4D Flow Pulse Wave Velocity Tool – MATLAB-based App
Date: November 3, 2021
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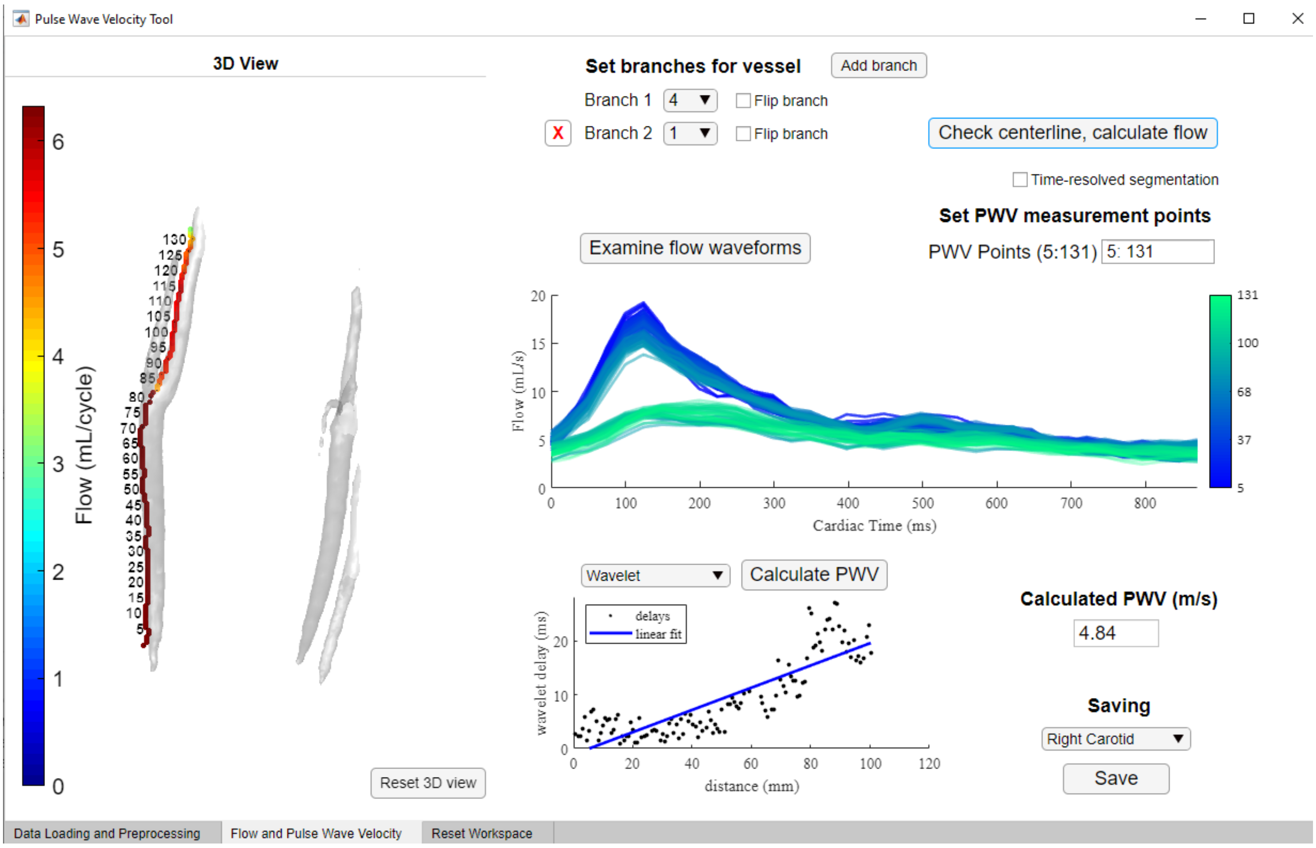



This software builds from previous work, and the use of this tool should be associated and cited with the following reference:
E. Schrauben, et al. "Fast 4D flow MRI intracranial segmentation and quantification in tortuous arteries." JMRI 2015, doi: 10.1002/jmri.24900.

Installation:

This app is built using MATLAB's appdesigner functionality. It was built using MATLAB version 2019a; it is therefore recommended to use this version or newer for running this app. Download and unzip all files. All functionality of the app is built into PulseWaveVelocityTool.mlapp and the corresponding utilities subfolder.

Required MATLAB Toolboxes:

PulseWaveVelocityTool requires the following MATLAB toolboxes:
Optimization Toolbox
Signal Processing Toolbox
Image Processing Toolbox
Statistics and Machine Learning Toolbox

Data needed:
The app works directly on reconstructed .par / .rec files from a Philips 4D flow acquisition. It assumes these are all located within a single folder. The files needed are as follows:

- SUBJECTID or other identifier_1.par, SUBJECTID or other identifier_1.rec
- SUBJECTID or other identifier_2.par, SUBJECTID or other identifier_2.rec
- SUBJECTID or other identifier_3.par, SUBJECTID or other identifier_3.rec

These correspond to the magnitude and phase images for each velocity direction (vx, vy, vz).

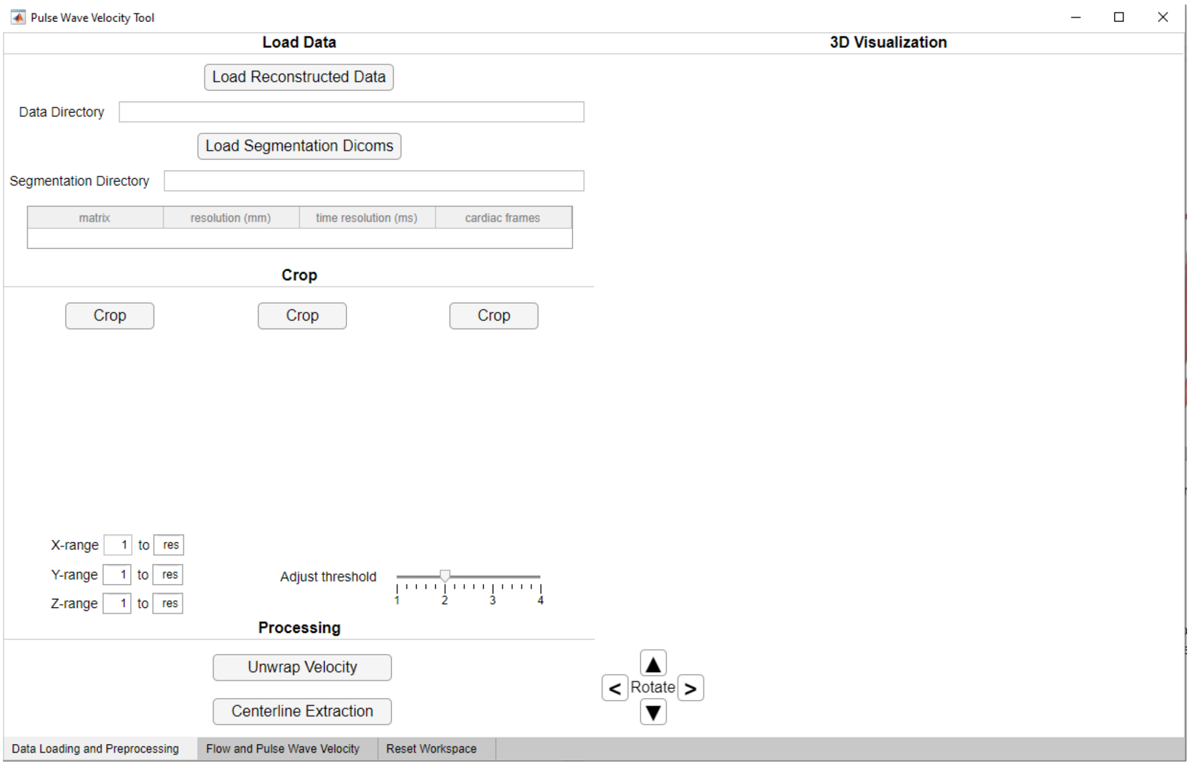
Basic Processing Steps and Information:

1. Getting Started

Within MATLAB, navigate to the folder containing PulseWaveVelocityTool.mlapp. Type this into your command window:

```
>> PulseWaveVelocityTool
```

Here is the initial screen:

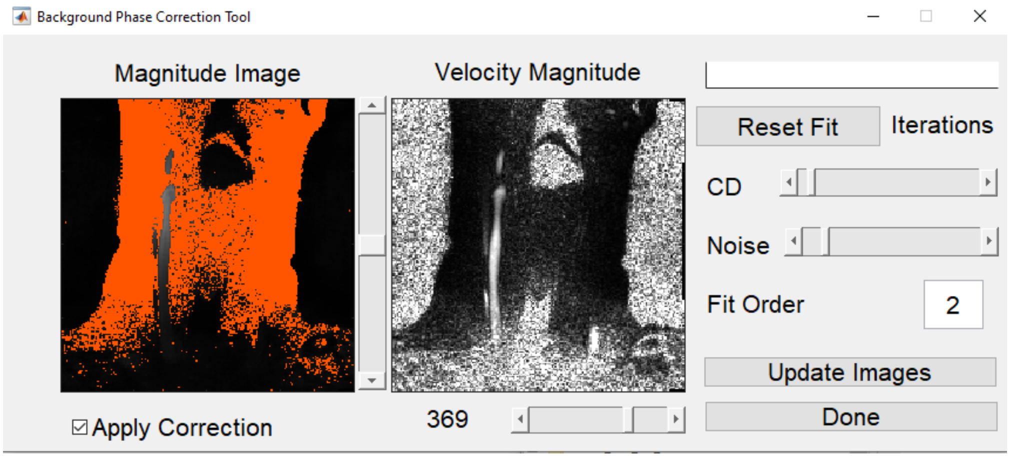



Processing is sorted into two main tabs: Data Loading and Preprocessing, and Flow and Pulse Wave Velocity

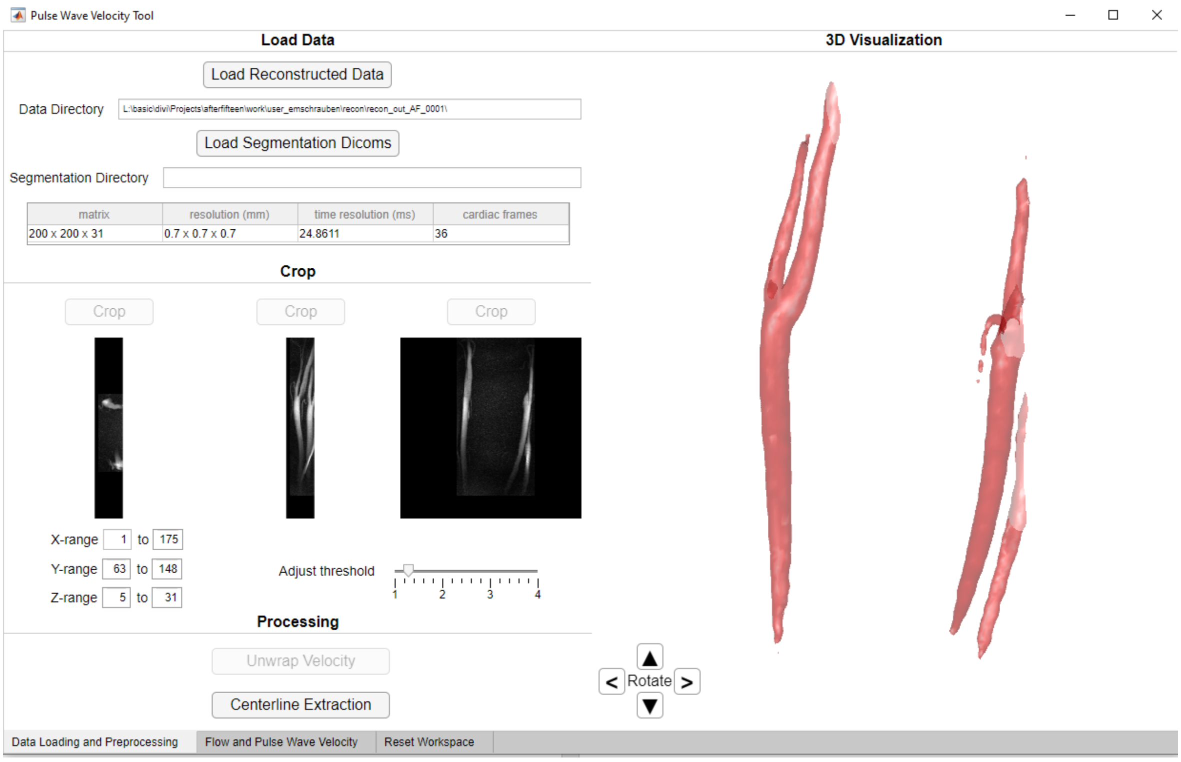
2. Loading and Preprocessing

Click Load Reconstructed Data. You will be prompted to find one of the reconstructed .rec files in order to locate the correct data folder. Example aortic and carotid 4D flow data are provided for initial testing.

Following loading of data, a background subtraction GUI is automatically opened. Adjust the complex difference (CD) and Noise sliders to create an orange mask that only includes static tissue (excluding blood and air). Then click Update Images to calculate the background phase fit, and click Done to apply this fit to the velocity data.




After loading completion, the tool will automatically display axial, coronal, and sagittal MIPs using a calculated angiographic image. It also automatically thresholds this image to produce a 3D isosurface within the field of view:




Cropping of data to include only the vessels of interest is recommended and can be performed using the individual Crop button above each MIP.

For best performance, a manual segmentation of the aorta should also be included. This segmentation is read in as dicoms produced from a given segmentation software. Click Load Segmentation Dicoms to load and view the manual segmentation in gray overlaid on the previously calculated 3D isosurface.

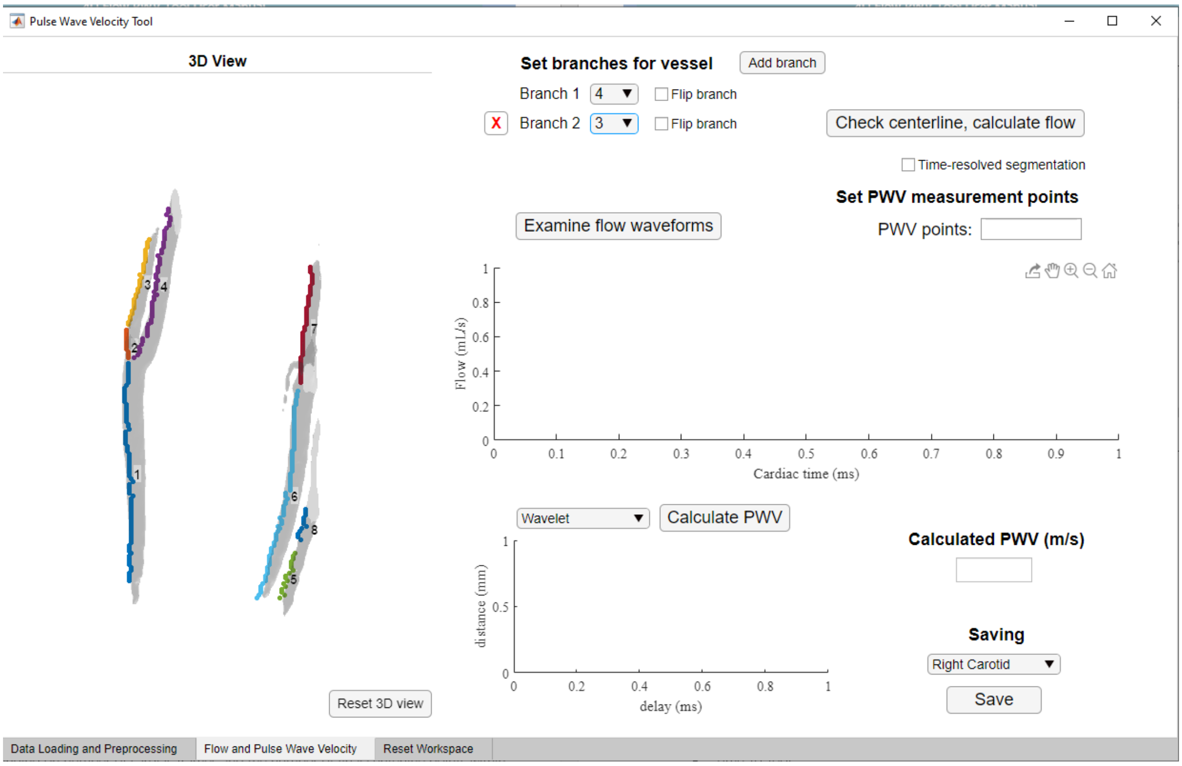
> *Optional:* Automatic velocity unwrapping can be performed using the Unwrap Velocity button. Note data cropping is no longer possible after velocity unwrapping. For details please see and cite this work:

> J Magn Reson Imaging. 2016 Apr;43(4):833-42. doi: 10.1002/jmri.25045. Epub 2015 Sep 28.
>
> **Phase unwrapping in 4D MR flow with a 4D single-step laplacian algorithm**
>
> Michael Loecher [1], Eric Schrauben [1], Kevin M Johnson [1], Oliver Wieben [1] [2]

If no manual vessel segmentation is provided, use the Adjust threshold slider to include more or less of the vasculature of interest.

Finally, to extract specific points within the vasculature to perform pulse wave velocity calculation, push Centerline Extraction. The 3D vasculature is skeletonized and individual vessel centerlines are extracted and labelled with unique identifiers. Upon completion, the Flow and Pulse Wave Velocity tab is opened.

3. Flow and Pulse Wave Velocity



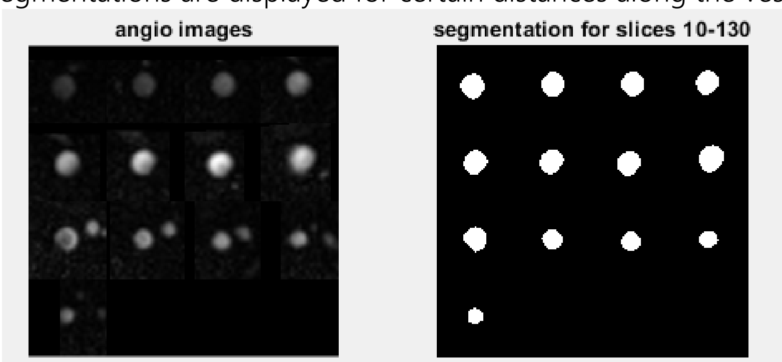

*Optional:* Time-resolved segmentation can be performed by checking the Time-resolved segmentation checkbox. Note this is experimental and NOT recommended for carotid PWV. For details please see and cite this work:

J Cardiovasc Magn Reson. 2017; 19: 47. PMCID: PMC5481950
Published online 2017 Jun 23. doi: 10.1186/s12968-017-0360-8 PMID: 28645326

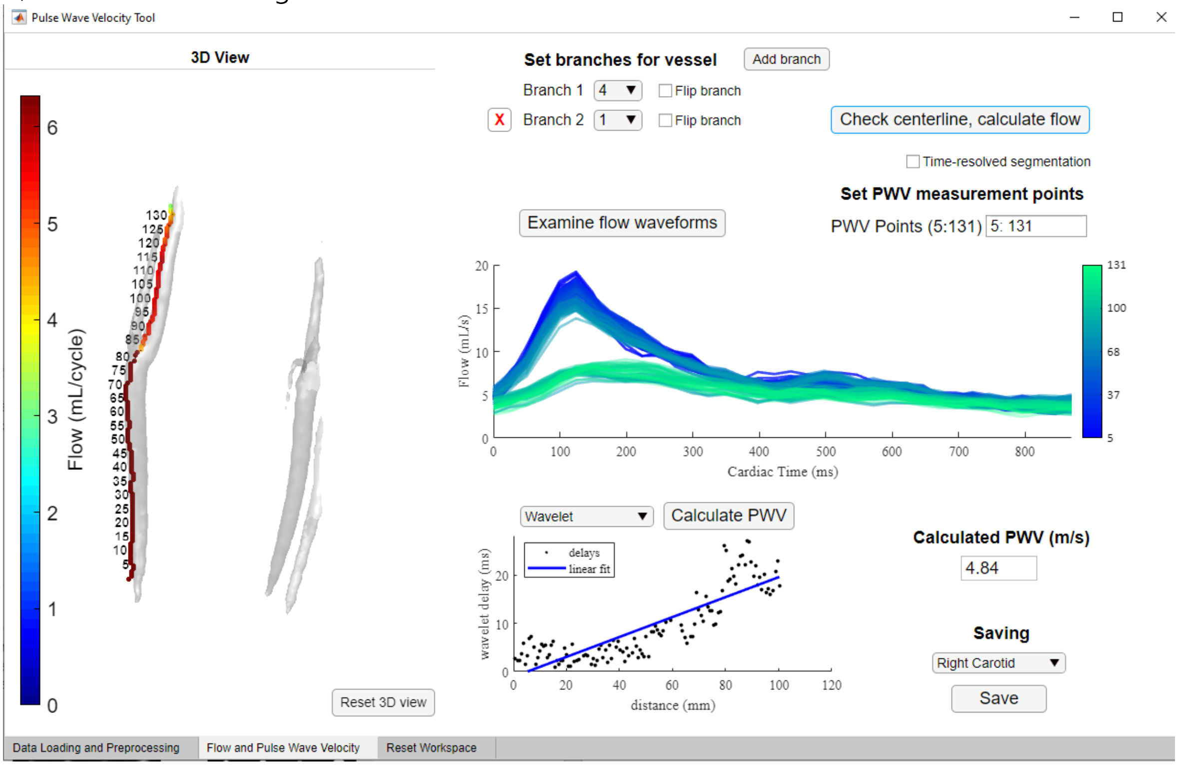
**Improving visualization of 4D flow cardiovascular magnetic resonance with four-dimensional angiographic data: generation of a 4D phase-contrast magnetic resonance CardioAngiography (4D PC-MRCA)**

Mariana Bustamante,[1,2] Vikas Gupta,[1,2] Carl-Johan Carlhäll,[1,3] and Tino Ebbers[1,2]

To segment the vessel of interest, individual branches need to be selected. Input the corresponding branch numbers in Set branches for vessel, adding or removing branches when necessary. Add branches from most distal (downstream) to most proximal (upstream). Example: to get internal carotid and common carotid arteries in one 'vessel,' set Branch 1 = 4 and Branch 2 = 1.
Then click Check centerline, calculate flow. At each centerline point, an orthogonal cross section is calculated (using the norm of the centerline). Flow is calculated within each cross section over all cardiac time frames. Resulting cross section segmentations are displayed for certain distances along the vessel for visual inspection:



Following flow calculation, the total flow at each point and corresponding waveforms are plotted for inspection, as well as an initial guess for PWV:




Finally, pulse wave velocity can be calculated over any number of points along the aorta. Input these points into PWV Points, then click Calculate PWV. The calculation of PWV has three options:

- Cross-correlation:

  > J Magn Reson Imaging. 2008 Jun;27(6):1382-7. doi: 10.1002/jmri.21387.

  **A new method for the determination of aortic pulse wave velocity using cross-correlation on 2D PCMR velocity data**

  Samuel W Fielden [1], Brandon K Fornwalt, Michael Jerosch-Herold, Robert L Eisner, Arthur E Stillman, John N Oshinski

- Wavelet cross spectrum analysis:

  Comparative Study > J Cardiovasc Magn Reson. 2015 Jul 30;17(1):65.
  doi: 10.1186/s12968-015-0164-7.

  **Estimation of aortic pulse wave transit time in cardiovascular magnetic resonance using complex wavelet cross-spectrum analysis**

  Ioannis Bargiotas [1], Elie Mousseaux [2 3], Wen-Chung Yu [4], Bharath Ambale Venkatesh [5], Emilie Bollache [6], Alain de Cesare [7], Joao A C Lima [8], Alban Redheuil [9 10 11], Nadjia Kachenoura [12]

- Maximum likelihood estimator:

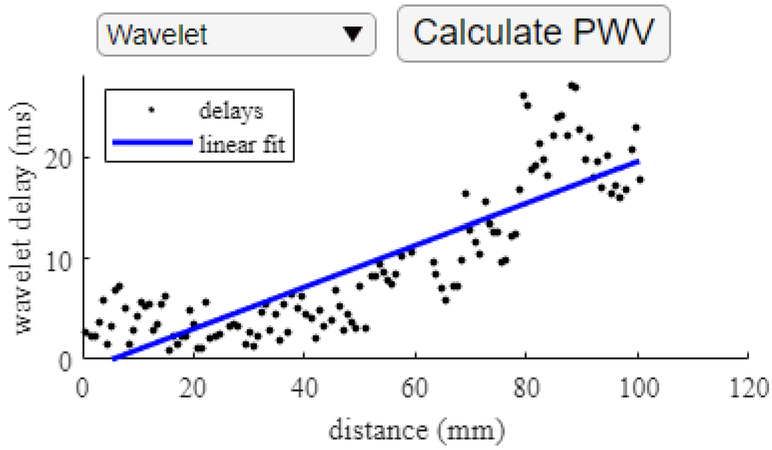
  *Original Article* JCBFM

  **Assessing cerebral arterial pulse wave velocity using 4D flow MRI**

  Journal of Cerebral Blood Flow & Metabolism
  2021, Vol. 41(10) 2769–2777
  © The Author(s) 2021
  DOI: 10.1177/0271678X211008744
  journals.sagepub.com/home/jcbfm
  SAGE

  Cecilia Björnfot[1], Anders Garpebring[1], Sara Qvarlander[1], Jan Malm[2], Anders Eklund[1,3] and Anders Wåhlin[1,3]

The output of this calculation is shown:




Resulting PWV can be saved by clicking Save. This records results in a MATLAB data struct, the PWV written to an Excel spreadsheet, and screenshot of the tool.

FUTURE to-dos:

- Read in other data formats (MATLAB .mat, Siemens 4D flow dicoms, GE PC-VIPR from UW Madison)