Analysis of the Common Carotid Arterial System in the Electrical Circuit Based on the Three-element Model: Effects of Neck Retrocollis

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短　報（査読あり）

Analysis of the Common Carotid Arterial System in the Electrical Circuit Based on the Three-element Model: Effects of Neck Retrocollis

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三要素電気回路モデルによる総頸動脈系の解析：頸部後屈の影響

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Keywords：Carotid artery, Three-element model, Resistance, Compliance, Electrical circuit

Introduction

The physical properties of arterial systems change by aging. In particular, the arterial wall becomes hard and loses its elasticity. The modification of such arterial wall is referred to as arteriosclerosis. Arteriosclerosis causes severe cerebrovascular disease and ischemic heart disease[1,2]. Most screening methods for arteriosclerosis in physiological function tests must measure the blood pressure at two points of the central and the peripheral sides[3,4]. It is essential to wrap the cuff around the limb to pressurize the artery in this case[3,4]. However, the artery of the head and neck system may not be used in this method. We considered that it can easily evaluate the physical properties of the arterial system from the blood flow and blood pressure waveforms in the proximal portion of the arterial system. In particular, we hypothesized that it is possible to easily calculate the physical properties of the arterial system by replacing the arterial system with a simple electrical circuit[5-8] comprising three elements. Then, the blood flow of the artery can be easily and accurately measured by ultrasonography, and because the blood pressure in the artery is approximately equal to lateral pressure, the pulse waveform of lateral pressure of the artery can be used as an alternative to the blood pressure waveform.

The nonelastic resistance and compliance of the common carotid artery and the total peripheral resistance of the common carotid arterial system in the supine posture with retrocollis of the neck and the normal supine posture were determined using an approximate calculation method that we devised in this study. The calculated parameters were qualitatively consistent with the results that can be estimated from the deformation of the blood vessels by retrocollis of the neck. In this paper, we investigated the disadvantages and advantages of our method from these results.

Subjects and Method

Subjects and Postures

The subjects were five healthy university students aged 21–22 years (2 males and 3 females). All subjects provided written informed consent prior to participation according to the ethical standards of the Declaration of Helsinki. Prior to the experiment, it was confirmed

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that the subjects would not cause the dizziness by the retrocollis of neck. Their postures at the measurement were the normal supine posture (Fig.1a) and the supine posture with neck retrocollis (Fig.1b).

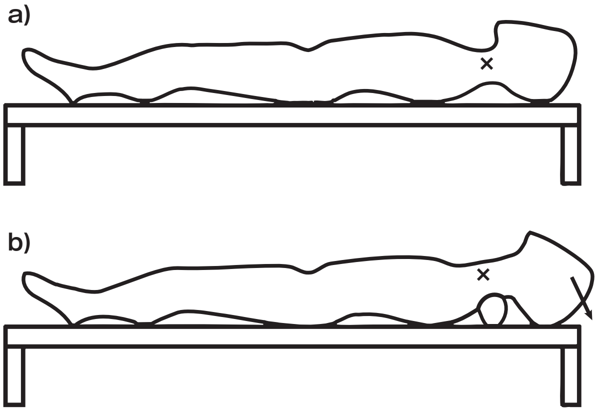

Fig.1:Measurement postures.
a) Normal supine posture.
b) Supine posture with neck retrocollis.
×:Sensor site

Measurement

Systolic and diastolic blood pressures of the subjects in the normal supine position were measured by auscultation. The diameter of and blood flow in the left carotid artery was then measured using ultrasonography (ProSound Alpha6; Hitachi Ltd, Tokyo, Japan), and the pulse wave of the left carotid artery was measured using a pulse wave sensor (TK-701T; Nihon Kohden Corp, Tokyo, Japan) in each posture. The carotid artery blood flow waveform used in this analysis was obtained by multiplying the cross-sectional area of the common carotid artery and the blood flow waveform measured by ultrasonography. The time elapsed from the pulse and blood flow waveforms was matched by Electrocardiogram.

Three-element model

A three-element model was used for this study as shown in Fig.2. The three elements of the model were the total peripheral resistance of the common carotid arterial system and the nonelastic resistance and compliance of the common carotid artery. The voltage source was connected by supplying a voltage waveform similar to the blood pressure waveform in the circuit, and the current waveform in the circuit was similar to the blood flow waveform in the common carotid artery. The translation of the electrical system to the fluid system is shown in Table 1.

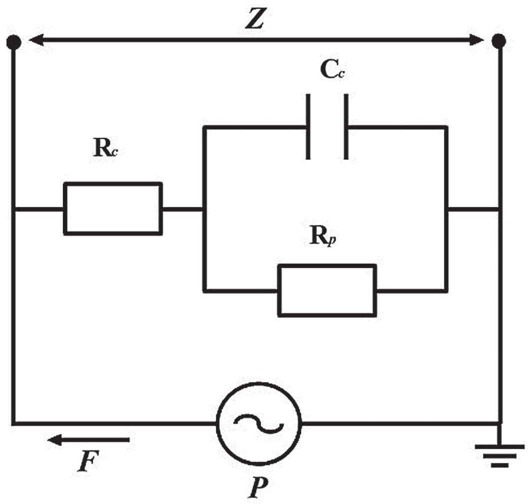

Fig.2:Three-element model of the common carotid arterial system.
R_c : Non-elastic resistance of the common carotid artery
R_p: Total peripheral resistance of the common carotid arterial system
C_c : Compliance of the common carotid artery
Z : Combined impedance of the common carotid arterial system
F : Blood flow in the common carotid artery
P : Power generating blood pressure waveform

Table 1 Correspondence of the electric system and fluid system

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

Calculation method

The combined impedance (Z) of the model was calculated by equation (1), where is the angular velocity of the heart rate.

$$Z = R_c + \frac{R_p}{1 + j\omega C_c R_p} \tag{1}$$

When changes in blood pressure and blood flow are fast enough, Z is equal to R_c. If there is an upstroke of the waveforms where both blood pressure and blood flow change rapidly as shown in fig.3, R_c is calculated by equation (2).

$$\underset{\omega\to\infty}{Z} = R_c = \frac{\Delta P}{\Delta t_1} \div \frac{\Delta F}{\Delta t_2} = \frac{\delta P}{\delta F} \tag{2}$$

When blood pressure and blood flow are the direct current (DC) as shown in fig.3, Z, which is equal to R_c +

R_p, is calculated by equation (3).

$$\underset{\infty\to 0}{Z} = R_c + R_p = \frac{P_{DC}}{F_{DC}} \tag{3}$$

Cc calculated by equation (4), where is the phase angle between the blood pressure and blood flow waveforms. is calculated by fast Fourier transform.

$$C_c = \frac{\dfrac{1}{\tan\theta} \pm \sqrt{\dfrac{1}{\tan^2\theta} - \dfrac{4R_c(R_c+R_p)}{R_p^{\,2}}}}{2\omega R_c} \tag{4}$$

There are two solutions in equation (4). The two solutions are C_{c1}, C_{c2} and $C_{c1} < C_{c2}$. If increased when the heart rate increased, then $C_c = C_{c2}$. If increased when the heart rate decreased, then $C_c = C_{c1}$.

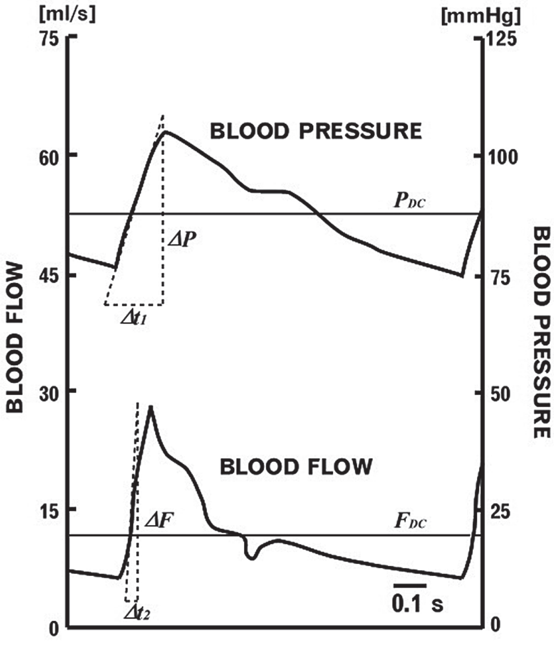

Fig.3:Scheme of blood pressure and blood flow waveforms in the proposed method.

The upper figure shows the blood pressure waveform. The lower figure shows the blood flow waveform.

ΔP: Amount of change in blood pressure per Δt_1 s

ΔF: Amount of change in blood flow per Δt_2 s

P_{DC}: Direct current conversion value of the blood pressure waveform

F_{DC}: Direct current conversion value of the blood flow waveform

Statistical analysis

Each value of the parameter calculated is reported as the mean ± standard deviation for each posture. Student's paired t-test was used to compare differences among the three parameters during the normal supine posture and during the supine posture with the neck in retrocollis.

Results

The average diameter of the common carotid artery and the three parameters calculated for each position are shown in Table 2. The average diameter of the common carotid artery during the supine posture with the neck in retrocollis was significantly shorter than that during the normal supine posture ($p < 0.05$). R_c and R_p during the supine posture with the neck in retrocollis were significantly greater than those during the normal supine posture ($p < 0.05$). C_c during the supine posture with the neck in retrocollis was significantly lesser than that during the normal supine posture ($p < 0.05$).

Table 2 Measured parameters for each posture

	Normal supine		Neck retroflexion
Rc **[mmHg･s/ml]**	**0.93±0.52**	*	**3.4±1.2**
Cc **[ml/mmHg]**	**0.20±0.12**	*	**0.082±0.025**
Rp **[mmHg･s/ml]**	**3.0±1.2**	*	**6.8±1.8**

mean±S.D., n=5, *p<0.05

Discussion

It is well known that the vertebral artery bends during retrocollis of the neck and very rarely develops a stroke[9]. When a subject's common carotid artery is pulled in the longitudinal direction, the skin and muscle tissue of the anterior neck are pressed on the common carotid artery during retrocollis of the neck. Thus, it can be expected that the cross-sectional area of the common carotid artery will be reduced and the volume change in the common carotid artery will be limited. In the analysis using the three-element model, these phenomena have been shown in the form of an increase in the nonelastic resistance and decrease in the compliance of the common carotid artery.

In addition, the cross-sectional area of the jugular vein reduces as the vein is compressed by the surrounding tissue and the vertebral vein bends during retrocollis of the neck. Venous return from the head is reduced by such a deformation of the veins and gravity acting against blood flow. In the analysis using the three-element model, these phenomena have been shown in the form of an increase in the peripheral resistance of the common carotid arterial system.

The analysis using the three-element model by the electric circuit qualitatively reflected the apparent change in the physical properties in the common carotid arterial system caused by retrocollis of the neck. Accordingly, it may be possible to detect organic changes caused in the arterial system of the head and neck by analyzing with this method.

On the other hand, electrical phenomena and fluid phenomenon are similar, but there are many differences10) including the time course between electrical and fluid phenomena. In this analysis, the phase angle between the blood pressure and blood flow waveforms is an important parameter, but the phase angle is most affected by the difference in the time course between electrical and fluid phenomena. Furthermore, it is difficult to reproduce the reflected wave11) in the blood pressure waveform at the electrical phenomenon. Because of such problems, the analysis of the arterial system using the electric circuit model will be used as tractable approximation methods. We must develop new technologies to simultaneously record the blood pressure and blood flow waveforms of the carotid artery without interfering with each other to take advantage of this method.

Conclusions

This study mentioned the possibility of the analysis of the arterial system using an electric circuit model of three elements. We have provided the accuracy of this analysis as follows: 1) The nonelastic resistance of the common carotid artery increased during retrocollis of the neck. 2) The compliance of the common carotid artery decreased during retrocollis of the neck. 3) The peripheral resistance of the common carotid arterial system increased during retrocollis of the neck.

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Abstract

This study investigated the physical properties of the arterial system originating from the common carotid artery (hereinafter called the common carotid arterial system) during retrocollis of the head by assuming the arterial system to the electrical circuit of the three elements to healthy men and women university students. A three-element model that represents the common carotid arterial system in the electrical circuit was constructed; the elements were the non-elastic resistance and compliance of the common carotid artery and the total peripheral resistance of the common carotid arterial system. In this model, the blood pressure waveform was utilized as a voltage source, while the carotid artery blood flow waveform was utilized as the current. The pulse waveform of the common carotid artery that fitted the systolic and diastolic blood pressures measured in the brachial artery was used instead of the blood pressure waveform of the common carotid artery. The non-elastic resistance and compliance of the common carotid artery and the total peripheral resistance of the system were calculated from the alternate blood pressure waveform and blood flow waveform using an approximate calculation method that we proposed. The parameters of three elements during retrocollis of the neck were as follows: the non-elastic resistance of the common carotid artery increased and the compliance of the common carotid artery decreased and the total peripheral resistance of the system increased, compared to those in the normal supine posture. These results could be easily expected from the deformation of the arteries of the neck and the increase in intracranial pressure with the decrease in venous return from the head during retrocollis of the neck.

Conflicts of Interest

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

要　旨

本研究は健康な男女大学生を対象に頸部後屈が総頸動脈系に及ぼす影響を三要素の電気回路モデルを使用して検討した。総頸動脈を起始部とする動脈系（以下，総頸動脈系とする）を総頸動脈の粘性抵抗を示す電気抵抗，コンプライアンスを示す電気容量，動脈系の総末梢抵抗を示す電気抵抗で表し，総頸動脈の血圧波形を電圧波形，血流波形を電流波形として，各要素のパラメータを我々が考案した近似法で算出した。その結果，仰臥位から頸部を後屈させると総頸動脈の粘性抵抗と総頸動脈系の総末梢抵抗は有意に増大し，総頸動脈のコンプライアンスは有意に低下した（$p<0.05$）。これらの結果は，頸部後屈による周囲組織による頸動脈の圧迫や頸動脈の屈曲，頸静脈圧迫による静脈還流の減少と頭蓋内圧の増大によって，理論的に推測できる結果とおおむね一致した。