Calculation of Vascular Impedance for Modeling the Arterial System in Patients with Cardiovascular Diseases

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The process of detecting pathologies in the human cardiovascular system remains challenging despite advancements in current technologies. It is imperative to devise new methods to aid in diagnosing the diseases. This study focuses on an approach employed in Cardiovascular Engineering, wherein the systemic arterial circulation is modeled using equivalent electrical circuits known as "Windkessel Models". The parameter values of these models are obtained through system identification techniques. This work covers two methods: Method 1 utilizes the tools available in the MATLAB software toolbox, while Method 2 involves expanding the Fourier series to calculate vascular impedance. Consequently, 2-element (2WK) and 3-element (3WK) models were developed with an accuracy of up to 83%. These models accurately represent arterial behavior and can serve as potential tools to aid in identifying cardiovascular diseases in patients.
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Cardiovascular diseases accounted for 31% of recorded deaths in 2016. Despite technological advancements, these fatalities persist due to late or sudden diagnoses. This statistic underscores the vital role of the Human Cardiovascular System (CHS) in supplying nutrients to sustain the body's organs. The CHS functions as a periodic pumping system, characterized by two distinct phases, systole, and diastole, driven by the heart's pumping action and observable throughout the circulatory system [1].

Understanding the CHS is paramount for effective diagnosis, and one method to achieve this is through mathematical modeling. For instance, a lumped parameter model can represent the hemodynamic behavior of a specific point in the circulatory system using an analogous electrical circuit known as the Windkessel circuit [2].

However, to develop this model and simulate the arterial physiological behavior of a patient, calculating cardiovascular impedance is imperative. Cardiovascular impedance represents the input-output relationship between pulsatile blood flow and pulsatile blood pressure in an artery, depicted by the transfer function Z_{in}, (Figure 1). The parameters of this function can be calculated using system identification methods [3,4].

Therefore, this research aims to calculate the parameters of the Windkessel models of the SCH of an adult patient, which can help in obtaining faster diagnoses of certain cardiac conditions, thus enabling the initiation of preventive treatments as soon as possible.

Materials and Methods

Using a lumped parameter model, we describe a fluidic system through an equivalent electrical circuit, which is the systemic arterial circulation in this study, given a uniform distribution of the fundamental variables (flow, pressure, and volume). This circuit model is called "Windkessel Model", which can be 2 elements (2WK), 3 elements (3WK) or 4 elements (4WK), in which each component represents a characteristic of the artery (Figure 2). The resulting transfer functions for each of these circuits are described in Equations (1), (2), and (3), respectively.

Two different methods were employed and subsequently compared to obtain this transfer function. Method 1 utilizes pre-existing computational system identification tools to determine a transfer function that depicts the

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Figure 1. A block diagram illustrating vascular impedance [6].

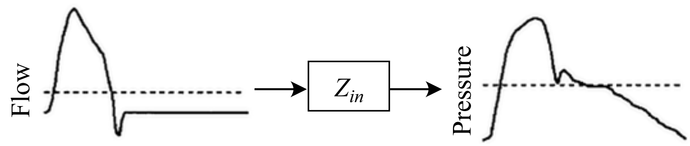
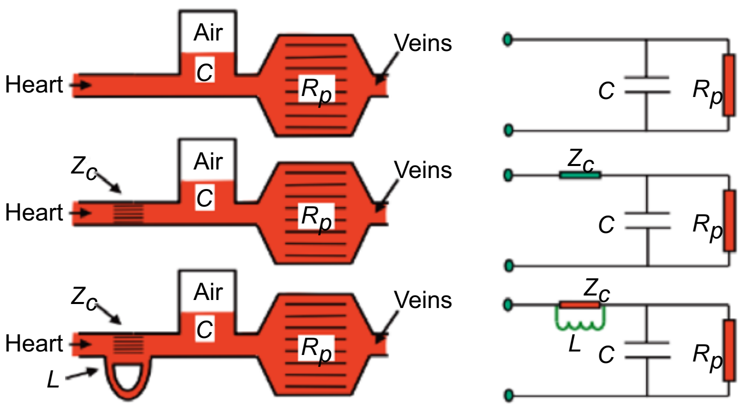


Figure 2. Relationship between Windkessel circuits and arterial behavior [2].



$$H_{2WK}(s) = \frac{P(s)}{Q(s)} = \frac{Rp}{sCRp + 1} \quad (1)$$

$$H_{3WK}(s) = \frac{P(s)}{Q(s)} = \frac{sCRpZc + Rp + Zc}{sCRp + 1} \quad (2)$$

$$H_{4WK}(s) = \frac{P(s)}{Q(s)} = \frac{s^2RpCLZc + sLRp + sLZc + RpZc}{s^2RpLC + sL + sRpCZc + Zc} \quad (3)$$

system represented by vascular impedance. This method considers the input and output data of the system (flow and pressure, respectively), sourced from a database derived from a study conducted by Harana and colleagues [5]. The database, generated virtually, aims to emulate the cardiovascular system of elderly individuals. The dataset pertaining to the ascending aorta, through which blood initially exits the heart, was selected to mitigate noise.

Method 2 involves constructing the graph of vascular impedance modulus and phase, as specified in Equation (4), to derive the parameters that characterize the desired circuit. Fourier Analysis represent the flow and pressure signals as the sum of sines and cosines, as depicted in equations (5) and (6).

The calculated impedance values make it possible to determine the parameter values for each type of Windkessel model. Subsequently, computer simulations can be conducted, enabling various analyses to derive a patient diagnosis.

Results and Discussion

An algorithm was developed using MATLAB software to compute impedance. This algorithm facilitated the calculation of vascular impedance based on data from a database. Subsequently, by employing the functions estimated by the algorithm, parameter values could be obtained by comparing the transfer function of the Windkessel circuit with that obtained via the software.

The desired resistance and capacitance values for the 2- and 3-element circuits can be extracted with the calculated vascular impedance. Table 1 presents the resulting values from both simulations.

Furthermore, Method 1, utilizing the MATLAB system identification toolbox, allowed for examining the model's response curve compared to the natural curve. Figure 3 displays the blood pressure data output obtained given a blood flow data input. It is evident that the more complex the represented system, the closer the output curve aligns with the natural curve.

Conclusion

Through this study on cardiovascular impedance, we could simulate a patient's systemic arterial circulation using concepts from equivalent electrical circuits. Such an approach holds promise for expediting and refining the diagnosis

$$|Z_n|\angle_z = \frac{|P_n|\angle\varphi_p}{|Q_n|\angle\varphi_q} \tag{1}$$

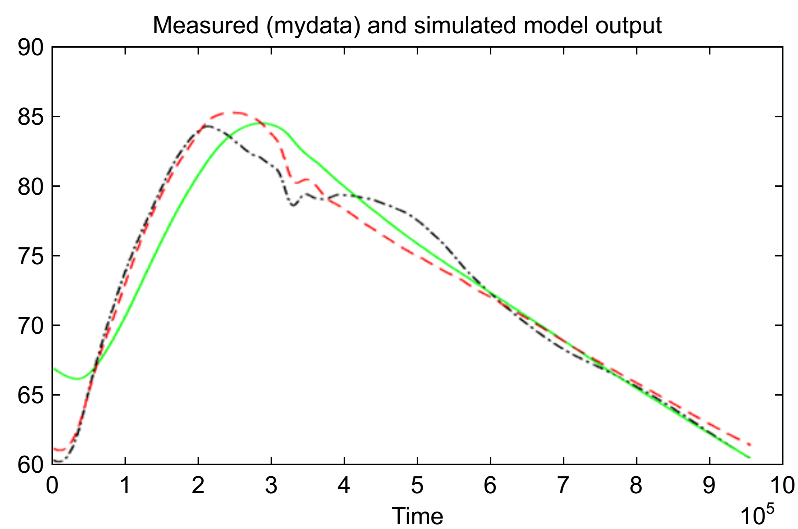
$$p(n) = P_0 + \sum_0^\infty Q_n cos(\omega_n t) + \varphi_p \quad \therefore \quad p_n = P_n cos(\omega_n t + \varphi_p) = |p_n|\angle\varphi_p \tag{2}$$

$$q(n) = Q_0 + \sum_0^\infty Q_n cos(\omega_n t + \varphi_q) \quad \therefore \quad qQ_n = {}_n cos(\omega_n t + \varphi_q) = |q_n|\angle\varphi_q \tag{3}$$

Table 1. Fluidic values obtained from the methods.

Circuit Parameter	Mathematical Model		
	Method 1: 2WK	**Method 1: 3WK**	**Method 2**
Capacitance (mL*mmHg^-1)	0.87	1.032	1.16114
Impedance (mmHg*mL^-1*s)	2.092	1.973	1.755
Characteristic Impedance (mmHg*mL^-1*s)	-	0.02394	0.02395

Figure 3. Response curves obtained for the Windkessel models.



The curve with black lines and dots represents the real pressure curve; the continuous green curve depicts the two-element Windkessel model; and the dashed red curve illustrates the three-element model. (2WK Accuracy: 51.34%; 3WK Accuracy: 83.32%).

of cardiovascular diseases, as variations in parameter values serve as indicators of potential pathologies.

However, our analysis only encompasses the arterial circulation of the cardiovascular system. Further insights could be gained by extending this modeling to encompass the entire Human Cardiovascular System (HCS), rendering the model more comprehensive and detailed. This expansion would enable a broader range of analyses and facilitate more accurate diagnoses.

One current challenge in implementing this project is the limited availability of technologies capable of measuring blood flow without invasive methods that disrupt circulation. With the advancement of technologies capable of indirectly and painlessly measuring blood flow, models such as this could become more widely applicable, thereby streamlining the identification of cardiovascular pathologies.

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