Spectral Analysis of Radial Pulse Wave for Non-Invasive Assessment of Arterial Aging

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Abstract. The radial pulse wave (OP) provides a valuable reflection of arterial system dynamics, offering insights into vascular aging. This study aimed to evaluate vascular aging by analyzing the spectral characteristics of the OP and determining the system's resonance frequency and its relationship with age, utilizing the four-element Windkessel model, which accounts for distal compliance. Pulse wave recordings from 100 healthy males aged 18 to 65 years were analyzed. Fourier analysis was applied to identify the frequency of maximum gain of the Windkessel model, analyzing the specific spectrum of the diastolic oscillation and using Lagrange interpolation for the accurate determination of this frequency. The Diastolic Pressure Augmentation (DPA) was also measured, examining its dependence on harmonics and age. Results indicated that frequency of maximum gain remained stable with age, averaging approximately 3.5Hz. Conversely, DPA decreased linearly with age at a rate of 0.11 mmHg by year. The third harmonic was identified as the principal spectral determinant of DPA for normal heart rate. The arterial system's behavior was consistent with an underdamped response, with resonance persisting across all age groups. In conclusion, while the resonance frequency of the arterial system remains constant with aging, its gain diminishes due to a reduction in distal compliance. Spectral evaluation of the OP offers a non-invasive, functional indicator for arterial aging, complementing traditional assessment methods.

Keywords: Arterial Diameter Variation, Radial Pulse Wave, Diastolic Pressure Augmentation, Arterial Aging.

1 Introduction

The analysis of the radial pulse wave (OP) is a straightforward technique for assessing the functional status of the arterial system. This wave can be recorded by placing a pressure transducer over the radial pulse palpation site at the wrist. The morphology of the pulse wave significantly varies with factors such as age, sex, and the condition of arterial walls.

A typical pulse wave recording in a young, healthy individual, as illustrated in Fig.1(a), distinguishes two main phases: systolic and diastolic. These phases are separated by the dicrotic notch, which corresponds to the opening of the aortic valve and marks the onset of diastole, $340ms$ after the onset of systole in the same figure.

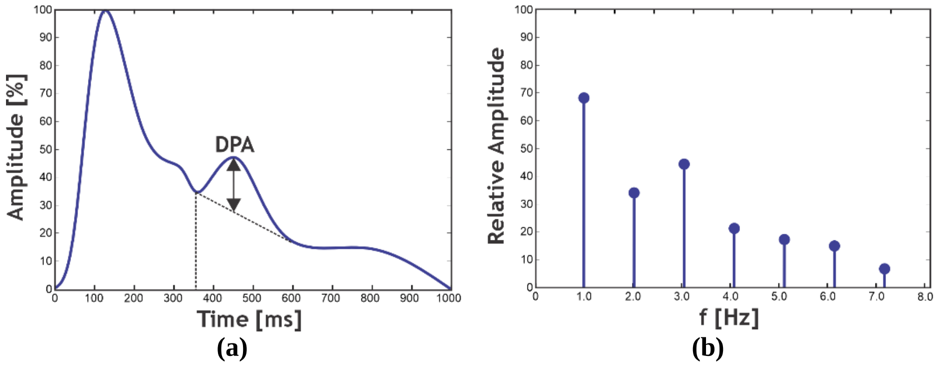

Fig. 1. Pulse wave recording in a young individual, normalized in amplitude (a). The vertical line indicates the beginning of diastole. DPA: Diastolic Pressure Augmentation. Corresponding spectrum (b). A predominant amplitude of the 3rd harmonic of the heart rate is observed, located at 3.12Hz.

During the systolic phase, the arterial system can be accurately modeled as a transmission line. A physical discontinuity at the aortic termination creates a reflection that, upon reaching the radial region, enables the calculation of clinically significant parameters like wave propagation velocity, augmentation index, and central aortic pressure, which differs from brachial pressure [1].

With the opening of the aortic valve, ventricular ejection concludes, and diastole begins, leading to changes in hemodynamic conditions. For this diastolic phase, the system's behavior can be described using the fluid-dynamic Windkessel model, originally proposed by Goldin and Watt [2]. The electrical equivalent of this model, widely used in its four-element version, is presented in Fig. 2.

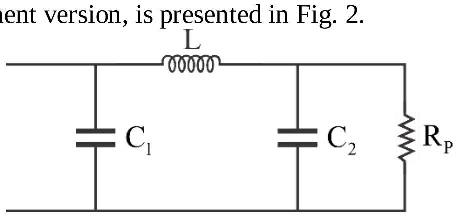

Fig. 2. a: Four-element Windkessel electrical model. It includes peripheral resistance (R_p), aortic compliance (C_1), distal compliance (C_2), and the inertance (L) of the interposed fluid column. The model describes the pressure drop in R_p during diastole.

This model is a resonant circuit comprising peripheral resistance (R_p), aortic compliance (C_1), distal compliance (C_2), and the inertance (L) of the interposed fluid column. Notably, C_2 is approximately ten times smaller than C_1, allowing for useful simplifications in the system's equations.

During diastole, arterial pressure exhibits a decaying exponential shape, overlaid with a damped oscillation. The exponential decay is primarily due to the discharge of C_1 through R_p, while the initial oscillation arises from the underdamped response of the resonant circuit formed by L, C_2, and R_p. C_2 is a valuable clinical marker of arterial aging, as it decreases almost linearly with age [3]. Furthermore, C_2 is influenced by cardiometabolic diseases that impair endothelial function, increase arterial wall stiffness, and reduce distensibility [4].

Given that C_2 determines the resonant properties of the Windkessel system, assessing vascular aging indirectly through the OP spectrum has been proposed. In previous work, the physiological and clinical implications of this resonant frequency were analyzed [5]. This study details the bioengineering principles, measurements, and mechanical interpretation of this technique.

2 Materials and Methods

The study analyzed pulse wave (OP) spectra from an existing database, encompassing 100 healthy male subjects ranging in age from 18 to 65 years. The cohort was stratified into two groups: a young group ($N = 49$) with a mean age of 26.9 ± 7.3 years, and an adult group ($N = 51$) with a mean age of 53.4 ± 10.3 years.

Pulse wave recordings were performed under resting conditions, captured with an 8-bit resolution and a $15Hz$ bandwidth. Concurrent arterial pressure measurements were obtained using a validated automatic sphygmomanometer (Omron® HEM-7120). Signal processing was made using Mathcad® software. From each recording, eight cardiac cycles exhibiting the highest correlation were selected and subsequently averaged. The resulting waveform was then represented in millimeters of mercury (mmHg), using the previously measured systolic and diastolic pressures as reference points.

Spectral analysis was performed on each averaged record using Fourier analysis to identify the frequencies and amplitudes of the continuous component and the first six harmonics. The Diastolic Pressure Augmentation (DPA), an initial oscillation of the diastole containing information on the resonant properties of the Windkessel model, was measured directly from the pulse wave, as depicted in Fig. 1(a).

To specifically isolate the spectral contribution originating from diastolic oscillation, a specialized procedure was applied:

- The diastolic oscillation was suppressed from the original signal resulting in diastole as a simple exponential decay, yielding a modified signal whose Fourier transform was denoted as $S_0(f)$.
- The difference between the original spectrum $S(f)$ and the modified spectrum $S_0(f)$ was then computed, which represents the spectral content exclusively from the diastolic oscillation. This process is illustrated in Fig. 3.
- Seven points of the spectrum (the continuous component and the first six harmonics) were considered, and the component with the highest amplitude

was identified. This component is the spectral line closest to the damped resonance frequency of the system, denoted as f_{mx}.

A sixth-order Lagrange interpolation was applied to these seven selected spectral points, generating a continuous curve. The frequency corresponding to the maximum amplitude (f_{mx}) was precisely determined by identifying the zero-crossing point of the first derivative of this interpolated curve. This value can be considered an accurate estimate of the model's natural resonance frequency (f_n).

Statistical analysis of f_{mx} was performed using MATLAB® (MathWorks, Natick, MA, USA). The Lilliefors test indicated that a normal distribution could not be assumed for this variable. Data acquisition adhered to the Declaration of Helsinki, and the processing protocol received approval from the Research Ethics Committee of the Universidad Nacional de Mar del Plata.

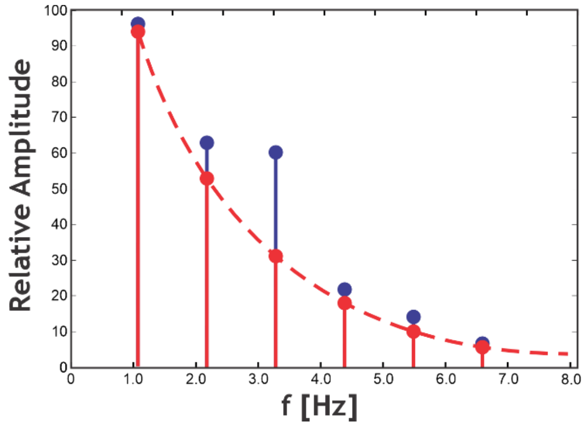

Fig. 3. Spectrum of the original pulse wave (blue) and with the oscillation suppressed (red). The differences between both correspond to the spectrum of diastolic oscillation.

3 Results

The overall study population exhibited a mean heart rate of 71.4 ± 11.4 beats per minute ($1.19 \pm 0.19 Hz$), which was confirmed to have a normal distribution by the Shapiro-Wilk test ($W = 0.97$, $p = 0.17$).

The individual values of the maximum gain frequency (f_{max}) of the Windkessel model, plotted as a function of age, are presented in Fig. 4.

A polynomial regression curve of the third order indicates a very weak correlation between f_{mx} and Age ($R^2 = 0.058$). The average f_{mx} values consistently ranged between 3.4 and $3.6 Hz$ for subjects across the age span of 18 to 70 years. Notably, no young subjects (under 20 years) presented an f_{mx} greater than $4 Hz$, nor did any older adults (over 60 years) show an f_{mx} less than $3 Hz$. These findings suggest that f_{mx} is largely independent of age.

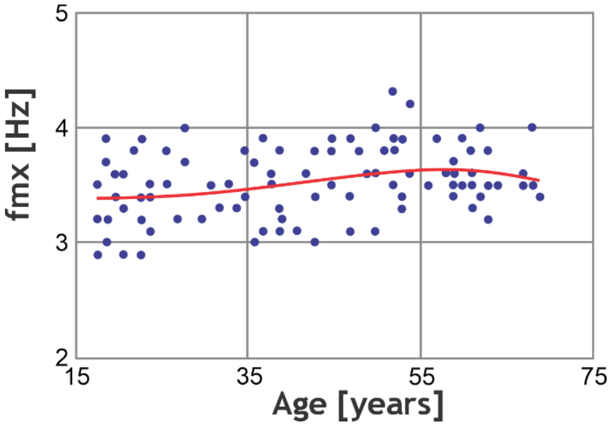

Fig. 4. Maximum gain frequency (f_{mx}) of the Windkessel model as a function of age. The third-order polynomial regression suggests that f_{mx} is independent of age.

The results concerning the diastolic pressure augmentation (DPA) with age are displayed in Fig. 5. DPA was observed to decrease with age in a nearly linear fashion, although it remained present even in advanced ages. The Shapiro-Wilk test indicated a non-normal distribution for DPA values ($W = 0.93$, $p < 0.001$). The average DPA across the population was $6.5 \pm 2.8 mmHg$. Specifically, in young individuals under 20 years, DPA reached $9.2 \pm 2.2 mmHg$, while in adults older than 60 years, it declined to $4.6 \pm 1.4 mmHg$. The rate of decrease for DPA was calculated to be 0.11 mmHg per year ($R^2 = 0.42$), with considerable dispersion.

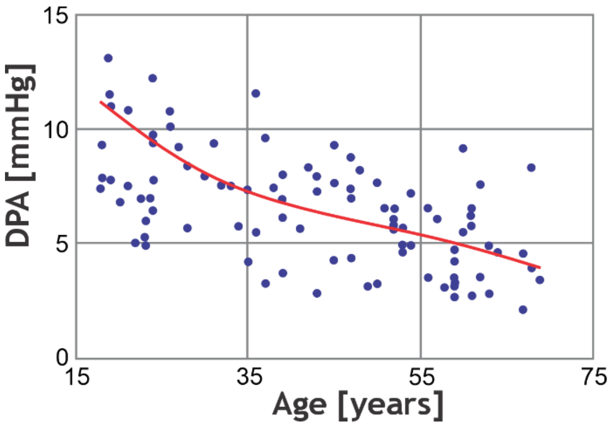

Fig. 5. Decrease in diastolic pressure augmentation (DPA) with age. Although it decreases, DPA remains present even in older adults.

Spectral analysis revealed that the relative amplitudes of the first three harmonics of the pulse wave diminished with increasing age:

- Second harmonic (A2): decreased from 73% to 54%.
- Third harmonic (A3): decreased from 57% to 31%.

- Fourth harmonic (A4): decreased from 29% to 14%.

Given that DPA quantitatively represents the pressure increase during diastole and is linked to distal compliance (C_2), its dependence on harmonic content, age, and heart rate (f_c) was investigated through linear regression analysis. The results of this regression model are summarized in Table 1. The analysis showed that, for normal heart rate values, the third harmonic (A3) was the most significant variable, alongside age, influencing DPA. The model did not demonstrate significant dependence on the other tested variables (A2, A4, f_c).

Table 1. Linear regression of the DPA variable. Amplitudes A2, A3, and A4 correspond to the second, third, and fourth harmonics of the spectrum, expressed relative to the amplitude of the fundamental component (f_c). Only A3 and Age were significant.

Variable	Coef. B	t-statistic	p-value
Age	**-0.047**	**-2.24**	**0.03**
A2	0.019	0.90	0.37
A3	**0.113**	**4.54**	**< 0.001**
A4	0.008	0.22	0.83
f_c	-0.016	-0.01	0.99
Intercept	2.344	0.95	0.35

4 Discussion

The methodology proposed for measuring the frequency of maximum gain (f_{mx}) proved to be computationally straightforward and did not present any relevant technical challenges. The measurement error, conditioned by the sampling frequency, was approximately $\pm 0.05 Hz$, which was adequate for evaluating the effects of aging on f_{mx}.

The primary finding of this study was the remarkable fact that the arterial system's resonance frequency (f_{mx}) with age remains stable across the evaluated age range. In contrast, the amplitude of diastolic oscillation, quantified as the diastolic pressure augmentation (DPA), exhibited a nearly linear decrease with age. This observation is consistent with previous studies on vascular aging [6].

The physiological significance of f_{mx} values near $3.5Hz$ lies in their ability to ensure that the closest heart rate harmonic reinforces pressure for approximately $300ms$ at the onset of diastole. This suggests a physiological mechanism for hemodynamic optimization, whereby energy stored in the resonant system is used to augment diastolic flow without increasing ventricular workload. The attenuation of this beneficial effect with aging indicates a potential loss of functional adaptation due to vascular deterioration.

Spectral analysis of the OP supported this interpretation: in almost all cases, a high amplitude was observed in the heart rate harmonic falling within the 3 to $4Hz$ interval. For typical heart rates around $1.2Hz$ (or 72 beats per minute), the most prominent component in the spectrum corresponds to the third harmonic. The strikingly elevated amplitude of the heart rate harmonic within this specific range implies that the arterial system behaves as an underdamped second-order system. This behavior can be precisely interpreted using the four-element Windkessel model, whose transfer function $H(f)$ is given by:

$$H(f) = \frac{{f_n}^2}{\sqrt{\left({f_n}^2 - f^2\right)^2 + 4\,\zeta^2\,{f_n}^2\,f^2}} \tag{1}$$

Given that aortic compliance C_1 is much greater than distal compliance C_2 ($C_2 \gg C_2$), the natural resonance frequency f_n is approximately defined as:

$$f_n = \frac{1}{2\pi\sqrt{L\,C_2}} \tag{2}$$

The gain at the natural resonance frequency H_{f_n} is:

$$H_{f_n} = R_p\sqrt{\frac{C_2}{L}} \tag{3}$$

The damping coefficient ζ is:

$$\zeta = \frac{\sqrt{\frac{L}{C_2}}}{2R_p} \tag{4}$$

And the damping time constant τ is:

$$\tau = R_p C_2 \tag{5}$$

Typical reported values for the Windkessel model parameters [3, 7, 8] include:

C_1: $1.1\ to\ 2\,\frac{mL}{mmHg}$;

C_2: $0.02\ to\ 0.19\,\frac{mL}{mmHg}$;

L: $0.01\ to\ 0.03\,\frac{mmHg\ s^2}{mL}$;

R_p: $0.6\ to\ 1.5\ \frac{mmHg\ s}{mL}$.

When represented in their electrical equivalent, these values directly translate to Farads (F), Henries (H), and Ohms (Ω), respectively.

For a young individual, using approximate values:

$R_p = 0.6\ \Omega$	$L = 0.014H$	$C_2 = 0.12F$
$C_1 \gg C_2$	$f_c = 1.1Hz$	

the following approximate derived values are obtained:

$$f_n = 3.7Hz;\ f_{mx} = 3.6Hz;\ H(3f_c) = 1.9;\ \zeta = 0.27;\ \tau = 0.16\text{s}.$$

These values characterize an underdamped response with a brief time constant, causing the initial positive oscillation hemicycle to dominate over the subsequent negative one, thereby generating a pressure increase during the cycle. Even in older adults within the study, ζ values remained below 0.7, consistently demonstrating an underdamped response during diastole, which is responsible for the transient increase in blood pressure.

Fig. 6 shows an example of a healthy 65-year-old male. The presence of a damped oscillation indicates that the response remains underdamped, although its amplitude is smaller than in a younger male.

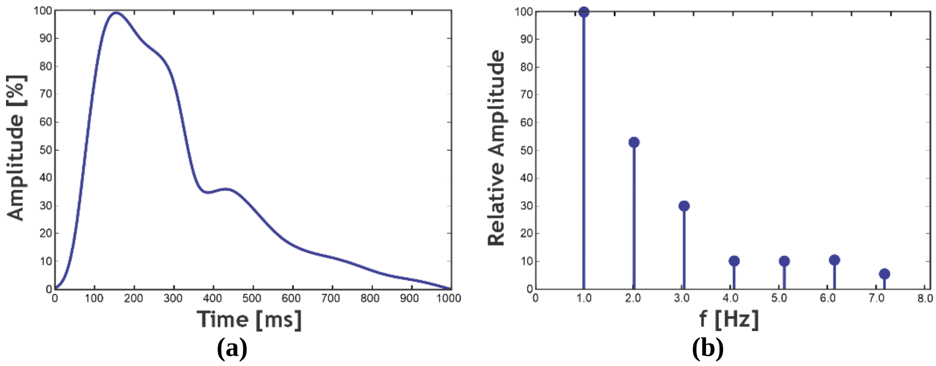

Fig. 6. - Recording (a) and spectrum (b) of a healthy older adult. A slight increase in pressure is observed at the beginning of diastole, and the amplitude of the 3rd harmonic does not stand out from the adjacent ones.

The f_{mx} was determined from the spectral amplitudes of diastolic oscillation. The Windkessel transfer curve around f_{mx} was meticulously reconstructed using a sixth-order Lagrange interpolation applied to the first seven spectral components, including the continuous component. This technique provided a reliable estimate of the system's gain profile in the proximity of f_{mx}, which consistently approximated $3.5Hz$ in the population average.

While the resonance frequency of the Windkessel model did not significantly vary with age, the amplitude of the diastolic oscillation (DPA) notably decreased with aging, a finding strongly supported by the linear regression analysis presented in Table 1. The third harmonic was identified as the primary determinant of DPA. For a normal heart rate of approximately $1.2Hz$, the third harmonic is located near $3.6Hz$, maintaining its proximity to f_{mx}. In scenarios of higher heart rates, such as $1.5Hz$ (90 bpm), the second harmonic shifts closer to the resonance frequency, fulfilling a similar function. This observation helps explain why DPA appeared independent of heart rate in the regression analysis.

The precise physiological interpretation of these age-related changes is complex. With increasing age, inflammatory factors affecting the vascular endothelium weaken the vasodilatory mechanism of arterial smooth muscle and concurrently heighten vasoconstrictor tone, thereby disrupting the normal equilibrium. Consequently, this leads to a reduction in the compliance of small distal arteries (C_2) and an increase in peripheral resistance (R_p) due to arteriolar vasoconstriction.

While increased stiffness in young adults can be functional and reversible, in healthy older adults, chronic inflammation induces further intima-media hypertrophy through proliferation of vascular smooth muscle cells and deposition of extracellular material, culminating in structural rigidity, a process termed arterial remodeling [9].

Given that the resonant behavior of the system is influenced simultaneously by L, C_2, and R_p, all of which are affected by aging, their interaction is intricate.

The results obtained suggest that the reduction of C_2 predominantly influences Eq. 4, thereby explaining the observed decrease in DPA. The constant values of f_{mx}, within the Windkessel model, could be explained by a compensatory increase in inertance. Some studies have reported an increase in inertance in the aortic region associated with larger diameters and lengths, although specific data concerning upper limb arteries are not available in the literature [10, 11].

5 Conclusions

The arterial system, accurately modeled using the four-element Windkessel concept, exhibits an underdamped response during diastole. This behavior is manifested as a transient pressure increase, known as diastolic pressure augmentation (DPA), which is intricately linked to the system's resonant properties.

A key finding of this study is that the resonance frequency (f_{mx}) of the system remained remarkably constant with age across the studied population. This suggests a robust physiological mechanism ensuring resonant stability, potentially maintained through compensatory changes in inertance (L).

In contrast, the amplitude of diastolic oscillation demonstrated a consistent linear decrease with age. This decline is indicative of a progressive loss of distal compliance (C_2), a change entirely consistent with the recognized processes of vascular aging.

Spectral analysis allowed to explain that the third harmonic of the pulse wave is the primary contributor to this diastolic pressure increase, and its reduction largely accounts for the observed decrease in DPA.

This non-invasive approach, centered on the spectral analysis of the radial pulse wave, represents a valuable bioengineering tool for the functional evaluation of arterial aging. Its potential integration into preventative strategies for cardiovascular health deserves further future exploration.

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