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THE SPECTRUM STUDY OF BLOOD PRESSURE DURING THE DISTURBANCE OF ORGANIC VASCULAR BEDS

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ABSTRACT

Like electrical circuit components, the vascular beds in organs present impedance to waves in systemic circulation. In this study, the authors design an animal experiment to study the effect of the impedance to the pressure waves. We view the systemic circulation as an electrical circuit network, and interpret the vascular beds in organs as lumped components in the electrical circuit. Nature's designing of the systemic circulation minimizes the pressure wave reflection, and maximizes blood distribution. This is very similar to the concept adopted by electrical engineers in designing electrical circuits.

器官血管床叢受擾亂時血壓頻譜之研究

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摘　　要

如同電子網路的元件一般，器官內之血管床叢對體循環中的波形傳遞呈現一定程度的阻抗現象。本文作者設計了一套動物實驗，以研究這種阻抗對血壓波形的影響。作者將體循環視同一個電子網路，而將器官內之血管床叢視爲網路中之等效集總元件，體循環系統的自然網路結構在於減少血壓波形的反射，而使網路對元件的血液分配達到最高效益，體循環系統之此一自然特性，與電子工程師設計電子網路所採行的觀念，有著異曲同工之妙。

INTRODUCTION

Traditional studies of systemic circulation are based on the measurements of pressure and flow waves [1, 3]. Other research topics have focused on the impedance of arteries [12]. The impedance patterns are used to characterize arteries, and to interpret the contours of the pressure waves in systemic circulation. The direct effects of arterial impedance on the pressure waves are reflections at the mismatch points. Womersley's [21], McDonald's [6] and other studies concluded that nature's design of arterial branching minimizes wave reflections. Hamilton [3], Taylor [18] and colleagues [14] stressed the arteriole-artery junctions to be the major sites of reflections. O'Rourke [7, 12] compromised all these studies, calculated the impedance of the major arteries, and suggested a T tube model to explain all their experimental results.

All of these studies placed most of their neglected other emphases on the aorta and arteries. They always measured the pressure and flow waves at some section of the aorta or a large artery [13], and analyzed the impedance patterns and their effects on the wave reflections [10]. However, they important factors which the vascular beds in organs. Wang [19] designed a physical model to simulate the organs in systemic circulation, and studied its frequency characteristic. In this study, we design an animal experiment to prove the suitability of such a model. We try to view organs as parts of the circulatory system, and investigate their effects on the wave propagation. We also induce the electrical circuit concept to explain our experimental findings.

THEORY AND PHYSICAL EXPLANATION

There are different degrees of reflections at all vascular beds. The reflective waves mix with the incident wave. The waves of pressure or flow measured in any artery are such mixed waves. It is difficult to separate the forward-traveling and the back-traveling components of the mixed waves in a wave measuring system. To study the characteristics of vascular beds, we can physically decompose the mixed waves into two components:

$$P=P_{in}+P_{re} \tag{1}$$

where P_{in} is the incident pressure wave generated by the left ventricular contraction, and P_{re} is the resultant reflective pressure wave from all vascular beds.

To consider the components of the reflective waves from vascular beds of organs, we can farther decompose the P_{re} into P_s, P_g, P_r, P_m and P'_{re}. P_s, P_g, P_r, and P_m present the reflections from the vascular beds of the spleen, stomach, kidneys, and intestinum, respectively. P'_{re} is the residual reflection wave from other vascular beds. There are large arteries to supply blood to the vascular beds of organs, such as the splenic artery to the spleen, the gastric artery to the stomach, the renal arteries to the kidneys, and the mesenteric artery to intestinum. When the supplying artery is clamped, not only will no pressure wave be traveling into the vascular bed, but also the reflective wave from this bed will be depressed. However, the clamp will generate a new reflective component P_c which is characterized by its frequency response property. Then when we study the reflective effect from the stomach vascular bed, we can clamp the gastric artery, and analyze the difference of the pressure waves before and during the ligation. The reflective effects then can be represented as follows:

$$P=P_{in}+P_g+P_s+P_r+P_m+'_{re} \tag{2}$$

$$P'_g=P_{in}+P_c+P_s+P_r+P_m+P'_{re} \tag{3}$$

$$P_{gc}=P-P'_g \tag{4}$$

$$=P_g-P_c. \tag{5}$$

P'_g is the pressure wave measured when the gastric artery is clamed. P_{gc} is the residue obtained by subtracting P'_g from P. In the same method, we can have the P_{sc}, P_{rc}, and P_{mc} by clamping the splenic artery, the renal artery, and the mesenteric artery respectively. If we use the same clamp, P_c will be nearly a constant. The P_{gc}, P_{sc}, P_{rc} and P_{mc} then can be used to study the characteristics of the vascular beds in organs.

METHODS AND EXPERIMENTS

1. Preparation of animals

All experiments were performed on adult Sprague-Dawley rats, weighing 330 g-550 g. The animals were maintained without food overnight but allowed free access to water. They were anesthetized by injecting alpha-chloralose (48 mg/kg) and urethane (0.6 g/kg) intraperitoneally. Alpha-

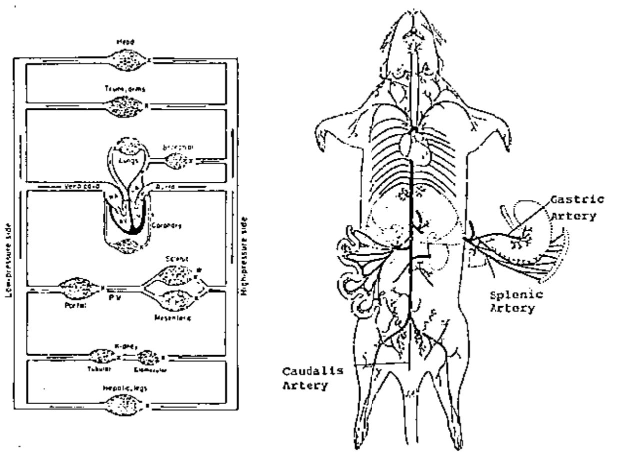

Fig. 1. The arterial anatomy and block diagram of rat.

chloralose is prepared as an 80 mg/ml solution in polyethylene glycol. The airways of the experimental rats were maintained clear and their respiration left in spontaneous manner.

The pressure waves were recorded from the caudalis artery of a rat. The artery was exposed and connulated with a 3/4 inch No. 24 G I. V. catheter placement unit (CRITIKON) which was attached to a Statham P23Dg small volume stain gauge. The frequency response and the phase shift characteristic of the entire recording assembly were identical up to more than 1000 Hz, easily exceeding five times the highest harmonic frequency encountered.

2. Experiments

In the course of the experiment, the pressure waves were recorded for reference before opening the abdomen. After opening the aobdomen, an experiment was performed on the gastric artery or the splenic artery (refering to Fig. 1) in each rat according to the group of the testing animals. The dissections of tissues were kept to the minimum required for exposing these arteries, so that little disturbance was introduced to the circulatory system. The exposed vessels were kept moist with physiologic saline during the experimental period.

After the surgical preparation, a 15-minute period was allowed for the circulatory system to become stable. A short interval of the pressure waves, about 5-10 cycles, was recorded for control before the clamp of an artery. The exposed artery then was clamped using a microsurgical artery clamp, and another pressure waves were recorded at once. These pressure waves, with those taken before the clamp, consist of one compared pair of data. After that, the clamp was released and an interval about 5 minutes was allowed for the circulatory system to become stable again. Such a process was repeated, and got 5 to 18 compared pairs of data for each rat.

3. Data acquisition and analysis

The output of the strain gauge amplifier was connected to an 8-bit A/D converter. The sampling frequency was 1000 Hz/sec and 135-180 sample points were record for each cycle of the pressure waves. The data was sent to an IBM personal computer through a WFS-2000 PC I/O board (DATAQ Instruments), and transferred to a hard disk for later analysis.

Interval records of the pressure waves with minimal best-to-beat variations over respiratory cycles were selected for analysis. Normally, about 3-5 cycles of the pressure waves were chosen for Fourier transform. A cycle was identified by its pit which was determined by the intersection of the terminal diastolic and the initial upstroke of the pressure waves. The trend of the pit-to-pit induced by respiration was also corrected, and the pit of each pressure wave was adjusted to a zero pressure level. A total of 128 samples for each cycle were analyzed. The contents of the first nine harmonics with their 0-th harmonic were determined by Fourier analysis. Beyond the ninth harmonic, the signal-to-noise ratios were too small and the interanimal variations were too great to be considered. The discrete Fourier transforms of these data were calculated using a radix-2 FFT algorithm written in compiler BASIC. The mean values and the standard deviations of all the harmonic moduli for the 3-5 cycles of each interval record were calculated. In order to standardize the presentations of the data, the mean values of the harmonic moduli were thus normalized by their associated 0-th harmonic mean value. The normalized mean values were used to represent the harmonic moduli of an interval record.

A comparison of the data obtained before and during the clamp of an artery was made by substracting the mean values of associated harmonic moduli. All comparisons of a rat were made between the pressure waves which corresponded to each other as closely as possible with regard to their cycle lengths, mean blood pressures, and times in respiratory cycles. Each harmonic modulus during the clamp was substracted by its corresponding harmonic modulus before the clamp, and the result was divided by the later. The differences were represented in percentage forms.

$$\mathrm{VAR.\%} = \frac{\mathrm{LIGA} - \mathrm{NORM}}{\mathrm{NORM}} 100\% \qquad (6)$$

where VAR.% is the percentage difference between the corresponding harmonic moduli before and during the ligation of the gastric or the splenic artery; LIGA is the harmonic modulus of the pressure wave obtained during the ligation of the gastric or the splenic artery; and NORM is the harmonic modulus of the pressure wave obtained before the ligation of the gastric or the splenic artery.

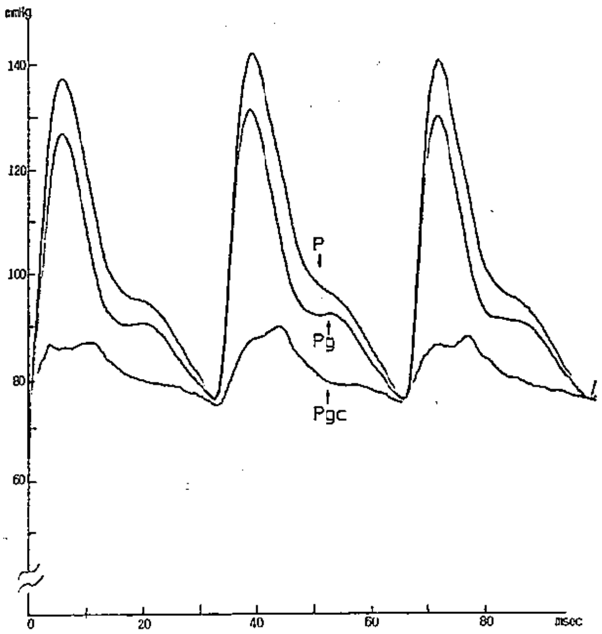

Fig. 2. The pressure waves before and during the ligation of the gastric artery. P is the wave before the ligation, and P_g' is one during the ligation. P_{gc} is residue wave subtracting P_g' from P.

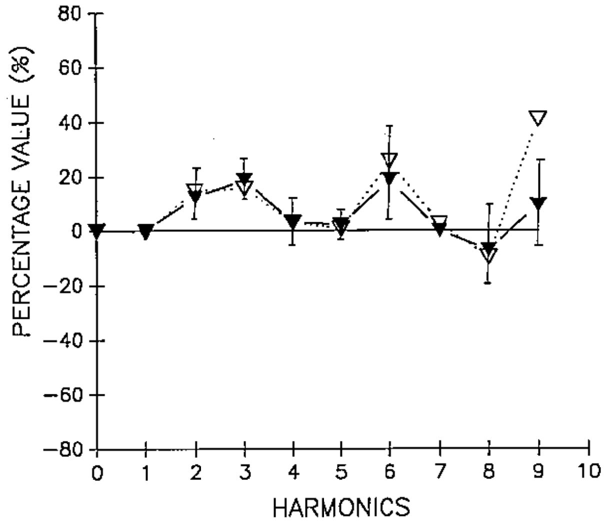

Fig. 3. The differences of the harmonic moduli of the experiments of a rat's data for the ligation of the gastric artery. The vertical bar in the figure is two of the standard deviations of compared pairs of data.
···· is one compared data.

RESULTS AND DISCUSSION

The pressure waves recorded before and during the clamping of the gastric artery are shown in Fig. 2 as curve P and curve P_g' respectively. Their difference P_{gc} is also plotted in the same figure. Similarly, we can get P_{sc}. However, the P_{gc} and P_{sc} give us just the time domain differences of the

Table 1. The first nine harmonic moduli of the pressure waves obtained before and during the ligation of the gastric artery. They are all presented in absolute pressure unit mmHg. NORM means the harmonic modulus before the ligation, and LIGA means the one during the ligation

No.	NORM (mmHg)	LIGA (mmHg)
0	29.21	22.85
1	25.56	19.89
2	16.56	14.86
3	6.95	6.29
4	3.83	3.08
5	2.38	1.87
6	1.13	1.11
7	0.64	0.51
8	0.58	0.41
9	0.28	0.31

The gastric artery (Rat No. 0.41).

pressure waves. It is difficult to interpret such differences quantitatively. Table 1 shows the first nine harmonic amplitudes of P and P_g' in Fig. 2. Almost 95% power of the pressure waves is contained in the first five harmonics. Figure 3 plots the harmonic amplitude differences between P and P_g' for one rat data. It can be viewed as a mapping of P_{gc} in frequency domain. The differences shown by P_{gc} are now clearer than that in time domain.

Figure 4 shows the differences of six rats in which the gastric arteries are clamped during the experimental procedures. Table 2 shows their values in the percentage forms. ANOVA test is used to test the significance of these differences. The second and the third harmonic amplitudes have significant differences between P and P_g' pressure waves ($P<0.01$). The differences of the sixth, the eighth, and the ninth harmonic amplitudes are consistent among rats but not significant ($P>0.01$).

Figure 5 is the statistical results of five rats of which the splenic arteries are clamped to study the vascular bed property of the spleen. The clamp of the splenic artery isolates the vascular bed of a spleen from the systemic circulation. It causes negative differences between P and P_s. The significant differences happen from the third to the ninth harmanic amplitudes. Table 3 shows that all the significant different values are larger than 18.8%.

Like electrical, acoustic, and mechanical impedance, there is vascular impedance to describe the pressure-flow relationship in a circulatory system [12]. The vascular impedance is obtained from Fourier analysis of pairs of pressure and flow waves. It is a frequency dependent quantity. This concept

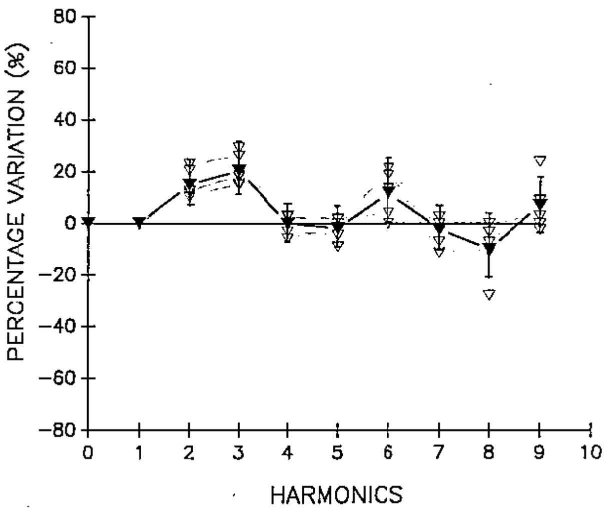

Fig. 4. The statistical results of the harmonic moduli differences for the gastric artery groups. ···· for the diferences of a rat individually; ---- for the statistical result of this group. The vertical bar in the figure is two of the standard deviations of data from six rats.

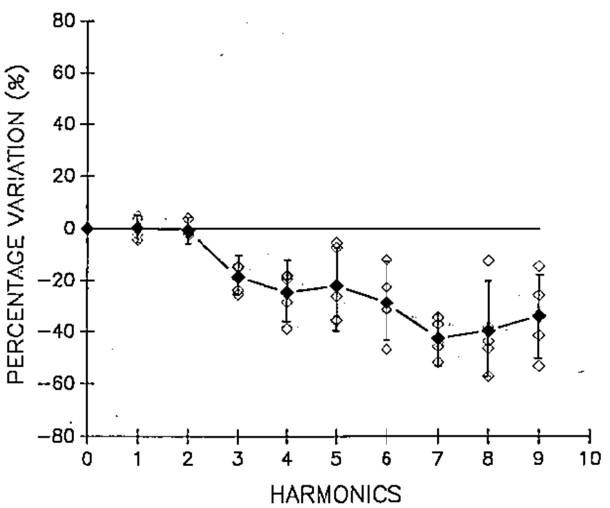

Fig. 5. The statistical results of the harmonic moduli differences for the splenic artery group. ···· for the differences of a rat individually; ---- for the statistical result of this group. The vertical bar in the figure is two of the standard deviations of data from five rats.

Table 2. The differences between the corresponding harmonic moduli before and during the ligation of the gastric artery. The VAR. % is obtained by the formula Eq. (6). STAR is the standard deviations of data gotten from six rats. It determines the significance of the associated differences

No.	VAR. %	STAR
0	0.00	0.00
1	0.00	0.00
2	15.10	5.36
3	20.46	5.88
4	− 0.2	3.67
5	− 1.80	4.22
6	11.88	8.29
7	− 2.06	4.89
8	− 9.93	9.73
9	7.11	9.50

The gastric artery group.

Table 3. The differences between the corresponding harmonic moduli before and during the ligation of the splenic artery. The VAR. % is obtained by the formula Eq. (6). STAR is the standard deviations of data gotten from five rats. It determines the significance of the associated differences

No.	VAR. %	STAR
0	0	0
1	0.21	3.81
2	− 0.64	2.61
3	−18.66	5.45
4	−24.59	9.06
5	−21.99	14.82
6	−28.81	12.85
7	−42.63	6.89
8	−39.55	16.73
9	−33.75	14.82

The splenic artery group.

was first introduced 30 years ago [5,20], and was generally used to discuss the deformations of pressure waves in the circulatory system. Taylor [15-17] showed that impedance patterns could be used to characterize the properties of the vascular beds, especially with regard to the pulse-wave reflections. O'Rourke [7-9,11] has studied the impedance patterns of the major arteries, and used the wave reflections to explain all his findings.

The waves and their reflections in the circulatory system can explain the impedance patterns in the arteries of various animals under different conditions. The effects of the reflections are presented in the deformations of the pressure waves. Thus, the analysis of the deformations of the pressure waves becomes a main approach to study the impedance and the properties of arteries. The wave reflections can occur at any discountinuity along the arterial tree [2]. Hamilton [3] stressed the artery-arteriole junctions to be the major sites of wave reflections. He calculated the reflective coefficients to be 0.8 in normal arterial conditions. Many other experiments placed considerable emphasis on the major arterial branching points as the sites of strong wave reflections. Latham [4] claimed that the renal arterial junctions have 0.43 reflective coefficients. McDonald's [6], Womersley's [21] studies showed that the wave reflections from the major branching points of the aorta would be very low. O'Rourke [12] suggest an asymmetric T model to lump all reflective effects. He suggested the presence of two functionally discrete reflecting sites in the systemic circulation. These two points appear to represent the resultant of all individual arterial terminations in the circulatory system, not any particular anatomical sites.

All these studies focused too much of their consequences on the waves and on the arteries, and obtained so many confused results. Two critical factors are neglected by these studies: The first is that they analyzed the reflective waves just in time domain. The reflective waves may mix with the incident waves in any phase in different arterial locations. They may construct or distory the incident waves. Different points must measure different reflective results. The second is that all of these authors neglected to discuss the effects of vascular beds in organs. The vascular beds are comprised of arterioles, capillaries and small vessels in organs. They are the terminals of pressure and flow waves, and affect the wave contours. They vasodilate or vasconstrict following a special tone, and eliminate or accentuate the wave reflections.

Wang [19] designed a physical model to study the effects of such beds. He used balloons with different sizes and elasticity to simulate the organs. His study suggested that the organs have some natural frequencies, and seem to resonate with the harmonics of the heart rate. Organs have different tissue structures, dispersions of arteriole trees, and distensibilities. The vascular beds in organs work to the pressure waves in the systemic circulation like circuit networks to electrical signals. Basing on the electrial circuit theory, a circuit delivers the most power when a network contains a resonant condition. McDonald [6] claimed the nature's design of arterial trees is to minize the wave reflections, that is to maximize pressure and flow transfer in the systemic circulation. Wang's model and McDonald's claim seem to be consistent.

The reflective waves in an organ back-travel to the aorta through the supplying artery. Since we study the pressure waves in a large artery, we can view the vascular bed in an organ with its supplying artery as an equivalent impedance. Clamping the supplying artery isolates a vascular bed from the systemic circulation. It is much like switching a subnetwork off from a circuit network. The reflective waves from this vascular bed will disappear, and the result shows up in the pressure waves. Studying the variations of the pressure waves in frequency domain will help us to characterize the property of a vascular bed in an organ. In this study, P_{gc} is the pressure wave variation when the stomach vascular bed is isolated from the aorta. It has a frequency profile which the second and the third harmonics increase their amplitudes. P_{sc} has an entirely different frequency profile from P_{gc}. It has negative variations of all harmonic moduli except for the first and the second hormonics. In another study [22], we also got P_{rc} and P_{mc}. They differed from each other in a manner similar to the observations in this study. All these results convince us to believe that all vascular beds in organs have different frequency characteristics. And they seem to support the suitability of Wang's physical model. Such characteristics project their effects on the pressure waves through the correspondent supplying arteries, and affect the measurements of the pressure waves in large arteries. They also heavily affect the calculation of impedance and the reflective coefficients. That is why no consistent impedance patterns and reflective coefficients were obtained by the authors who studied these topics in different methods and different locations in the systemic circulation.

Systemic circulation works like a complex electrical network. The heart is an alternating power supply, and vascular beds in organs are like lumped components. Each lumped component in this network selects some frequency components in the pressure waves to transfer and to reflect according to its frequency characteristic. The resultant of all vascular beds is designed to minimize the heart effort, and to enrich the blood distributions to vascular beds in organs. This concept is very similar to the design of an electrical circuit for electric engineers.

CONCLUSIONS

We focus our study on the vascular beds in organs. This study shows that the vascular beds in organs play important roles in the systemic circulation. To compromise the different results from different reseaches, one may have to seriously consider the frequency characteristics of organ vascular beds. We also suggest that the systemic circulation works like a complex electrical network, and each vascular bed can be viewed as a lumped electrical component with a special frequency property. To study the systemic circulation in more detail, maybe we can construct an electrical simulation circuit. However, it is beyond this study, and will be investigated in the future.

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Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-Chief.

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