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Technical note

A low-pass differentiation filter based on the 2nd-order B-spline wavelet for calculating augmentation index

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ABSTRACT

The key point to calculate augmentation index (AIx) related to cardiovascular diseases is the precise identification of the shoulder point. The commonly used method for extracting the shoulder point is to calculate the fourth derivative of the pulse waveform by numerical differentiation. However, this method has a poor anti-noise capability and is computationally intensive. The aims of this study were to develop a new method based on the 2nd-order B-spline wavelet for calculating AIx, and to compare it with numerical differentiation and Savitzky–Golay digital differentiator (SGDD). All the three methods were applied to pulse waveforms derived from 60 healthy subjects. There was a significantly high correlation between the proposed method and numerical differentiation ($r = 0.998$ for carotid pulses, and $r = 0.997$ for radial pulses), as well as between the proposed method and the SGDD ($r = 0.995$ for carotid pulses, and $r = 0.993$ for radial pulses). In addition, the anti-noise capability of the proposed method was evaluated by adding simulated noise (>10 Hz) on pulse waveforms. The results showed that the proposed method was advantageous in noise tolerance than the other two methods. These findings indicate that the proposed method can quickly and accurately calculate AIx with a good anti-noise capability.

1. Introduction

Augmentation index (AIx) is widely used in assessing arterial stiffness [1,2]. Many clinical researches have proved that the AIx is closely related to cardiovascular diseases [2–4]. Recently, AIx was also used in evaluating the treatments, drug effects, and other related medical researches [5–7]. The key step to calculate AIx is the precise identification of the shoulder point on the waveform. In 1989, Kell et al. first proposed that the shoulder point could be extracted by the fourth derivative of the pulse waveform [8]. And in 1995, Takazawa et al. described the algorithm in detail [9], which has been widely used to calculate AIx [9,10]. As shown in Fig. 1, for type A pulse waveforms, the shoulder point located on the upstroke wave coincides with the first positive-to-negative zero crossing of the fourth derivative; whereas for type C and radial waveforms, the shoulder point located on the downstroke wave corresponds to the second negative-to-positive zero crossing. With diverse positions of shoulder points, the corresponding definitions of AIx are also different (Fig. 1).

Traditionally, the method based on numerical differentiation is used to approximate to the derivate of a signal [11]. However, this method has inherent flaws degrading it in pulse wave analysis (PWA). A major problem is that the numerical differentiation can greatly amplify the noise, especially at high frequencies. Therefore, it is essential to perform appropriate denoising of the pulse wave signal prior to differentiation [12,13]. Unsatisfactorily, it further increases the complexity of the algorithm and may filter out useful information contained in the pulse wave signal [14]. For example, the Savizky–Golay (SG) filters are popularly applied in many fields. When a SG filter is used, high-frequency noise in the pulse wave signal can be largely eliminated by increasing the length or the order of the SG filter. However, some useful details of the signal will be also smoothed out at the same time. In addition, Savitzky–Golay digital differentiator (SGDD), another choice for acquiring the derivative of the pulse wave signal, has the same problem in the choice of lengths and orders [15].

Consequently, it is crucial to develop a new method for calculating the derivative of the pulse waveform, which is able to overcome

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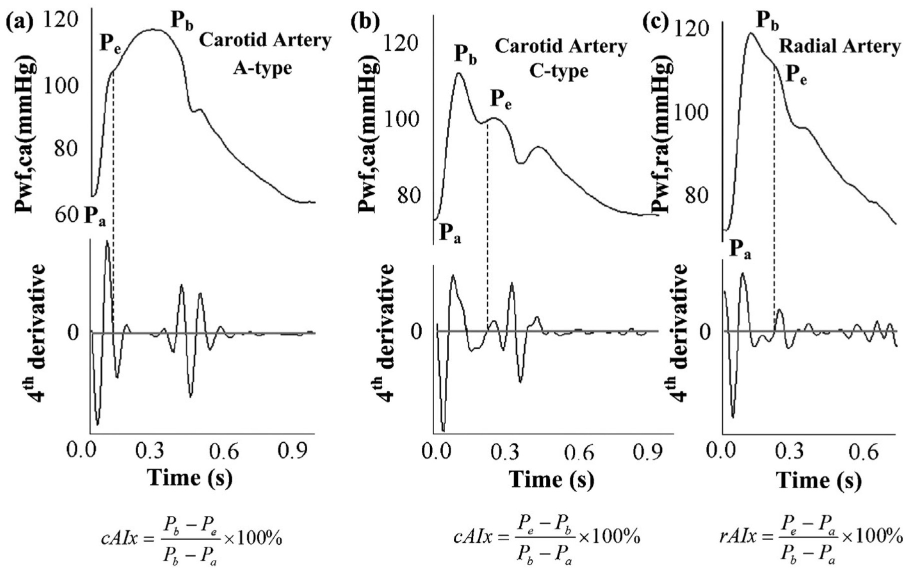

Fig. 1. The relationship between the shoulder point and the 4th derivatives of the pulse waveforms, as well as the corresponding formulae of AIx. (a and b) The types A and C carotid waveforms, while (c) displays a radial waveform.

the aforementioned drawbacks. The differential property of convolution and spline wavelets make it a potential solution. Spline wavelets are widely used in chemistry, image processing and biological signal processing, because they have explicit formulae in both the time and frequency domain [16–18]. In particular, the 2nd-order B-spline wavelet has been used to calculate the high order derivative of chemistry signal successfully [16]. However, the 2nd-order B-spline wavelet has not yet been applied to the calculation of AIx.

The aim of this study is to investigate the accuracy and the anti-noise capability of the proposed method for identifying the shoulder points by the convolution of the pulse wave signal and the function constructed by a cascade of two 2nd-order B-spline wavelets (hereinafter referred to as the convolution method). In the remainder of this paper, we first introduce the principle of the algorithm. Then will be a comparison by form of figure display among AIx calculated by the convolution method, the numerical differentiation and the SGDD for the fourth order differentiation. Subsequently, some waveform examples and a table are given to show the performance of the convolution method on noise tolerance.

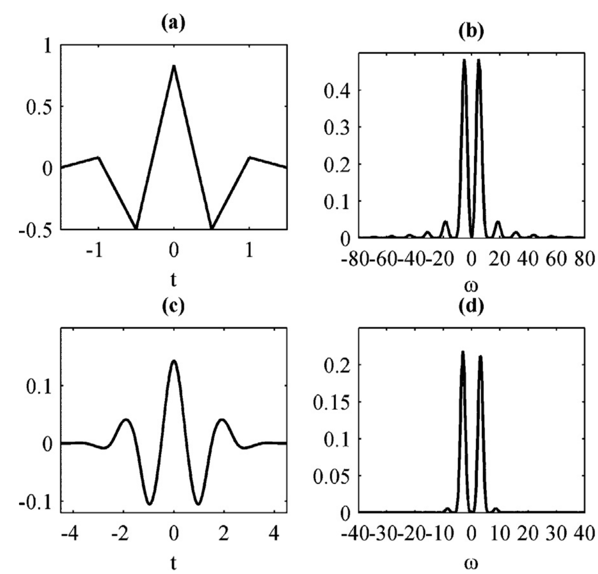

Fig. 2. 2nd-order spline wavelet, function $\varphi_1(t)$ and their Fourier transforms (FT). The 2nd-order spline wavelet (a), FT of the 2nd-order spline wavelet (b), function $\varphi_1(t)$ (c), FT of function $\varphi_1(t)$ (d).

2. Theoretical background and algorithm

Wavelets consist of the dilations and translations of a function $\psi(t)$ satisfying a certain condition,

$$\psi_{a,b}(t) = |a|^{-(1/2)}\psi\left(\frac{t-b}{a}\right), \quad a, b \in R; \quad a \neq 0, \tag{1}$$

where a and b are, respectively, the scale and position parameter expressed in real number R. $\psi(t)$ is known as the mother wavelet.

A B-spline wavelet of order m is defined as:

$$\psi_m(t) = 2^{-m+1}\sum_{j=0}^{2m-2}(-1)^j \beta_{2m}(j+1-m)\beta_{2m}^{(m)}(2t-j+m-1) \tag{2}$$

where $\beta_m(x)$ is central B-spline of order m. 2nd-order spline wavelets are used as the tools in this study due to their good performance on calculating the high order derivative of signals [16]. The mother wavelet is defined as

$$\psi_2(t) = \begin{cases} -\frac{1}{6} \times |t| + \frac{1}{4}, & 1 < |t| \leq 1.5, \\ -\frac{7}{6} \times |t| - \frac{13}{12}, & 0.5 < |t| \leq 1, \\ -\frac{8}{3} \times |t| + \frac{5}{6}, & |t| \leq 0.5. \end{cases} \tag{3}$$

$\psi_2(t)$ is an even function and its value is a real number as shown in Fig. 2a. Then we define a new function using $\psi_2(t)$ as:

$$\begin{aligned} \varphi_a(t) &= \psi_{2a}(t) * \psi_{2\times 2a}(t) \\ &= |a|^{-(1/2)}\psi_2\left(\frac{t}{a}\right) * |2a|^{-(1/2)}\psi_2\left(\frac{t}{2a}\right) = \varphi_1\left(\frac{t}{a}\right) \end{aligned} \tag{4}$$