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Modeling radial artery pressure waveforms using curve fitting: Comparison of four types of fitting functions

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Mean absolute error

Abstract *Background:* Curve fitting has been intensively used to model artery pressure waveform (APW). The modelling accuracy can greatly influence the calculation of APWs parameters that serve as quantitative measures for assessing the morphological characteristics of APWs. However, it is unclear which fitting function is more suitable for APW. In this paper, we compared the fitting accuracies of four types of fitting functions, including Raleigh function, double-exponential function, Gaussian function, and logarithmic normal function, in modeling radial artery pressure waveform (RAPW).
Methods: RAPWs were recorded from 24 healthy subjects in resting supine position. To perform curve fitting, 10 consecutive stable RAPWs for each subject were randomly selected and each waveform was fitted using three instances of the same fitting function.
Results: The mean absolute percentage errors (MAPE) of the fitting results were 5.89% ± 0.46% (standard deviation), 3.31% ± 0.22%, 2.25% ± 0.31%, and 1.49% ± 0.28% for Raleigh function, double-exponential function, Gaussian function, and logarithmic normal function, respectively. Their corresponding mean maximum residual errors were 23.71%, 17.83%, 6.11%, and 5.49%.
Conclusions: The performance of using Gaussian function and logarithmic normal function to model RAPW is comparable, and is better than that of using Raleigh function and double-exponential function.

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Introduction

It has been widely accepted that changes of artery pressure waveform (APW) characteristics are risk indicators of cardiovascular diseases.[1–3] Pulse transit time (PTT), pulse wave velocity (PWV), and reflection index (RI) have been derived from APWs as parameters of clinical interest.[1,4–6] Many techniques are used to obtain information on human physiology or pathology by studying changes in APWs. Traditionally, derivative methods can acquire the morphological changes of APWs by extracting parameters and wave intensity analysis can obtain changes of wave reflections in the nature and timing according to APWs' pressure and flow velocity.[7–10] Though simple and can be used for real-time computing are the advantages of these technologies, they fail to analyze the features of the complete APWs and their performance is relatively poor when APWs are weak and noisy.

Curve fitting has been intensively studied recently to quantitatively assess the morphological changes of APWs. APW is a composite of a forward wave and a reflected wave.[11] Each wave can be approximated by a fitting function. The change of APW is completely reflected by the parameter changes of the fitting function. Whether or not the reflected wave can be found in an intuitive way, this analysis method can easily represent the reflected wave and make the characteristics of APW very clear. The fitting parameters are obtained by least squares method, which is a macroscopic method, so it can effectively suppress noise and greatly improve the precision of measurement. Several different fitting functions have been applied, e.g., triangular function,[12] Raleigh function,[13] Gaussian function,[14] and logarithmic normal function.[15] Among them, triangular function showed much deviation between the fitting result and original waveform and is thus rarely used currently.[12] A mean square error (MSE) of $<0.5\%$ was achieved in reconstructing finger photoplethysmographic (PPG) waveform using two Raleigh functions.[13] An average maximum residue error of 4% was reported based on five logarithmic normal function to decompose finger and tip PPG waveform.[15,16] Four Gaussian functions resulted in a residual error of $<10\%$ for decomposing ear and finger PPG.[14] To reconstruct the digital volume pulse waveform detected on the left index finger, four or five Gaussian functions were used with both suggesting a root mean square error of $<2.0\%$.[17] A similar fitting approach using five Gaussian functions has also been applied in order for extracting feature points from finger PPG.[18] For modelling carotid and radial APWs, Liu et al. have demonstrated that three positive Gaussian functions are already optimal, resulting in a mean absolute percentage error (MAPE) of as low as 1.1% and 1.0%, respectively, for carotid and radial APWs.[19] Double-exponential often has been used as fitting functions for corona discharge and high voltage[20] and bimodal waveform occasionally appears in sleep apnea patients' waveforms obtained from finger PPG, which is what we will study next. In this paper double-exponential has been used as contrast fitting function.

The modelling accuracy can greatly influence the calculation of APWs parameters that serve as quantitative measures for assessing the morphological characteristics of APWs. However, it is unclear which fitting function is more appropriate, even though relatively low fitting errors have been reported for all those functions. Besides, APWs detected at different sites have been used in those studies which makes the results less comparable. In this work, we aimed to compare the performance of four fitting functions, i.e., Raleigh function, logarithmic normal function, Gaussian function, and double-exponential function to model the APWs collected at the radial site.

Methods

Data

Data used in this paper came from our previous study.[21] Table 1 shows the participants' basic clinical information. Ethical permission was received from the ethical committee of Shandong Provincial Hospital and all participants gave their informed consent. In short, the radial artery pressure waveform (RAPW) of right arm were recorded for 40 s with a sampling rate of 500 Hz by piezoelectric sensor from 24 healthy participants in a supine position and then were filtered by the band-pass filter (0.05–35 Hz). An open-source algorithm[22,23] was used to detect the feet of each recording and 10 successive normal sinus cardiac cycles were intercepted based on the feet, then 10 separate beats were extracted respectively between two adjacent pulse feet. Each separate beat was normalized to eliminate pressure effects, that was, each separate beat was finally to having a fixed length of 1000 (by interpolation) and 1-unit amplitude (i.e., pulse foot has an amplitude of 0 and pulse peak of 1).

Table 1 The 24 participants' basic clinical information.

Variables	Value	Range (min–max)
Number (M/F)	24 (14/10)	–
Age (year)	29 ± 8	21–50
Height	169 ± 8	151–183
Weight (kg)	63 ± 11	41–87
BMI (kg/m^2)	22 ± 3	15–27
SBP (mmHg)	115 ± 12	93–137
DBP (mmHg)	70 ± 10	57–95
MAP (mmHg)	85 ± 10	69–107

Value: mean ± SD.

Reconstruction of RAPW using curve fitting

Curve fitting was performed to reconstruct each specific RAPW segment. Here, we examined four different fitting functions:

i) *Raleigh function as defined by*:

$$f_k(n) = A_k \times n \times \exp\left(-\frac{1}{2} \times W_k \times n^2\right) \quad (1)$$

wherein $n = 1, 2, \ldots, 1000$ (i.e., the length of Raleigh function is 1000 points). The subscript k represents