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Electrical Analogue of Arterial Blood Pressure Signals

Arteriyal Kan Basınç Sinyallerinin Elektriksel Analojisi

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Abstract
In this study, we propose an electrical circuit model that will be useful for understanding of the mechanisms and dynamics of the human cardiovascular system, which is considered as a complex system in the field of physiology. The electrical circuit model, defined as the Windkessel model, plays an important role in the observation of the characteristic effect of the blood pressure on the arterial system. An electrical circuit model, which we have connected to the input terminals of the Windkessel model, ensures that the mean arterial blood pressure signals are observed within the expected range of values. The Windkessel circuit model that we have tried to develop in this study was constructed in a laboratory environment and the results were observed. It is thought that this study will contribute to the literature in terms of the development of the Windkessel model by increasing the number of parameters involved in the models of heart and arterial system.

Keywords: Arterial system, Mean arterial blood pressure, Windkessel model

Öz
Bu çalışmada, fizyoloji alanında karmaşık bir sistem olarak kabul edilen insan kardiyovasküler sistemin sahip olduğu mekanizmaların ve dinamiklerinin anlaşılabilmesine fayda sağlayacak elektriksel bir devre modeli önerilmektedir. Windkessel model olarak tanımlanan elektriksel devre modeli, kalpten pompalanan kan basıncının arteriyel sistemdeki karakteristik etkisinin gözlemlenmesinde önemli rol oynamaktadır. Windkessel modelin girişine entegre ettiğimiz ayrı bir elektrik devre modeli, ortalama arteriyel kan basıncı sinyallerinin beklenen değer aralıklarında gözlemlenmesini sağlamaktadır. Bu çalışmada ele alınan ve geliştirmeye çalıştığımız Windkessel devre modeli laboratuvar ortamında kurulumu gerçekleştirilmiş ve sonuçları gözlemlenmiştir. Kalp ve arteriyel sistem ilişkisinde rol alan parametre sayılarının arttırılarak, Windkessel modelin geliştirilmesine bir alt yapı olması açısından bu çalışmanın literatüre katkı sağlayacağı düşünülmektedir.

Anahtar kelimeler: *Arteriyel sistem, Ortalama arteriyel kan basıncı, Windkessel modeli*

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1. Introduction

Human physiology has a complex structure in terms of system dynamics. Direct computation or modeling of this structure is difficult. Using modeling techniques and technologies helps to the researchers to analyze and understand physiological systems. Modeling on physiological systems has become a popular research field in recent years with major contributions coming from a mix of physiologists, mathematicians, and engineers (Guyton et al., 1972; Khoo, 2000). Human physiology includes major systems that maintain vital functions. The human cardiovascular system (CVS) is one of the major systems of physiology that it consists of the heart and vascular system (Guyton and Hall, 2006; Bora et al., 2017). Various modeling techniques of different disciplines are used to explain dynamics of CVS, such as blood pressure, blood flow, blood flow velocity, blood volume, etc. Behavior of CVS is tried to be modeled by techniques, such as fluid mechanics (Olufsen, 2001), electrical circuit model (Westerhof et al., 2009; Fazeli and Hahn, 2012; Kokalari et al., 2013), computer based modeling (Bora et al, 2017; Al-Jaafreh et al., 2005), control theory (Wu et al., 2005), mathematical and numerical modeling (Quarteroni et al., 2002).

In comparison to several mathematical and electrical models of CVS, the researchers have used different approaches with the aim of providing better understanding and modelling of the vascular system dynamics and heart mechanism in the CVS (Abdolrazaghi et al., 2010). In this work, an electrical circuit model is defined to observe the arterial system dynamics. Windkessel model which is represented by electrical model of the arterial system is a mathematical model related to the relationship of between blood pressure and blood flow. In the literature, Windkessel model has been implemented for several numbers of compartment lumped parameters by using differential equations, laplace transforms, the equations of fluid dynamics, block diagrams, and conceptual formulation of the effects between the heart and systemic arterial system (De Pater and Van Den Berg, 1964). In this study, we use 3-elements Windkessel model. Unlike other studies, we have added a clamper circuit to the Windkessel model to observe the desired results in normal conditions, assuming the physical parameters of a healthy adult individual. This work contributes to the electrical analogue of the Windkessel model; thus we propose to extend the model with electronic components to improve the Windkessel model behavior. We plan to improve the model with integrated circuits in the future.

We have organized this paper as follows: Section 2 offers a detailed account of the arterial system. Details of the Windkessel model, the electrical circuit model of the arterial system, are described in Section 3. Proposed Windkessel model and its results are illustrated in Section 4. Evaluated of the results of this study and suggestions are given in the Conclusions section.

2. Arterial System

CVS can be described as a closed circuit model which consists of the heart (cardio) and blood vessels (vascular). CVS provides blood circulation within the body through the blood vessels (Guyton and Hall, 2006; Marieb and Hoehn, 2010; Bora et al., 2017). The heart is an important vital component of CVS. The blood is pumped from the heart to the blood vessels. Therefore, parameters such as blood pressure, blood flow, resistance, in terms of vascular system dynamics are important. Vascular system consists of the arterial system, capillary and venous system. The arterial system consists of arteries and arterioles which carry oxygen-rich blood away from the heart through the body. The aorta is the largest and main artery of the human body. Capillaries are the smallest vessels where diffusion occurs between blood and cells in tissues. Venous system involves veins, like the vena cava and pulmonary veins that carry oxygen-poor blood back to the heart (Guyton and Hall, 2006; Jahangir, 2016; Bora et al., 2017). The oxygen-rich blood pumped from the artery is transported to the tissues and organs through the capillaries from the arterial system, where the circulation of the oxygen-poor blood through the venous system is defined as systemic circulation (Figure 1).

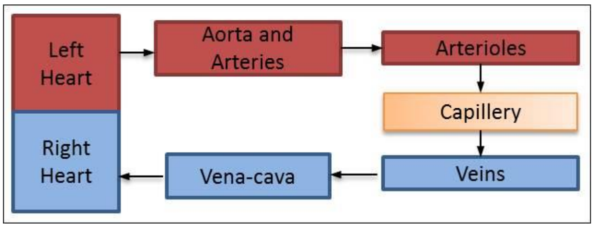


Figure 1. Systemic circulation

The left ventricle, defined as the left heart in Figure 1, is the only gate to the arterial system. The left ventricle pumps oxygen-rich blood under a certain pressure. Blood vessels are flexible and this flexibility significantly affects blood flow dynamics (Capoccia, 2015). For example, the aorta has the highest elasticity due to its distinctive elastic layers (Guyton and Hall, 2006). The aorta has a significant dynamic structure when analyzing local blood flow characteristics such as pressure and blood flow fluctuations in the arterial system. The mechanism of a fluid in a straight pipe relative to hydrodynamic laws (Kinsky, 1982) has a similar meaning to the mechanism by which pressure is transmitted through the blood, which is a propelling force through the vessel (Oertel, 2005). This thrusting force arises from the energy difference between any two points of the vessel. This is actually Ohm's law, which is based on hemodynamics (Guyton and Hall, 2006). According to Ohm's law, the blood flow (F) in the vessel is calculated by equation (1). ΔP is pressure difference (pressure gradient) between the two endpoints of the vessel. R is resistance against the blood flow along the vessel.

$$F = \frac{\Delta P}{R} \tag{1}$$

The main purpose of hemodynamics is to deliver blood to the tissue capillaries at a sufficient pressure and to ensure the continuity of circulation through the mechanisms that will allow the oxygen-poor blood to return to the heart. The time from the heartbeat to the next beat is defined as a heart cycle. For this reason, blood pressure pumped from the heart can change as a function of time. The mean arterial blood pressure curve during a cardiac cycle is shown in Figure 2.

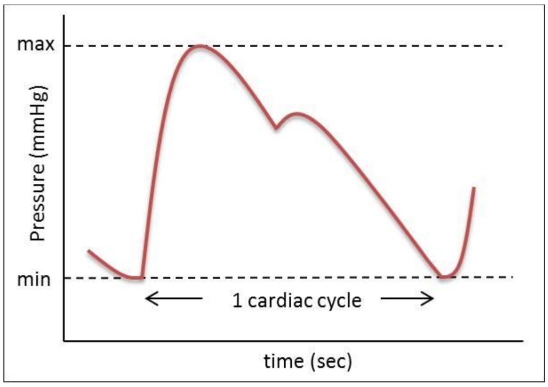


Figure 2. The mean arterial blood pressure (Guyton and Hall, 2006)

In Figure 2, the minimum pressure is between 60 and 89 mmHg and the maximum is between 100 and 140 mmHg (Bora et al., 2017).

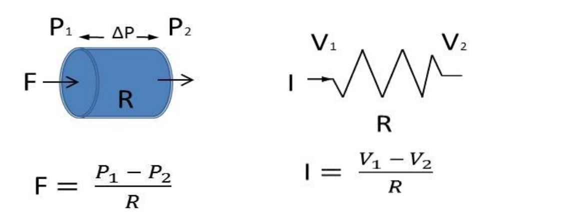
There are various methods that are used in modeling the CVS (Creigen et al., 2007). The Windkessel model explained in Section 3 was included to the literature as an electrical analogue where the parameters of CVS were represented by electrical components in an electrical circuit model.

3. Electrical Circuit Model

The German physiologist Otto Frank (Frank, 1899) introduced the Windkessel model in his article. Frank has identified the heart and arterial system as a closed hydraulic circuit. This circuit consists of a water pump connected to an old type of firefighting mechanism, which is connected to a chamber filled with water except for some air. When the pump starts to work, water tries to push the water towards the outlet of the compartment by compressing the air (Westerhof et al., 2009; Mei et al., 2018). This mechanism can be represented as an electrical circuit model. In the electrical circuit model, the fluid defined as the water in the fluid spaces of the fluid mechanism corresponds to electric charges which describe all electrical phenomena: 1) electric force, i.e. potential difference (voltage) and 2) the motion of charge creating electric fluid, i.e. electric flow (current). The blood flow in the vessel in the CVS can be represented based on the relation of current, voltage and resistance in the electric circuits under Ohm's law. The electrical analogue of the CVS parameters is shown in Table 1 (URL-1, 2017).

Table 1. Electrical analogue of some CVS parameters

CVS parameters	Electrical analogue
Blood pressure (P)	Potential difference (V)
Blood flow (F)	Current (I)
Resistance (R)	Resistance (R)
Compliance (C)	Capacitance (C)



Hemodynamic parameters of the CVS exhibit the characteristic behavior of the blood vessel. The flow in the blood vessel is determined by two factors: (1) the pressure difference (ΔP) of the blood between the two ends of the vessel; (2) resistance to blood flow through the vessel, called vascular resistance. P_1 denotes the pressure at the beginning of the vessel, and P_2 denotes the pressure at the other end of the vessel. Resistance is caused by friction along the entire inner surface of the vessel. The blood flow in the vessel can be calculated according to Ohm's law, as shown in equation (1). Ohm's law refers to the most important relationships that are necessary to understand circulatory hemodynamics. Transmission of the blood flow (F) to the tissues is caused by the pressure difference. The compliance (C) is related to flexibility and extensibility of the vessel. In electrical analogue of the capacitor, it means that it stores potential energy electrostatically in an electric field. Capacitance (C) means the effect of the capacitor. In physiology, we can define compliance as the total amount of blood that can be stored in response to an increase in pressure per mmHg in a given area of circulation.

In CVS, blood flow to the vascular system is achieved by pumping the heart under a certain pressure. The aortic valve opening into the arterial system from the left ventricle of the heart transmits the blood flow in a single direction. The blood that is pumped under high pressure from the left ventricle opens the aortic valve, causing the constriction and dilation of the vessel. The 3-element Windkessel model definition of this system is shown in Figure 3.

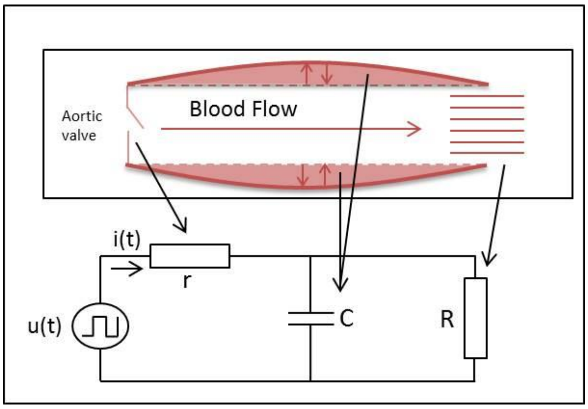


Figure 3. Representation of the arterial system along the aorta in the 3-element Windkessel model

In Figure 3, the input signal u(t) representing a blood pressure is applied to the circuit. The 1 kΩ resistor represents resistance of the aortic valve to the blood flow. A 1μF capacitor in the circuit defines the constriction and dilation of the vessel. The 10 kΩ resistor is defined as the resistance of arterial vessels to the blood flow.

The Windkessel model is a mathematical model with 2, 3 and 4 elements in the literature (Westerhof et al., 2009; Kokalari et al., 2013). This circuit model can be calculated by differential equations. In this study, 3-element Windkessel circuit model is observed in the laboratory by adapting to CVS parameter values.

4. Experimental Study

In this study, an electrical circuit was constructed in the laboratory environment so that we could observe the effect of the blood pressure on the arterial system. This circuit, which is defined as a 3-element Windkessel model, is shown in Figure 4.

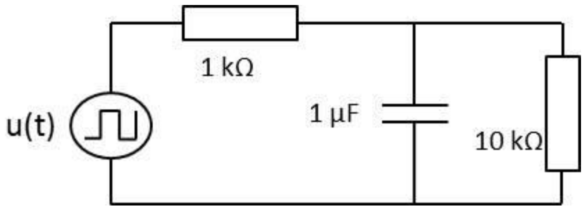


Figure 4. 3-element Windkessel model

When a square wave input of ± 5 volts 0.66 kHz is applied to the input of the circuit given in Figure 4, the input and output waveforms observed from the circuit are shown in Figure 5. Since the time constant τ (0.05 sec. with given a 10 kΩ resistor and a 1μF capacitor) is greater than the period of the input signal (0.0015 sec.), the capacitor does not charge to the peak of the input and it only has a potential to charge to a value of 2.5 volts. On the other hand, when the input voltage goes negative, the capacitor does not fully discharge and sinks down to -2.5 volts.

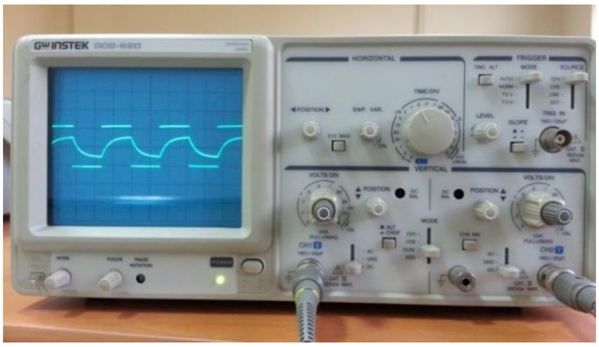


Figure 5. The square wave input signal applied to the 3-element Windkessel circuit model and the observed output signal

The signals observed in Figure 5 do not reflect the expected range of the mean arterial blood pressure. For this reason, a diode clamper is added to the 3-element Windkessel model (Selek, 2017), which can provide the expected consistency of the results. This circuit clamps the AC signal to the DC level so that the arterial blood pressure remains at the minimum and maximum levels. This circuit is shown in Figure 6.

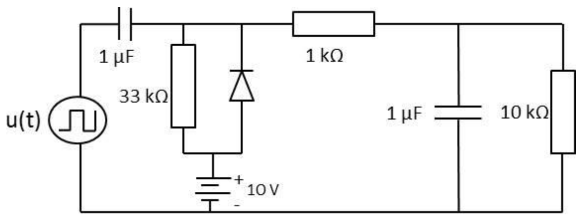


Figure 6. Windkessel circuit model and a clamper

In Figure 6, a square wave input of ± 5 volts 0,25 kHz is applied to the input of the circuit. This circuit can show the mean arterial pressure between 8 and 12 volts as in Figure 7.

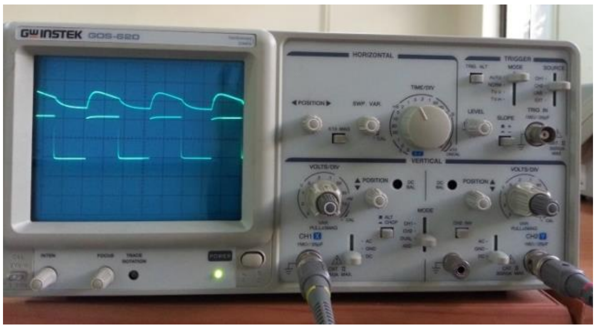


Figure 7. Input and output signals defined as the mean arterial pressure of the Windkessel model

Figure 8 shows an electrical circuit representing the arterial system, an experimental set-up providing input signal to the circuit and power supply, and an oscilloscope.

Blood pressure is a non-electrical biological signal. In order to be able to observe blood pressure signals in a circuit model, it is necessary to make some assumptions as in this study. Under normal circumstances, the average arterial blood pressure in an adult individual can be measured as between 80 and 120 mmHg (Guyton and Hall, 2006). These values were represented with the peaks of output voltages observed as 8 and 12 volts with the signal which was applied to the input of the circuit under laboratory conditions.

5. Conclusions

In this study, the electrical analogy of the basic parameters of the arterial system (blood flow, compliance and resistance) was examined. The characteristic behavior of the arterial system is described with the electrical circuit model known as the Windkessel model. This work has some limitations in defining of the model. We consider that Windkessel models consist of differential equations that relate the CVS dynamics. We do not make any calculations for the models we offer in this study. We present an experimental study which we interpret the dynamics of vessel behaviors by observing the results. In this study, it is expected that Windkessel model, which is supported by a separate circuit, achieves a suitable circuit potency to be further improved by increasing the system parameters.

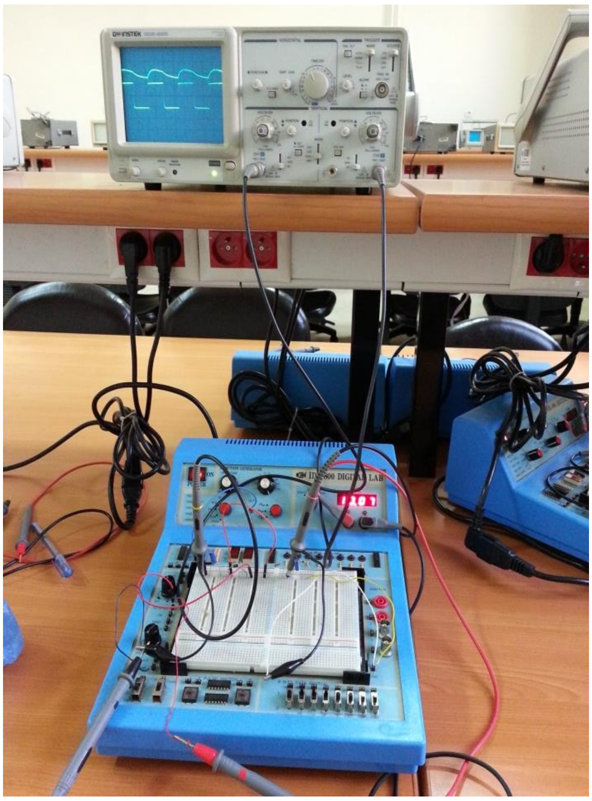


Figure 8. Electrical circuit representing the arterial system

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