by the solution of the one-dimensional equations for flow in an elastic artery using the method of characteristic. Then the pressure, diameter and velocity waveform can be calculated summing the differences on the cardiac cycle [2,3].

When the windkessel model is included the separation of the pressure in P_{ex} and P_r is made according to [4]:

$$P_r = P_\infty + (P_0 - P_\infty)e^{-t/\tau} + \frac{e^{-t/\tau}}{C}\int_0^T Q\, e^{-t/\tau}dt \tag{5}$$

$$P_{ex} = P_r - P \tag{6}$$

where P_∞ is the pressure at which flow through the microcirculation is zero, P_0 the pressure at the onset of the ejection, Q the blood flow, R the resistance of the peripheral systemic circulation, C the compliance of the whole arterial tree and $\tau = RC$.

3. Conclusion

The proposed platform represents a tool to investigate the hemodynamics of the circulatory system. The platform offers an immediate response providing plots of the measured signals, the calculated waveforms and results. The platform is interactive, allows the user to investigate and resolve the effects of the lag between the signals and the error in wave speed computation. The platform is easy to use, able to deal with large amounts of data, saves computational time and effort for the assessment of a cardiac performance and arterial stiffness.

References

[1] Parker KH. An introduction to wave intensity analysis. Med Biol Eng Comput 2009;47:175-188.
[2] Khir A, O'brien A, Gibbs J, Parker K. Determination of wave speed and wave separation in the arteries. J Biomech 2001;34:1145-1155.
[3] Feng J, Khir A. Determination of wave speed and wave separation in the arteries using diameter and velocity. J Biomech 2010;43:455-462.
[4] Wang J, O'Brien AB, Shrive NG, Parker KH, Tyberg JV. Time-domain representation of ventricular-arterial coupling as a windkessel and wave system. American Journal of Physiology-Heart and Circulatory Physiology 2003;284:H1358-H1368.
[5] Savitzky A, Golay MJ. Smoothing and differentiation of data by simplified least squares procedures. Anal Chem 1964;36:1627-1639.
[6] Chernenko S. http://www.librow.com/.
[7] Swalen M, Khir A. Resolving the time lag between pressure and flow for the determination of local wave speed in elastic tubes and arteries. J Biomech 2009;42:1574-1577.

Address for correspondence.
Ashraf William Khir
Brunel Institute for Bioengineering
Kingstone Lane
Uxbridge UB8 3PH,
UK
ashraf.khir@brunel.ac.uk