SYNTHESIZED CARDIAC WAVEFORM IN THE EVALUATION OF AUGMENTATION INDEX ALGORITHMS

Case Study for a New Wavelet based Algorithm

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Abstract: We developed and tested the performance of a new wavelet based algorithm for Augmentation Index (AIx) determination. The evaluation method relies on reference cardiac-like pulses that are synthesized using a weighted combination of exponentially shaped sub-pulses that represent the three main components of real pulses: the systolic stroke, its reflected replica and the carotid reservoir or windkessel effect. The pulses are parameterized so as to reproduce the main types of cardiac waveforms. The values of AIx yielded by the new algorithm are compared with the ones computed directly from the synthesized waveform and with the values produced by standard Probability Density Function (PDF) analysis.

1 INTRODUCTION

It has become commonly recognized that, in addition to the the traditional systolic/diastolic pressure values, the morphology arterial pressure waveform (APW) bears a great deal of clinically relevant information.

As a consequence, a trend has emerged inside the hemodynamics research community to extract this information using non-invasive techniques that can circunvent catheterization. Along the years, this quest opened new fields of investigation in sensoring techniques and algorithms capable of faithfuly rendering the APW from signals collected at the major artery sites (carotid, brachial, femural and radial, mainly) .

On the algorithm side, major areas of interest are under developement to extract information from the APW, reflecting the relevance of the clinical parameters they address. Focus on themes such as wave intensity analysis, wave separation, augmentation index, cardiac output have been studied by several authors over the last few years.

Interfacing between signal acquisition and algorithm development, the search for efficient transfer functions capable of rendering the central APW from peripheral data (Hope et al., 2004) remains an important theme of debate with some authors advocating its accuracy (Chen et al., 1997 and McConnel et al., 2004) while others show some caution (Hope et al., 2002; Hope et al., 2004).

In addition to these two major areas – APW acquisition and algorithm development – new areas of interest have also emerged collaterally along the last few years. Bench testing is an examle. It plays a fundamental role in reproducing one or more features of the arterial system (Khir and Parker, 2002; Feng and Khir 2007; Hermeling et al., 2007) with high enough repeatibility, for testing both, sensoring devices and algorithm performance.

Arterial modeling, as another example, has also developed in a multitude of forms. From blood flow and pressure in arteries (Olufsen, 1999) to pulse synthesis (Rubins, 2008), modeling always shows the possibility of bringing new insights to the problems in study.

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The use of the wavelet transform in extracting information from the APW has emerged as a preferred tool due to its decomposition properties (De Melis et al., 2007). Following this trend, this work focus on studying the performance of a new wavelet based algorithm developed for determining AIx and explores the virtues of modeling APW with a simple mathematical expression using filtered exponential functions.

2 CARDIAC PULSE SYNTHESIS

The usefulness of synthesizing cardiac-like waveforms is associated to their adquacy in playing the role of reference signal for the algorithms under test.

We synthesize the cardiac-like pulse, *c(t)*, by summing three exponentially shaped sub-pulses that represent the components of the cardiac waveform with a physiological meaning: the systolic stroke, its reflected replica and the aortic reservoir or windkessel effect. Each sub-pulse is build up with two exponentials that account for the rising and falling edges, respectively.

The general expression of the synthesized pulse is

$$c(t) = \sum_{k=1}^{3} \boldsymbol{A_k}\left(\boldsymbol{\varepsilon}^{-\frac{t-D_{Rk}}{\tau_{Rk}}} - \boldsymbol{\varepsilon}^{-\frac{t-D_{Fk}}{\tau_{Fk}}}\right) \quad (1)$$

(1)where A_k is the amplitude D_{Rk} and D_{Fk} are the delays of exponential rising and exponential falling, respectively ,τ_{Rk} and τ_{Fk} are the rising and falling exponential time constants for systole (k=1), reflection (k=2) and windkessel effect (k=3).

Prior to summing, the sub-pulses are submitted to a moving average filtering process in order to smooth the corners that, otherwise, would show up in *c(t)* .

3 AUGMENTATION INDEX

The index evaluated along this work, AIx, carries an important and very intuitive physiological meaning as an index of arterial condition in general, and of arterial stiffness in particular.

3.1 Definition

The main purpose of AIx is to quantify the augmentation of the systolic pressure peak (SPP) imparted to the APW by the reflected, or backward propagating, wave.

The commonly accepted definition of AIx is given by the quotient $\mathrm{AIx} = \frac{P_S - P_i}{P_S - P_D}$, where P_S is the APW peak pressure, P_i its pressure at the inflection and P_D is the diastolic blood pressure.

The definition is extended by arbitrarily considering as negative the values of AIx obtained when the reflected wave arrives after the systolic peak (Murgo et al., 1980). For computational purposes, these values of AIx are given by $\mathrm{AIx} = \frac{P_i - P_S}{P_S - P_D}$.

3.1.1 Misleading Situations

The prognostic value of AIx in clinical practice has not yet reached its full potential (Swillens and Segers, 2008). This can be a consequence of the compounding nature of its definition.

For one, the physiological meaning of AIx would be better served by the formula $\mathrm{AIx} = \frac{P_S - P}{P_S - P_D}$, where P is the increment in pressure imparted to P_D by the systolic stroke alone, making it clear that P is the one that can be augmented. Only the fact that P is unknown (or, at least, very hard to come by) justifies the adopted simplification of taking P_i instead.

Secondly, the signal convention mentioned above can be misleading. In fact, when the reflected wave arrives shortly after the SPP, the formula yields a negative AIx but, nevertheless, physical augmentation still occurs, as represented in figure 1.

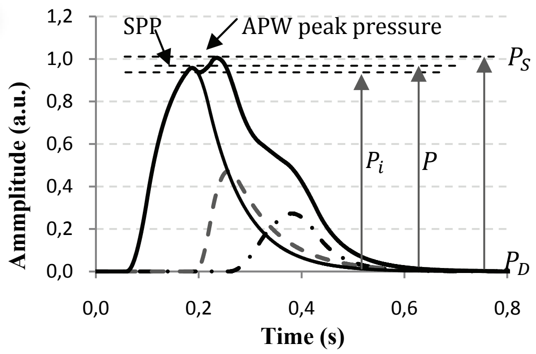

Figure 1: Example of a cardiac waveform where the time of arrival of the reflected wave occurs shortly after systolic peak.

Thin solid line – systolic pressure wave, Dashed line – reflected wave, Dash-point line – windkessel effect, Thick solid line – APW, P_S- APW peak pressure, P_i- pressure at inflection, P_D- diastolic pressure and P- increment in pressure imparted to P_D by the systolic stroke alone.

4 ALGORITHM EVALUATION

The key feature of any algorithm for determining AIx is its ability to precisely identify the inflection point associated to the arrival of the reflected wave.

Evaluation is made by building up a set of waveforms, obtained by gradually varying one of its parameters, in such a way that a range of interesting conditions are swept. In practice, this range of "interesting conditions" must include the limit case where the time of arrival of the reflected wave coincides with the systolic peak. This critical transition from positive to negative values of AIx, the so called type A to type C (Murgo et al., 1980) waveforms, unavoidably yields a discontinuity in the output of any of the algorithms.

The values of AIx derived from the synthesized waveforms are taken as a reference in all measurements, since these values are not impaired by any identification error. We use this methodology to evaluate the performance of two intrinsically different algorithms: the PDF algorithm and the WBior1.3 algorithm, as represented in the flowchart of the figure 2.

Behaviour under noisy conditions is also an important feature that is studied in WBior1.3 algorithm.

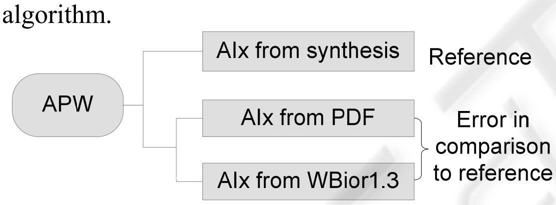

Figure 2: Flowchart diagram depicting the test methodology.

4.1 Probability Density Function

The working principle of this algorithm was described by other authors (Tsui et al., 2007), relies on the PDF property of creating a local maximum for the amplitudes close to the inflection point that defines AIx.

Unfortunately, other maxima are also created whenever the signal amplitude is slow varying, as happens close to its peaks. To make things worse, these confounding peaks can occur for amplitudes of the same order of magnitude of the inflection point, making the algorithmic identification task very hard to accomplish. To avoid biasing the results with the error of such an algorithm, we adopted to determine the inflection point using a cursor based interaction. Figure 3 plots a typical result of this procedure.

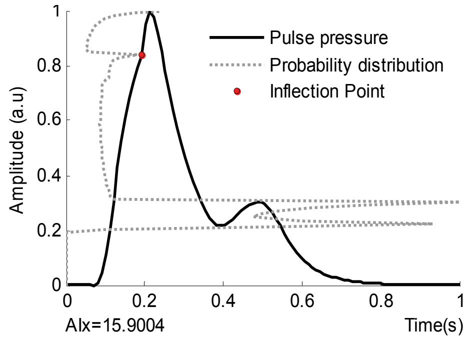

Figure 3: APW and its associated PDF.

4.2 Bior 1.3 Mother Wavelet

The Bior 1.3 mother wavelet (WB1.3) was selected among a few candidates for its ability in identifying the inflection point, when used in a scale of 20 (roughly equivalent to a 1.3 ms period).

Figure 4 illustrates a typical detection event characterized by its distinctive narrow peak located in coincidence (vertically aligned) with the inflection point. The abscissa of the peak is the key to the computation of AIx. Any loss of contrast in the peak definition or any eventual uncertainty in its location (jitter), as happens when noise is present, will reflect in the error magnitude.

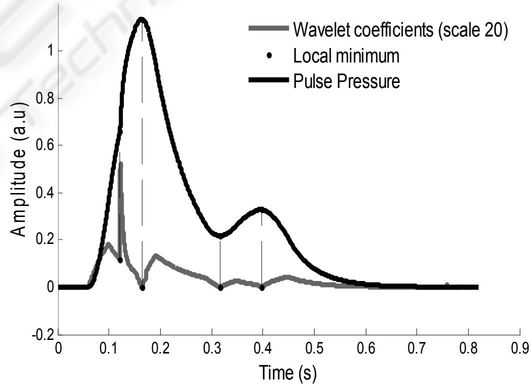

Figure 4: Cardiac pulse and its WB1.3 (scale 20) wavelet decomposition (gray curve). Vertical dashed lines show local peaks detected by the WB1.3.

4.3 Results

Figure 5 depicts results for a family of cardiac pulses, where D_{R2} sweeps the interesting area that crosses the systolic peak, showing the discontinuity that results from the definition. Notice the magnitude of the errors shown in the lower panels, where the superior performance of the WB1.3 algorithm shows up: less than 0.5% for the WB1.3 and greater than 2% in the PDF case.

The performance of the WB1.3 algorithm was also tested with noise added to the cardiac pulses. The results obtained for a 36 dB limit (where the discrimination capability of the algorithm is lost) demonstrate that in presence of noise the characteristic discontinuity of the AIx curve vanishes away and the values of AIx scatters and rise.

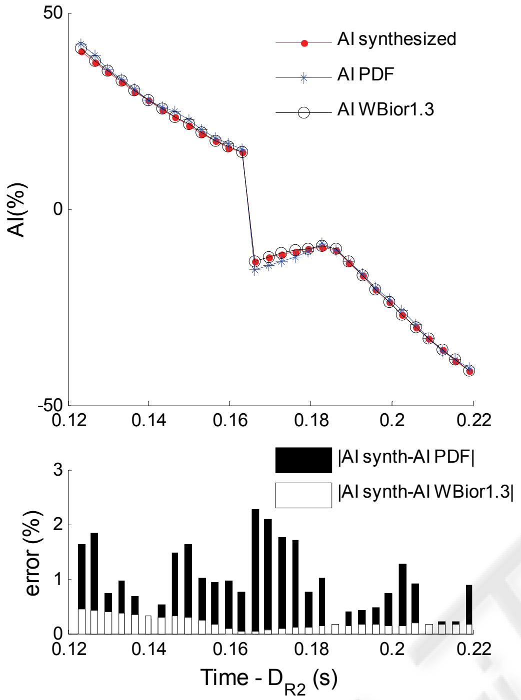

Figure 5: AIx results yielded by the three methods (upper panel) and plot of errors of PDF and WB1.3 algorithms (lower panel).Time scale is referred to the delay rising of reflected wave.

5 CONCLUSIONS

The developed algorithm WBior1.3 in comparison with the algorithm based in the PDF function provides an efficient tool to determine AIx.

One possible pitfall of the definition of AI lays in the fact that the lawful association of negative values of AIx to a generally favourable arterial condition can configure a misinterpretation of the true physiological situation in some situations.

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