Changes in Non-Invasive Wave Intensity Parameters with Variations of Savitzky-Golay Filter Settings

Nicola Pomella[1], Mark Rakobowchuk[2], Christina Kolyva[3], Ashraf W Khir[1]

[1]Brunel University London, London, United Kingdom
[2]Thompson Rivers University, Kamloops, Canada
[3]Middlesex University London, London, United Kingdom

Abstract

Ultrasound-measured waveforms, such as vessel diameter and blood flow velocity, are used to perform analysis of waves in the cardiovascular system. Wave intensity analysis is one of the tools used for this purpose.

The waveforms are commonly filtered to eliminate high-frequency noise, however the filter settings affect the features of these signals and especially of their time derivatives, upon which wave intensity analysis is based.

This study aims to investigate the alterations of wave intensity parameters with varying Savitzky-Golay filter settings, one of the most common smoothing algorithms used in this context.

A broad spectrum of variations was observed in all the wave intensity variables. It is therefore important to always specify the filter settings applied to the signals in a wave intensity study, so that appropriate comparisons can be made.

1. Introduction

Wave Intensity Analysis (WIA) is a powerful tool developed by Parker and Jones [1] to study wave propagation in the cardiovascular tree and has been proved useful in the clinical setting [2]. The original formulation required invasive simultaneous measurements of blood pressure and flow velocity (U), but the parallel development of ultrasound systems enabled performing WIA through ultrasound-measured diameter (D) and U instead [3, 4].

D and U are commonly filtered (smoothed) to eliminate high-frequency noise; however the filter settings affect WIA parameters, calculated not directly from D and U, but from their time derivatives (dD, dU) [5]. One of the most common smoothing algorithmsfor these signals is the Savitzky-Golay (SG) filter [6], which fits a sub-set of data points of the signal, contained in a window of specific length (w), with a polynomial of a specific degree (p), via the least-squares method.

This study aims to investigate the alterations of WIA parameters with varying SG filter settings (i.e. w and p).

1.1. Wave intensity analysis

Wave Intensity (dI) can be defined as the product dD·dU [4]. The calculation of local wave speed (PWV) (i.e. at the site of the measurement of D and U) is performed through the lnDU-loop [4], assuming that there is no contribution of reflected waves to the pressure, diameter and velocity waveforms in early systole. Using the calculated PWV value one can separate dI into forward (dI_+) and backward components (dI_-) in so far as $dI=dI_+ + dI_-$.

Three waves can be assessed: the forward compression wave (FCW), generated by the contraction of the left ventricle, the backward compression wave (BCW), attributed to reflections from the downstream capillary bed, and the forward expansion wave (FEW), generated by the deceleration of the heart's contraction in late systole. The energy carried by each wave is calculated by the time integral of the corresponding wave.

2. Methods

2.1. Instrumentation and measurements

A SSD – 5500 ultrasound system (Aloka, Tokyo, Japan) equipped with a 7.5 MHz linear array vascular probe was used to acquire single-beat D and U from the right common carotid artery (CCA) of a young, healthy individual (25 years) at rest in a supine position. The CCA was insonated ~ 2 cm proximal to the bifurcation. D and U were measured with a resolution of 0.013 mm and 0.012 m/s, respectively. The sampling frequency was 1000 Hz. The D waveform was calculated as the distance

Computing in Cardiology 2016; VOL 43 ISSN: 2325-887X DOI:10.22489/CinC.2016.300-302

between the two walls of the vessel over time. The gates were positioned manually between the media and the intima of the anterior and posterior walls, and parallel to them. The U waveform was acquired ensuring that the Doppler gate was at the centre of the vessel, parallel to the walls, with an insonation angle equal to 60°.

2.2. Data analysis

Data analysis was performed via custom-made algorithms written in Matlab (version R2010b, The MathWorks, Inc., Natick, Massachusetts, USA). D and U were filtered with 42 SG settings, derived from combining 6 polynomial degrees p: 2-7, with 7 selected window lengths w: 9-21-33-45-71-99-119 points. PWV was calculated through the lnDU-loop and non-invasive WIA was performed [4]. PWV, maximum values, energies and durations of FCW (FCW_{max}, FCW_e, FCW_{time}), BCW (BCW_{max}, BCW_e, BCW_{time}), FEW (FEW_{max}, FEW_e, FEW_{time}) were compared between the 42 settings.

3. Results

PWV increased with increasing w and decreasing p (12% at p=2 between w=9 and w=119, 6% at p=7 in the same window range). FCW_{time}, BCW_{time} and FEW_{time} increased with w and decreased with p (25%, 100%, 80% at p=2 between w=9 and w=119, respectively, and 60%, 40%, 25% at p=7). The maximum variation along p was 22%, 32% and 59% for FCW_{time}, BCW_{time} and FEW_{time}, respectively.

Variations were much greater for peak and energy values. FCW_{max} (Fig. 1) and FEW_{max} decreased with increasing w and decreasing p (up to 4-fold at p=2, up to 4-fold at p=7 for FCW_{max}; up to 4-fold at p=2, up to 43-fold at p=7 for FEW_{max}). Although the pattern of changes is similar for FCW_{max} and FEW_{max}, the latter exhibited an unexpected huge gap between w=9 and w=21, the two shortest window lengths, for p=3-7.

In fact, the variation between the two shortest windows was about 8-fold at p=7, and only about 4-fold between w=21 and w=119 at the same p. The combined overall gap is therefore around 43-fold. The maximum variation along p was 100% for FCW_{max} and 9-fold for FEW_{max}. If w=9 had been excluded, the variation would have lowered to 2.25-fold for $FEW_{max.}$

BCW_{max} decreased with w (up to 81-fold at p=2, up to 7-fold at all other values of p) and decreased with p up to 14-fold, only excluding p=6 and p=7, which would have brought the variation up to 1040-fold. In fact, the maximum change between p=2 and p=5 is about 14-fold while the maximum change between p=5 and p=7 is about 75-fold. Too high polynomial degrees caused an unrealistic variation. Also in the case of BCW_{max}, w=9 presented some unrealistic values.

FCW_e (Fig. 1) and FEW_e decreased with increasing w and decreasing p (100% at p=2 and 8% at p=7 for FCW_e, 1.6-fold at p=2 and 9-fold at p=7 for FEW_e). The maximum variation along p was 100% and 6-fold for FCW_e and BCW_e, respectively. In contrast, BCW_e increased with increasing w up to p=4 (about 2.5-fold at p=2-4) and decreased for high p (up to 100% at p=7). The maximum variation along p was 5.6-fold.

Finally, a general shift of the signal towards increasing time values can be seen with increasing w. Large window lengths cause a significant truncation of the signal and some early-systolic features could be lost (Fig. 2).

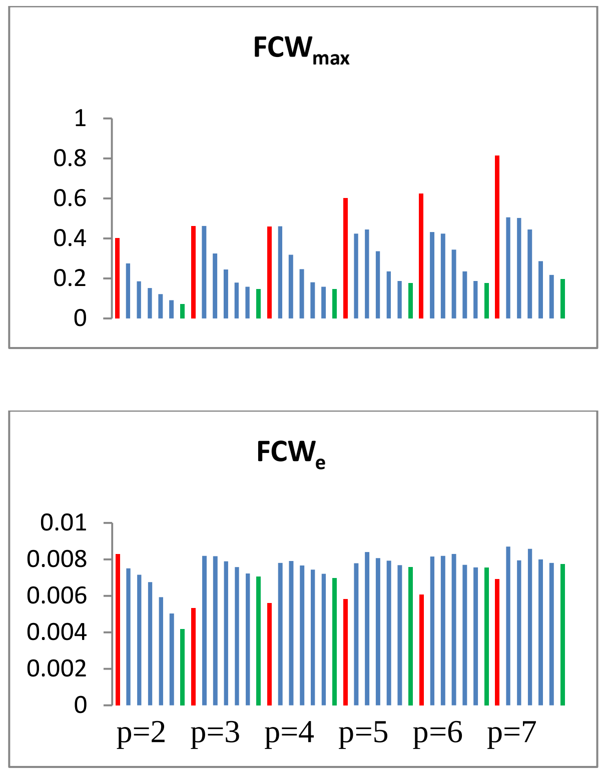

Figure 1.Variations of FCW_{max} (top) and FCW_e (bottom) with changes of Savitzky-Golay filter settings. The value of p (polynomial degree) is indicated in the horizontal axis. For each p, columns represent different increasing w values (window lengths): 9-21-33-45-71-99-119 points. In particular, the red column stands for w=9 and the green column for w=119. Units of FCW_{max} and FCW_e are of mm^2/s and mm^2, respectively.

4. Discussion

WIA parameters are highly affected by the change of SG filter settings, showing a broad spectrum of variation. The correct choice of w is critical, as it affects the signal more than p.

Energy parameters (FCW_e, BCW_e, FEW_e) appeared to be less sensitive to the filter settings than their corresponding intensities (FCW_{max}, BCW_{max}, FEW_{max}). This is likely due to the way these variables are computed: peaks involve the detection of single points, while areas involve an integral which takes account of a number of points. FCW_e values, compared to the other energy values, are mostly affected by the truncation of the signal, especially at large windowlengths. This phenomenon in fact causes loss of information during the early systolic period.

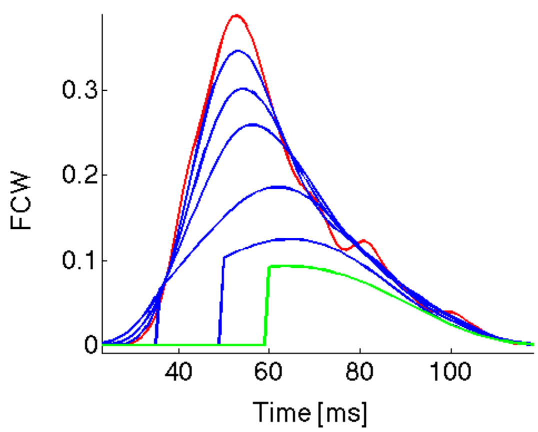

Figure 2. Variation of FCWwith the window length w, at a constant polynomial degree p=2. Red line corresponds to w=9 and green line to w=119. Intermediate values w=21-33-45-71-99 are represented in blue. The decreasing pattern of FCW_{max} with increasing w is clearly visible, as well as the shift of the signal to the right. Noise can be seen on the red curve, while at large window lengths the signal is truncated ($w \geq 71$). Units are of mm^2/s.

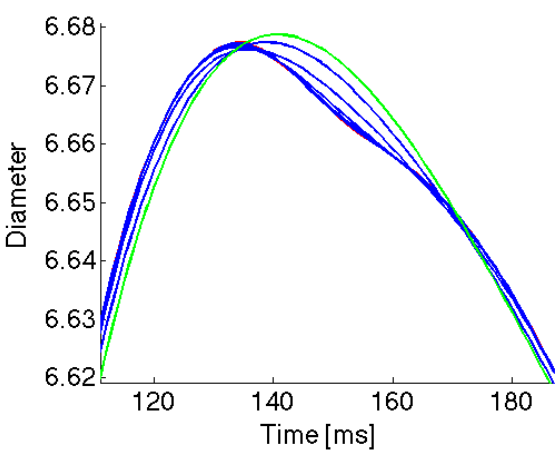

Figure 3. Variation of the maximum value of D with the window length w, at a constant polynomial degree p=2. Red line corresponds to w=9 and green line to w=119. Intermediate values w=21-33-45-71-99 are represented in blue. The truncation of the signals at high w is not visible, as it happens at earlier time points. Physiological features of the waveform are lost at high w (see the green line). The overall variation of maximum value of D with window length is not significant (< 0.013 mm, the resolution of the ultrasound machine). Units of D are of mm.

BCW seemed the most affected among the main three physiological waves by the change of filter settings. Too high a polynomial degree or too short a window caused unrealistic values. This is likely due to the fact that small windows and high polynomial degrees tend to preserve the high-frequency noise producing artifacts. In contrast, large windows and low polynomial degrees tend to dampen natural variations of the waves and of the original signals (Fig. 2-3).

5. Conclusions

Ultrasound-measured vessel diameter and blood flow velocity waveforms were not significantly affected by the Savitzky-Golay filter settings (the variations of the peak of D are depicted in Fig. 3) but their time derivatives dD, dU and wave intensity parameters showed a broad spectrum of variation with changes of filter settings.

We recommend to always specify the Savitzky-Golay filter settings applied to the signals in a wave intensity study, so that appropriate comparisons can be made between studies.

The present findings hold for waveforms that were sampled at 1000 Hz. Different sampling frequencies could produce different results.

Acknowledgements

The authors would like to thank E. N. Wilhelm and J. González-Alonso for their technical support with the ultrasound measurements. The authors would also like to thank the participant in this study.

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Address for correspondence.

Ashraf W. Khir.
Institute of Environment, Health and Societies – Biomedical Engineering Research Theme, Brunel University London, Kingston Lane, Uxbridge, Middlesex, UB8 3PH, United Kingdom. Email address: Ashraf.khir@brunel.ac.uk