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Identification Method for Blood Pressure Reflected Wave Based on Electric Circuit Model: A Proposal

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電気回路モデルによる血圧反射波同定法の一試案

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Keywords：augmentation index, reflexed wave, stiffness, arteriosclerosis, electric circuit

Introduction

The proceeding blood pressure wave in an artery is generated when the ventricle ejects blood. The reflected pressure wave is what the proceeding wave reflects at the arterial bifurcation in the periphery and returns to the recording position[1-4]. The blood pressure waveform recorded on the central side of a large artery is what the proceeding pressure wave and the reflected pressure wave overlap in the recording position. Owing to the enhanced velocity of the pressure wave propagating in the artery with the progress of arteriosclerosis, the technology that extracts the reflected wave from the blood pressure waveform could be used for the evaluation of arteriosclerosis. Precisely, the augmentation index (AI), which is clinically used as the scale of arteriosclerosis, demonstrates the relative proportion of the reflected wave in the blood pressure waveform[5-7]. Although AI is the ratio of the amplitude of the reflected wave to the amplitude of the proceeding wave, the blood pressure wave is not separated accurately into the proceeding wave and reflected wave for its calculation.

Conversely, the relationship between voltage and current and between blood flow and blood pressure are very similar[8]. Although the reflected wave of the blood pressure exists in the blood flow circuit, that of the voltage, such as the blood pressure wave, does not exist in the current circuit in the low-frequency range. This variation is attributed to the difference in the propagation speed between the electrical and fluid phenomenon, thereby challenging the accurate simulation of the fluid phenomena using an electric circuit. It can be considered as a disadvantage in simulation, which in turn, could be an advantage for obtaining the blood pressure waveform without the reflected wave.

This study proposes a new method to calculate the reflected wave by subtracting the blood pressure waveform produced using the electric circuit simulator from the actual blood pressure waveform. In addition, this study compares the blood pressure reflected wave obtained from a healthy male university student and a middle-aged male. Finally, it was assessed whether the signs of arteriosclerosis because of aging appeared in the blood pressure reflected wave of the middle-aged male.

The method proposed in this study is based on a principle different from the conventional method of evaluating the blood pressure reflected wave. Although this study is in its initial stages, inadequate data is presented to seek relevant feedback on the calculation

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method based on this principle.

Subjects and Method

1. Subjects

This study examines three healthy male university students aged 21-22 years and a healthy 4-year-old middle-aged male. All participants provided written informed consent before participating according to the ethical standards of the Declaration of Helsinki.

2. Measurement

In this study, all participants were examined in the standard supine position for all assessments. Systolic and diastolic blood pressures of participants were evaluated by auscultation. Then, the blood flow of the left ventricular outflow tract was assessed using ultrasonography (ProSound Alpha6; Hitachi Ltd., Tokyo, Japan), and the pulse wave of the left carotid artery was assessed using a pulse wave sensor (TK-701T; Nihon Kohden Corp., Tokyo, Japan). Finally, the pulse waveform with the systolic and diastolic blood pressure at the peak and bottom of the pulse waveform, respectively, was defined as the blood pressure waveform.

3. Calculation method

1) Simulation by an electric circuit

Figure 1 shows the Windkessel model by an electric circuit that was used in this study. The two elements of the model were the total peripheral resistance of the arterial system (R_p) and compliance of the aorta (C_A). The current source supplied a current waveform similar to the blood flow waveform ejected from the left ventricle in the circuit, and the blood pressure was recorded as the output voltage.

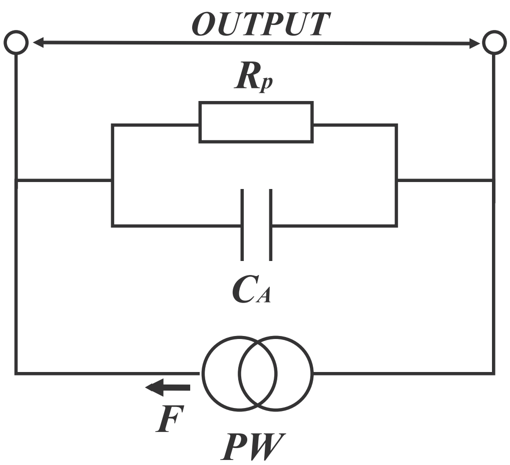

Fig.1 : The Windkessel model by an electric circuit used in this study. F, blood flow ejected from the left ventricle; PW, constant-current power source; OUTPUT, simulated blood pressure.

The two parameters of the circuit were adjusted to simulate the actual blood pressure waveform and output voltage waveform. Figure 2 shows that the diastolic blood pressure of the actual blood pressure waveform and the minimum voltage of the output voltage were equal at the time when the slope of the up-stroke of the actual blood pressure waveform and the output voltage waveform were equal.

Table 1 shows the translation of the electric system to the fluid system.

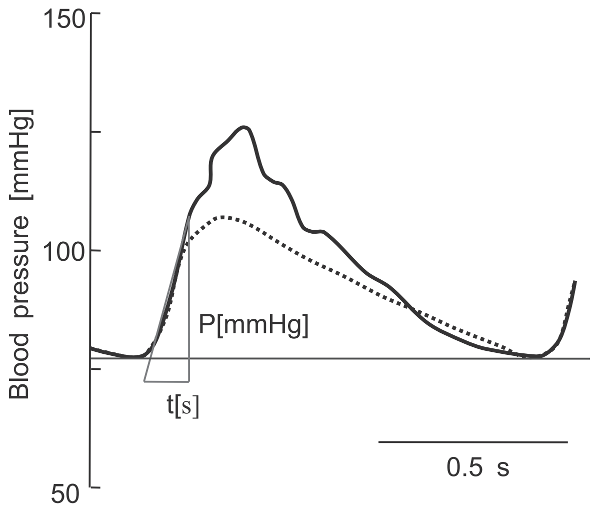

Fig.2 : An arrangement to determine two elements of the circuit. Solid line, actual blood pressure waveform; dotted line, the blood pressure waveform simulated the following:
1) The diastolic blood pressure shown with a blue line in two blood pressure waveforms is equal.
2) The angle of the slope shown with a blue line in two blood pressure waveforms is equal.

Table 1: Correspondence between the electric system and fluid system.

	Fluid system	Electrical system
Blood pressure	1 mmHg	1 V
Blood flow	1×10^{6} ml/s	1 A
Compliance	1×10^{6} ml/mmHg	1 F
Vascular resistance	1×10^{-6} mmHg･s/ml	1 Ω
Time	1 s	1 s

2) Extraction of the reflected wave

Figure 3 shows that the waveform obtained by subtracting the blood pressure waveform by the simulation place from the actual blood pressure waveform was considered the blood pressure reflected wave.

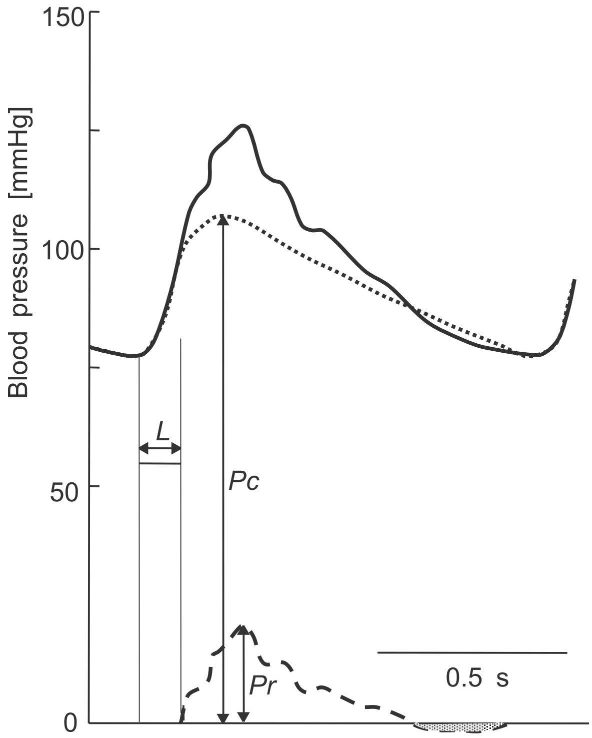

Fig.3 : Two parameters measured on the reflected wave. Solid line, actual blood pressure waveform; dotted line, simulated blood pressure waveform; dashed line, reflected blood pressure waveform; *Pc*: systolic blood pressure of the simulated blood pressure; *Pr*: max blood pressure of the reflected blood pressure; reflected wave rate: *Pr*/*Pc*×100[%]; reflected wave latency: *L*[s].

Results

The time difference between the starting point of up-stroke of the actual blood pressure waveform and that of the reflected wave was considered the reflected wave latency, and the percentage of the amplitude of the reflected waveform with respect to that of the blood pressure waveform by simulation was considered the reflected wave rate (Fig. 3).

Table 2 shows the reflected wave latency and the reflected wave rate. The reflected wave latency of the middle-aged participant was shorter than that of the three young subjects. In addition, the reflected wave rate of the middle-aged subject was higher than that of the three young subjects.

Table 2: The reflected wave rate and latency of all subjects.

	Reflected wave latency	Percentage of the amplitude of the reflected waveform
Student A	0.11 s	19 %
Student B	0.12 s	11 %
Student C	0.12 s	10 %
Middle-aged man	0.07 s	24 %

Furthermore, a small negative component other than the primary reflected wave was detected in a case.

Discussion

AI is the most popular index used in the reflected wave[2-4]. Figure 4 shows that the pressure difference obtained by subtracting the blood pressure of inflection point on up-stroke of the blood pressure waveform from the systolic blood pressure is defined as the amplification by the reflected wave in the calculation of AI[2-4]. Then, AI is the percentage of the pressure difference to the pulse pressure. Because the intensity of the reflected wave depends on the physical properties of the peripheral reflection point, quantifying the intensity of the reflected wave corresponds to evaluating sclerosis in the small artery[9]. However, the pressure difference between the blood pressure of the inflection point and the systolic blood pressure does not precisely reflect the amount of blood pressure augmentation by the reflected wave. Hence, in my view, the substitution of AI with a more appropriate index is essential. Conversely, an inflection point on up-stroke of the blood pressure waveform implies the arrival of the reflected wave. Therefore, the time difference between the starting point of the blood pressure waveform and the inflection point on up-stroke is the time required for the blood pressure wave to reciprocate between the recording position and reflection point. In addition, the time difference between the starting point of the blood pressure waveform and inflection point on up-stroke could be an appropriate index of sclerosis in the large artery because the pulse wave velocity increases with the progression of sclerosis in the large artery[10,11].

The reflection wave rate corresponds to the amount of blood pressure augmentation by the reflected wave, and the reflected wave latency is equivalent to the time difference between the starting point of the blood pressure waveform and inflection point on up-stroke. In my opinion, the stiffness of large and small arteries in the middle-aged subject resulted from the shorter reflected wave latency and higher reflected wave rate than those recorded in the three young participants. It is, thus, necessary to separate proceeding wave and reflected wave to calculate these two indices.

In this study, the electric circuit was applied to reproduce the blood pressure waveform without reflected waves because the presence of reflected waves can be ignored when the length of the electric circuit is short and the frequency of the signal is low. However, this study used the most uncomplicated electric circuit comprising only two elements to simulate the blood pressure waveform as an electric circuit imitating the arterial system. The two elements are the electric capacity corresponding to the compliance of the large artery and an electric resistance corresponding to the peripheral resistance. Despite conducting the blood pressure wave through the large artery, the nonelastic resistance of the large artery is not assumed in this model. This resistance can be ignored if the artery is considerably large, a condition that was observed in this study. In addition, this study did not assume the inertial component of the blood. However, this should not be a problem because the inertial component of the blood is mostly determined by the blood density, and there was little individual difference in the blood density. It is essential to consider the appropriateness of this procedure for determining the simulated blood pressure waveform by an electric circuit. In this study, because the number of elements of the simulation circuit is not necessary, it suffices the high accuracy of the blood pressure waveform, which does not include reflected waves. Therefore, further investigation is required to study methods for evaluating the appropriateness of the reproduced blood pressure waveform.

Conclusions

This study proposes a method for extracting the reflected wave from the blood pressure waveform using an electric circuit model. The signs of arteriosclerosis due to aging in a middle-aged male were estimated from the two calculated parameters of the reflected waves.

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Abstract

In this study, an electric circuit model was used to isolate the reflected waves from the blood pressure waves recorded in a large artery. The flow waveform of the blood ejected from the left ventricle was recorded as a constant current source of an electric circuit model comprising electric capacity C_A, corresponding to the aorta compliance, and electric resistance R_p,

corresponding to the total peripheral resistance. This model is commonly referred to as a two-element windkessel model. The parameters of the two elements varied in a way that the slope of up-stroke of the output voltage waveform and one of the blood pressure waveform accord and that of the minimum output voltage and diastolic blood pressure accord at the same time. Because the reflected wave is not included in this output voltage waveform at this time, a waveform obtained by subtracting the voltage waveform from the assessed blood pressure waveform could be considered a reflected wave. The peak latency of the reflected wave calculated by this method from the blood pressure waveform recorded in a 48-year-old male was shorter than the one recorded in three healthy college students. In addition, the amplitudes of the reflected wave in the 48-year-old male were higher than the ones in these students.

These results reflect the increase in the pulse wave velocity because of the decrease in the arterial compliance in middle-aged male and the enhancement of the reflected wave because of the increase in the peripheral resistance of the arterial system of the head and neck. On the other hand, there was an example where a small negative component other than the main reflected wave component was detected.

Conflicts of Interest

The author has no conflict of interest directly relevant to the content of this article.

要　　旨

本研究は太い動脈で記録される圧脈波から反射波を抽出するために電気回路モデルを利用した。大動脈のコンプライアンスに相当する電気容量CA，総末梢抵抗に相当する電気抵抗Rpからなる2要素のWindkessel modelを電気回路シミュレータ上で再現し，定電流源として左室流出路血流波形を入力した。出力電圧と血圧波形の上行脚の傾きと，出力電圧と血圧の最低値が等しくなるように2つの要素のパラメータを変化させた。この電圧波形を反射波が重畳していない血圧波形すなわち進行波と仮定した。実測した血圧波形から電圧波形を差し引いた波形を反射波と仮定した。２１才の青年期健常男子大学生3名と比較し，中年期48才男性は反射波のピーク潜時が短く，振幅は大きかった。本法によって，頸動脈血圧波形から反射波が分離され，青年期健常大学生より中年期男性で頭頸部の動脈系の末梢抵抗の増大による反射波の増強と動脈コンプライアンスの低下による脈波伝播速度の増大を反映した結果が得られた。一方で，メインとなる反射波以外に小さな負の成分が検出された例があった。