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The filter properties of the arterial beds of organs in rats

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The frequency properties of arterial beds in organs were studied by temporarily ligating the renal, the gastric, the splenic or the superior mesenteric arteries of rats. Blood-pressure waves of the tail arteries were recorded before and during the ligations, and were analysed by Fourier's transformation. Their frequency spectra have been found to change profiles following specific patterns with the ligations of different arteries. The results were significant with regard to the frequency selectivities of the organic arterial beds. Such frequency properties can be clearly explained when the circulation system is viewed as an electrical circuit network in which the organic arterial beds work as filters.

Key words: arterial beds, electrical network, filters, frequency spectra, pressure waves.

Blood pressure and flow waves are two important measurements when studying the circulation system (Hamilton 1944, Womersley 1958). The relations between these measurements derive the impedance of arteries (O'Rourke 1982). The impedance is usually used not only to explain the deformation of pressure waves, but also to characterize the frequency properties of arteries (McDonald 1990).

Many phenomena concerning the deformation of pressure waves and the frequency properties of arteries have still been debated. Many reports (Womersley 1958, McDonald 1990) have concluded that the arteries are designed to maximize the matched impedance and to lessen the wave deformation. Some others (Hamilton 1944, Taylor 1973), however, have stressed the existence of major unmatched sites in arteriole–artery junctions. There have been a series of studies (O'Rourke 1967, O'Rourke *et al.* 1984) about the frequency properties of arteries and wave deformation. A T-tube model has been suggested to compromise the contraction from different studies. This model, however, has also been debated by other experimental reports (Latham *et al.* 1985, 1987).

The emphasis in all of these studies has been on the aorta and large arteries. To be the terminals of pressure waves, the arterial beds in organs, meanwhile, have been neglected. Our earlier study (Young *et al.* 1989) has shown that the renal and the superior mesenteric arterial beds strikingly affect the frequency spectra of pressure waves. The study suggested that the effects of the organic arterial beds should be separately accounted for when studying the circulation system.

The frequency properties of the organic arterial beds have been studied in detail in this article. We have studied the frequency selectivities and their effects on pressure waves. The similarity between the organic arterial beds in the circulation system and the filters in an

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electric network are also discussed. This concept has not been explored in other relative literature (Taylor 1959).

MATERIALS AND METHODS

Preparation of Animals. Twenty-four male, adult Sprague–Dawley rats weighing 380–550 g were divided into four groups to ligate respectively the left renal, the gastric, the splenic, or the supermesenteric arteries. The rats were maintained without food excepting water overnight before the experiments began. They were anaesthetized by intraperitoneal injection of alpha-chloralose (48 mg kg^{-1}) and urethane (0.6 g kg^{-1}). Their airways were maintained clear to keep the respirations spontaneous during the experiments.

Blood-pressure waves were recorded by cannulating the tail artery with a $\frac{3}{4}$ inch No. 25G I.V. catheter placement unit (CRITIKON, Johnson-Johnson, FL, USA). The pressure transducer was a Statham P23Dg small-volume strain gauge (Coulbourn Instruments, Pennsylvania, USA). The strain gauge and its amplifier, respectively, had the frequency response up to 100 and 1500 Hz. The assembly system was tested by a sinusoidal pressure pump (McDonald 1990). Its frequency response and phase shift characteristics were uniform ($+5\%$) to 45 Hz (about the eighth harmonic of pressure waves for normal rats).

Experiments. A train of blood-pressure waves was recorded for reference before opening a rat's abdomen. A minimal tissue was then dissected for exposing an artery, and little disturbance was introduced to the circulation system. Only one of the left renal, the gastric, the splenic or the superior mesenteric arteries was exposed in each rat. The exposed artery was kept moist with physiological saline during the experiment.

A period of 15 min after the surgical operation was allowed for the circulation system to become stable. The exposed artery was temporarily ligated by a microsurgical arterial clamp. Little damage was done to the arterial surface. Short trains of pressure waves, about 10–20 cycles, were taken before and during the ligation. Such records consisted of a pair of compared data. The artery was then released and a 5-min rest period elapsed to allow for the stability of the circulation system. The procedure was repeated and 5–20 pairs of compared data were obtained for each rat.

Data acquisition and analysis. An analogue/digital (A/D) converter converted the pressure waves into digital data. Its sampling frequency was 1000 Hz. The A/D converter sampled 135–180 data for each cycle of pressure waves. The data were sent to an IBM personal computer through a WFS-200PC I/O board (DATAQ Instruments, Ohio, USA).

The pressure waves, which had minimal beat-to-beat variations over respiratory cycles, were chosen and analysed. Their frequency spectra were obtained by Fourier's transformation. The first nine harmonic moduli of frequency spectra were calculated and were normalized to their mean levels (the area under the pulsatile waves). The profile changes of the frequency spectra were achieved by comparing the normalized harmonic moduli for each pair of data. The normalized harmonic moduli during the ligation were subtracted by their corresponding ones before the ligation. The results were then divided by the latter, and were represented in percentage forms.

The heart rates and the mean pressures were also monitored. A paired t-test was used for checking the variations of the harmonic moduli, the heart rates, and the mean pressures.

Theory and physical explanation. When blood-pressure waves propagate in the circulation system, reflections are generated from arterial beds. The reflective waves mix with the incident waves. Separating the reflective waves from the mixed waves is difficult. The mixed waves can, however, be physically decomposed into two components:

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

P_{in} is the incident pressure wave generated by the left ventricular contraction. P_{re} is the reflective pressure wave generated from all arterial beds.

The reflective waves affect and deform the pressure waves in the circulation system. P_{re} can be decomposed into P_k, P_g, P_s, P_m and P'_{re} in order to consider the effect of an individual organic arterial bed. P_k, P_g, P_s and P_m respectively represent the reflective waves from the arterial beds of the kidneys, the stomach, the spleen and the intestine. P'_{re} is the residual reflective wave from the other arterial beds. The propagation and reflection of pressure waves in an arterial bed must be affected when an organic artery is ligated. The pressure waves, by ligating the renal artery, can be represented as:

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

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

$$P_{kc} = P - P'_k \tag{4}$$

$$= P_k - P_c \tag{5}$$

P'_k is the pressure wave recorded when ligating the renal artery. P_c is a new reflective wave generated near the clamping site. P_{kc} is the difference between P and P'_k. It must include the effect and characteristics of the renal arterial bed on the circulation system. P_{gc}, P_{sc} or P_{mc} can also be obtained by ligating the gastric, the splenic or the mesenteric arteries. They can be used to study the characteristics of the organic arterial beds.

RESULTS

Figure 1 illustrates the pressure waves before

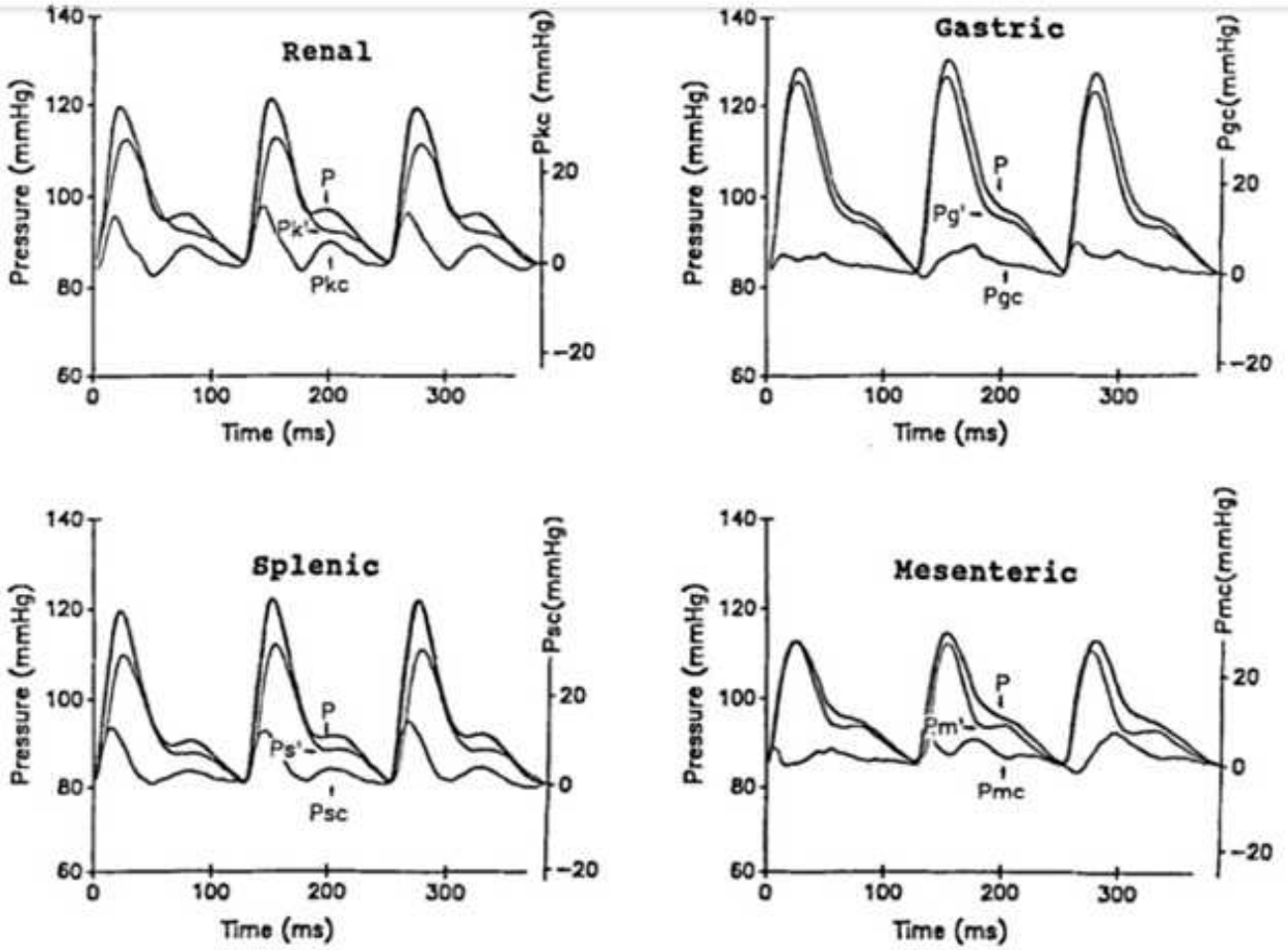

Fig. 1. The pressure waves before and during artery ligation. Each P means the waves before ligation. P'_k, P'_g, P'_s and P'_m refer to the waves during the ligation of the left renal, the gastric, the splenic, and the supermesenteric arteries. P_{kc}, P_{gc}, P_{sc}, P_{mc} refer to the differences between each P and P'_k, P'_g, P'_s or P'_m.

and during the ligations of arteries. P_{kc}, P_{gc}, P_{sc} and P_{mc} were the differences between each two waves. They differed significantly from each other; however, such results were hard to interpret quantitatively.

The frequency spectra of the pressure waves have been shown in Figure 2. The frequency spectra before the ligations of arteries were almost the same in all groups. Their harmonic moduli were plotted as blank bars. Another set of bars were the harmonic moduli of P'_k, P'_g, P'_s and P'_m. There were changes among the absolute values of harmonic moduli; but the changes were ambiguous in such a form.

Figure 3 indicates the percentage variations of the harmonic moduli before and during the ligations of arteries. The renal group had significant variations ($P < 0.01$) from the second to the fifth harmonic moduli. The values varied from -18.75 to -51%. The variations of the gastric group were significant in the second (15.10%), the third (20.26%) and the sixth (11.88%) harmonic moduli. The splenic group varied significantly from the third to the seventh harmonic moduli. The values varied from -18.66 to -42.63%. The superior mesenteric group had significant variations from the third to the fifth harmonic moduli. The values from 17.11 to 19.73%.

The heart rates and the mean pressures before and during the ligations have been shown in Table 1. No significant changes ($P > 0.1$) occurred.

DISCUSSION

The organic arterial beds are viewed as lumped elements, and they have been isolated from the circulation system by temporarily ligating arteries. The frequency properties of the organic arterial beds and their effects on pressure waves have been studied. Such a total occlusion method

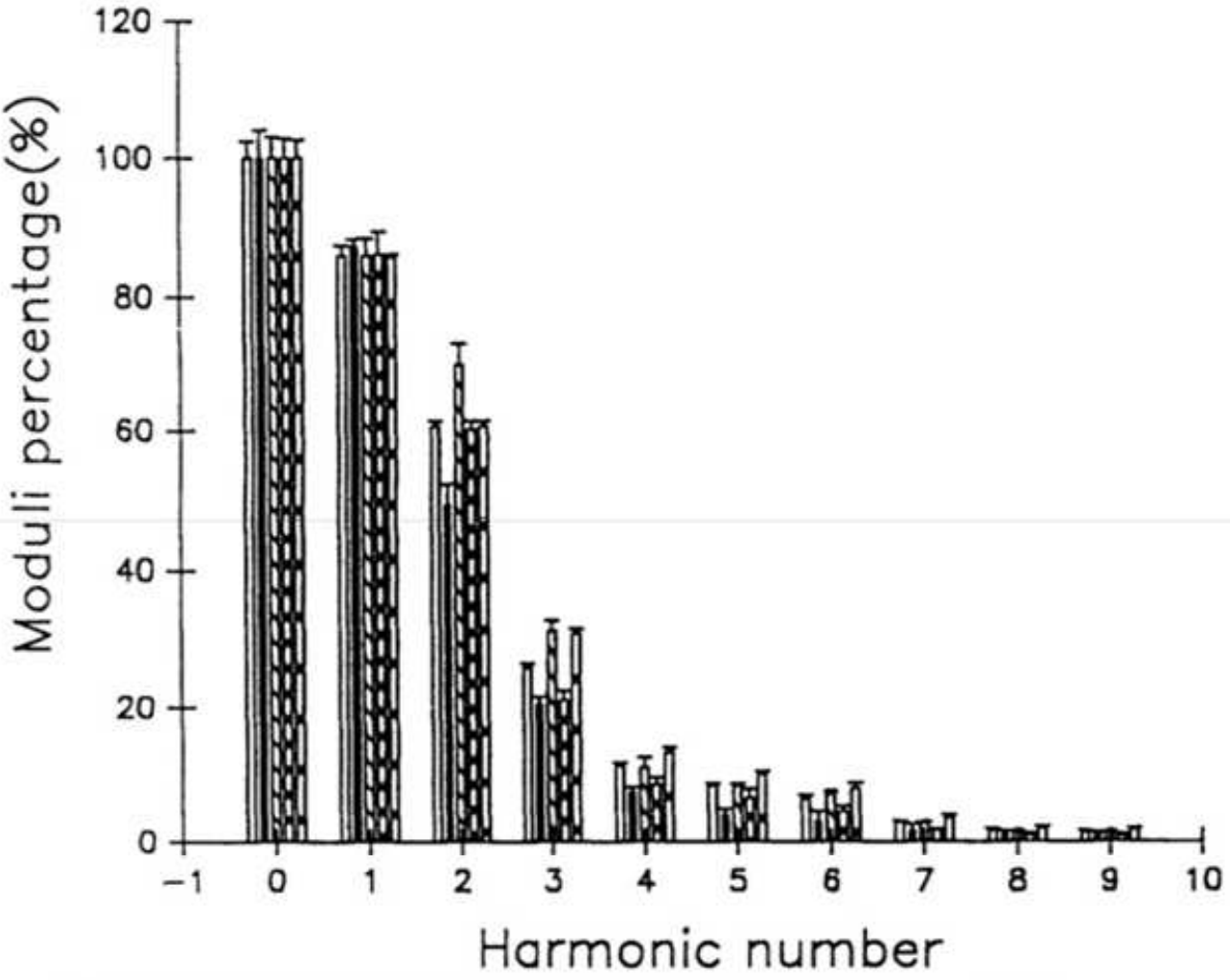

Fig. 2. The normalized harmonic moduli of each group. ═══: the harmonic moduli before artery ligation. ——: the group ligated with the renal artery. ▭▭: the group ligated with the gastric artery. ▭▭: the group ligated with the splenic artery. ▭▭: the group ligated with the supermesenteric artery. The error bars represent the standard deviations.

Table 1. The heart rates and the mean pressures before and during artery ligat… difference was found ($P > 0.1$)

		Renal	Gastric	Splenic	Mesenteric
Heart rate	Before	6.37±0.37	6.60±0.28	6.39±0.34	6.41±0.29
	During	6.17±0.46	6.46±0.31	6.30±0.37	6.28±0.27
	Variation	0.16±0.12	0.15±0.16	0.10±0.08	0.13±0.04
Mean pressure	Before	104.7±2.6	104.2±2.9	105.6±3.3	108.8±3.3
	During	105.8±2.8	106.0±3.7	105.3±4.7	105.5±4.3
	Variation	3.5±1.2	4.5±1.8	4.4±1.5	4.0±1.3

has also been widely used for studying the properties of arteries (Greenwald & Newman 1982, O'Rourke 1982, Latham 1985). The frequency spectra of P_{kc}, P_{gc}, P_{sc} and P_{mc} in this study changed differently from each other. The specific frequency properties of the organic arterial beds were suggested by this phenomenon. The path from the abdominal aorta to the femoral artery has been reported to resemble a low pass filter (Li *et al.* 1981). The pulmonary circulation system has been shown to have the strongest effect on the fourth harmonic of pressure waves (Wiener *et al.* 1966). Another study (Farrow & Stacy 1961) has also shown

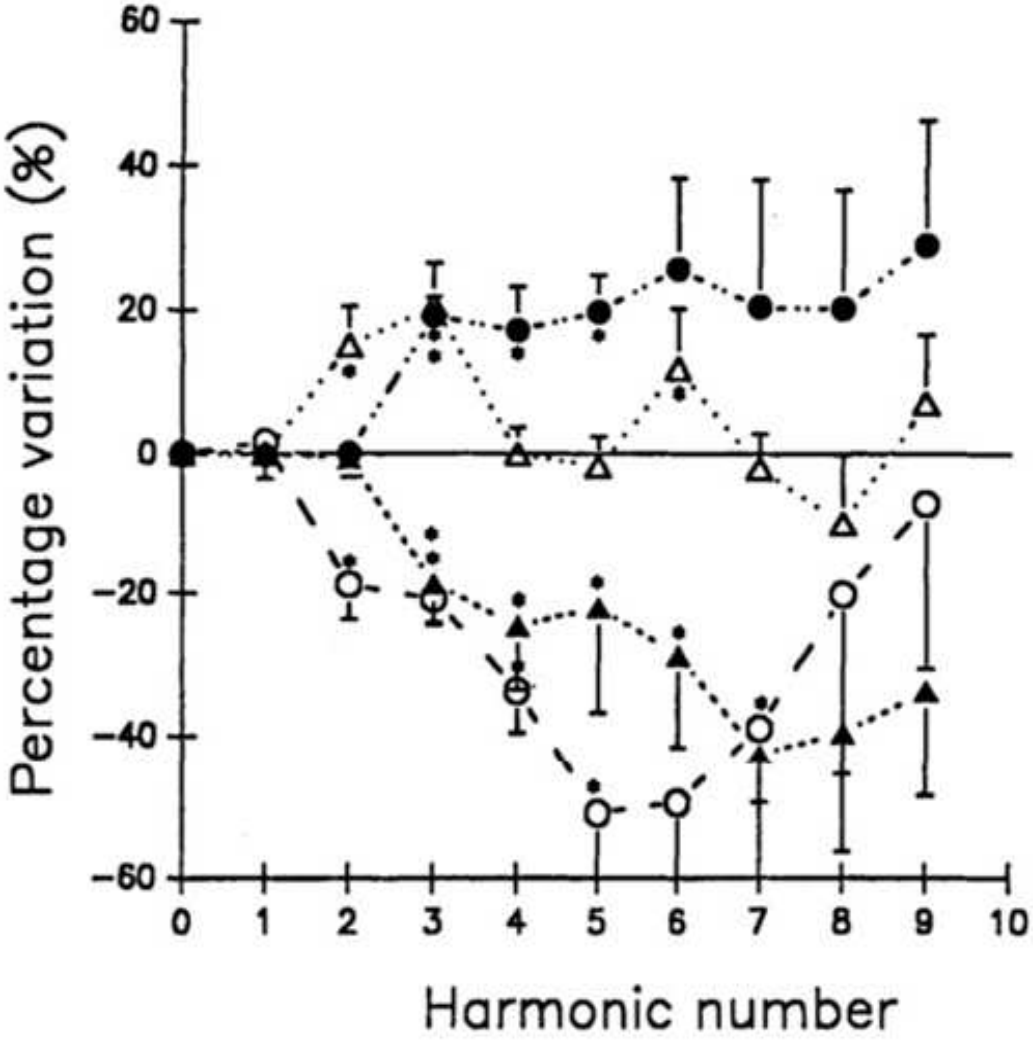

Fig. 3. The percentage variations of frequency spectra before and during artery ligation. Each group had six rates. * Represents items with significant change ($P < 0.01$). ○−—○ curve was for the group ligated with the left renal artery. △. . . . △ was the curve for the group ligated with the gastric artery. ▲. . . . ▲ curve was for the group ligated with the splenic artery. ●−..−● curve was for the group ligated with the supermesenteric artery. The error bars represent the standard deviations.

great variation on the third harmonic, even when the others were stable with the clamp of the femoral artery. All these results imply that the organic arterial beds have frequency selectivities. The organic arterial beds are inhomogeneous to different frequency components of pressure waves. Each arterial bed selects specific frequencies on which to propagate and reflect. As a result some harmonic moduli are then varied dominantly when arterial beds become isolated.

It is reasonable to expect that the organic arterial beds have specific frequency properties, and have different effects on pressure waves. The organic arterial beds are abundant in arterioles, capillaries and small vessels. In organs their dispersions and surrounding tissues differ from each other. The beds are attached to the aorta at different sections and with different lengths of arteries. These effects result in organic arterial beds having different frequency properties, as the frequency selectivities show in this study. The frequency selectivities are heavily dependent on the positions and the physical properties of organs. Such a dependence has been discussed in Wang's report (Wang 1991). The organic arterial beds vasodilate or vasoconstrict following special tones (O'Rourke 1967, Milnor 1985, McDonald 1990). They affect blood perfusion and pressures (Garcia *et al.* 1989). The beds must have specific effects on pressure waves when they are isolated from the circulation system. These effects have been demonstrated by many previous reports (Remington, 1963, O'Rourke 1982, Latham *et al.* 1985).

Discussion about different changes when one kidney or the spleen is excluded from the

circulation system in comparison to exclusion of the stomach or the intestine is interesting. A very simple physical model has been established for explaining these results (Wang, 1991). The kidney and the spleen are more rigidly encapsulated organs, and communicate with the aorta through shorter arteries. Such organic beds may couple strongly with the aorta and amplify the high-frequency components of pressure waves. The amplification decreases when these beds are excluded from the circulation system. The high-frequency components then significantly reduce as the results of this report have shown. The arteries of the stomach and the intestine are much longer and more divergent. Such arterial beds simply work as reflective sites. The sites move closer towards the aorta when the arteries are ligated. The reflection of high-frequency components then increases, which is contrary to the situation of the kidney and the spleen.

The frequency selectivities of the organic arterial beds are quite similar to the filter properties of an electrical circuit network. The heart is an alternating power supply in such an analogue network. The arterial beds in organs are lumped electrical elements which work as filters. All these filters select specific frequency components of pressure waves to transfer and reflect on. They deform pressure waves following specific patterns in different sections of the aorta (Hamilton 1944, O'Rourke 1967, Latham *et al.* 1985). The resultant design of all arterial beds minimizes the heart effort and maximizes the efficiency of the circulation system (Womersly 1958, McDonald 1990, Wang 1991). The same concept is adopted to design filters for the most efficient power delivery in an electrical network. The filter properties are good causes of certain characteristics of the organic arterial beds. Their frequency selectivities are precise explanations for the specific variations of pressure waves found in this study and other previous reports.

REFERENCES

Farrow, R.L. & Stacy, R.W. 1961. Harmonic analysis of aortic pressure pulses in the dog. *Circ Res* **9**, 395–401.

Garcia, A.C., Costa, A.F., Rocha, E. S. & Peixoto, P.C. 1989. Ascending aorta input impedance during hemorrhagic and after hyperosmotic solution infusion. *Braz J Med Biol Res* **22**(2), 253–257.

Greenwald, S.E. Newman, D.L. 1982. Impulse propagation through junction. *Med Biol Eng & Comp* **20**, 343–350.

Hamilton, W.F. 1944. The patterns of the arterial pressure pulse. *Am J Physiol* **141**, 235–241.

Latham, R.D., Rubal, B.J., Weserhof, N., Sipkema, P. & Walsh, R.A. 1987. Nonhuman primate model for regional wave travel and reflections along aortas. *Am J Physiol* **253** (2 Pt. 2), H299–306.

Latham, R.D., Westerhof, N., Sipkema, P., Rugal, B.J., Reuderink, P. & Murgo, J.P. 1985. Regional wave travel and reflections along human aorta: a study with six simultaneous micromanometric pressures. *Circulation* **72**, 1257–1269.

Li, J.K.J., Melbin, J., Riffle, R.A. & Noordergraaf, A. 1981. Pulse wave propagation. *Circ Res* **49**, 442–452.

McDonald, D.A. 1990. *Blood Flow in Arteries*, 3rd ed. Edward Arnold, London. pp. 125–195.

Milnor, W.R. 1985. *Haemodynamics*, 2nd ed. Williams, London. pp. 167–259.

O'Rourke, M.F. 1967. Pressure and flow waves in systemic arteries and the anatomical design of the arterial system. *J Appl Physiol* **23**, 139–149.

O'Rourke, M.F. 1982. Vascular impedance in studies of arterial and cardiac function. *Physiol Rev* **62**, 570–623.

O'Rourke, M.F., Yaginuma, T. & Avolio, A.P. 1984. Physiological and pathophysiological implications of ventricular/vascular coupling. *Ann Biomed Eng* **12**(2), 119–134.

Remington, J.W. 1963. The physiology of the aorta and major arteries. *Handbook of Physiology Circulation*, sect. 2, Vol. 2, Chapt. 24, pp. 799–838, Am Physiol Soc. Washington DC.

Taylor, M.G. 1959. An experimental determination of the propagation of fluid oscillation in a tube with a viscoelastic wall; together with an analysis of the characteristics required in an electrical analogue. *Phys Med Biol* **4**, 63–82.

Taylor, M.G. 1973. Hemodynamics. *A Rev Physiol* **35**, 87–116.

Wang, Y.Y.L., Chang, S.L., Wuy, Y.E., Hsu, T.L. & Wang, W.K. 1991. Resonance: the missing phenomenon in hemodynamics. *Circ Res* **69**, 246–249.

Wiener, F., Morkin, E., Skalak, R. & Fishman, A.P. 1966. Wave propagation in the pulmonary circulation. *Circ Res* **19**, 834–850.

Womersley, J.R. 1958. Oscillatory flow in arteries: the reflection of the pulse wave at junctions and rigid inserts in the arterial system. *Phys Med Biol* **2**, 313–323.

Young, S.T., Wang, W. K., Chang, L.S. & Kuo, T.S. 1989. Specific frequency properties of the renal and the supermesenteric arterial beds in rats. *Cardiovasc Res* **23** (6), 465–467.