18 191-197 1992

Medical Progress through Technology 00: 000–000. 1991.

Biomedical engineering basis of traditional Chinese medicine

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Accepted 2 October 1991

Key words: hemodynamics, chi, resonance, organ

Abstract:

Traditional Chinese medicine is an ancient medical science that can be traced back for three to four thousand years of written history. Using the transient response characteristic method, we studied the frequency property of some simulated organs. We tried to explain the concept that the energy in the blood pressure wave is distributed to different organs in the body according to the frequency. This will elucidate the ancient teaching of Chinese medicine in terms of current engineering terminology.

Introduction

The body is a masterpiece of art by nature. We may appreciate its beauty from many different facets.

In this report we will try to introduce an ancient science which will surely enlarge our horizon of the understanding of the efficiency of the body.

'Feel the movement of the nine internal organs' is a sentence written in an ancient Chinese book *Chou Li* (周礼) about three thousand years ago. It says by scrutinizing the pulse of the surface artery, we may understand the movement of the internal organs. The Chinese, beginning in ancient times, thought that each organ has its own movement, and this movement is like a forced oscillation or a coupled oscillation. The movement is related to the blood flow into each specific organ. In other words, each organ has its own 'Chi' (氣). The concept that 'Chi' can facilitate the pumping of blood into different organs is the engineering basis of Chinese medicine.

Some hemodynamics facts

The artery web is a hollow one, filled with blood. Pressure wave and blood propagate in it. During the propagation of a blood pressure wave, little drop happens until reaching the sphincter [1]. This large hollow web is tied up at the terminal by the sphincters and blown up by a large diastolic pressure. A systolic pressure wave propagates in it.

There are hundreds of papers dealing with pressure wave propagation and blood flow in the artery [2, 3]. We will briefly discuss the results of Womersley [4–6].

To deal with wave propagation in a cylindrical artery, Womersley has made assumptions about laminar flow, newtonian fluid, uniform cylindrical tube, linearization of equations, no entry effects, no reflected wave, and some properties about the artery wall.

The result he got is:

$$Q = \mathrm{Real}\left\{ \frac{Pe^{i\omega t}}{pC}\pi R^2 \left(1 + \frac{2\upsilon}{Rz}\right)(1 + NF10)\right\} \quad (1)$$

$$\left(\frac{Co}{C}\right)^2 \Big|_{K = -\omega} = \frac{(1-\sigma^2)}{(1-F_{10})} \quad (2)$$

Q: Flow rate
F10: $2J1\,(j^{3/2}\alpha)/[j^{3/2}\alpha J0\,(j^{3/2}\alpha)]$
σ: Poisson's ratio
C: Complex wave velocity
Co: Theoretic wave velocity from Moens-Korteweg equation in a non-viscous system
K: Elastic constraint and loading constant of the wall
p: Density of the blood
R: Internal radius
υ: Time varying radial displacement

$$N = \frac{2}{X(F10-2)} - \frac{(1-2\sigma}{(F10-2\sigma)} \quad (3)$$

$$X = \left(\frac{Co}{C}\right)^2 \left(\frac{2}{1-\sigma^2}\right) \quad (4)$$

To compare his result with experiments, the complex wave velocity C was separated into real and imaginary parts as follows

$$\frac{1}{C} = \frac{b-ja}{\omega} \quad (5)$$

In other words, we may think of this equation as

$$-\left(\frac{dP}{dx}\right)/Q = Zl \quad (6)$$

$$Zl = R + j\omega L; \quad (7)$$

or, more experimentally,

$$\frac{\Delta P}{\Delta x} = RQ + L\frac{dQ}{dt} \quad (8)$$

Due to its linearized character, we may fit this equation to experimental data with different frequencies ω or different α ($\alpha^2 = R^2\omega p/\eta$).

During the 1960s and 1970s, several groups compared this equation to experiments in vivo. They tried to fit the parameters that would give the correct value of L in equations 6 and 8. The discrepancy between the derived R that used the same parameters was 200% to 800% different from the measured quantities at low α [7–9].

Afterwards, many scientists have checked the assumptions made by Womersley. They studied the tube with tapering shape, entrance effect, nonlinear effects and so on; each one picked up 10% to 15% difference. However, this is quite far from the more than 200% discrepancy [3].

To explain this discrepancy, the theory of reflection [2, 3] then became popular. Whenever a branch is met, it is treated as two tubes with a junction. The junction will partially reflect and partially transmit the pressure wave. This theory has become the main explanation for the discrepancy. There is, however, the ambiguity that the reflection coefficient and the point of reflection seem to be chosen somewhat arbitrarily so as to fit all kinds of different experimental results.

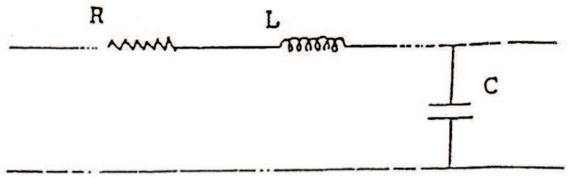
The reflection may be able to deal with branches; however, the arbitrariness of the reflection coefficient and the center of reflection give no clue to the involvement of the organs with respect to the shape of the blood pressure wave.

Electrical power line analogy

Womersley has also suggested that some further correction must be made due to the arterial wall dilation. Since the arterial wall does not dilate too much, he estimated the correction would be about 11% for the first harmonic (for higher harmonics, the correction should be somewhat larger).

In other words the solution of Womersley's equation may be simplified as $Zl = R + j\omega L$

With the addition of arterial dilation, we have



This is also the result of Lande and Noordergraaf [10] who started from the electrical power line analogy. Actually, this analogy is quite good for wave propagation in a single elastic tube filled with water [11]. It is puzzling that it does not work for the aorta.

Effect of organs on the pressure wave propagation

We started the study by tying the artery toward some internal organ [12, 13]. If an organ on a side branch of the aorta was damaged severely and blood flowing through it was greatly reduced, what would be the effect on the propagation of the blood pressure wave in the aorta? We found that attachiny the organ to the side branch of the aorta actually enhances the intensity of high frequency components.

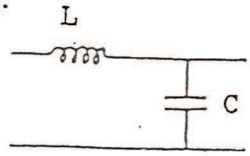
From our experiments, we have found that the organ's condition can affect the shape of the blood pressure wave in the artery. This is the teaching of the ancient Chinese book *Chou Li* (周礼). However, what is the mechanism? Actually, the clue to resolve the discrepancy between Womersley's equation and experimental results seems to be found here also [14, 15].

Experimental method and results

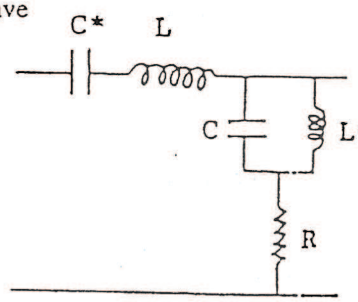
We may the use transient response frequency characteristic method to understand this coupled oscillation or the resonance between organ and aorta. From general system theory we know that any linear system can be fully described either in the time domain or in the frequency domain. Therefore, all information concerning the frequency characteristics of a linear system is contained in the transient response of the system [16–18].

The frequency characteristics of a simulated artery with a closely attached side branch organ were studied to illustrate the property of resonance. The organ was simulated by a balloon.

From electrical line analogy, an elastic uniformed blood vessel is equivalent to an inductance with a branch capacitance.



However, in this study, the vessel also has a short side branch which is connected to a balloon. If we look at this side branch as a perpendicular vessel and couple these two vessels into one equivalent circuit we will have



This is a resonance circuit that will select two resonance frequencies

$$\omega_1 = \frac{1}{\sqrt{LC^*}} \qquad \omega_2 = \frac{1}{\sqrt{L^*C}}$$

with reduced resistance.

Therefore, in a plot of transmission versus frequencies for this simulation, we will see two peaks at ω_1 and ω_2.

A stepping motor was controlled by PC to generate impulses to meet our requirement. An elastic tube (length $\simeq 50$ cm, ID $\simeq$ 0.8 cm) had a side branch to which a small balloon of volume 1.5 cm^3 was connected via a hard tube (length $\simeq 10$ cm, ID $\simeq$ 0.25 cm). We measured the pressure wave after the impulse propagated through this elastic tube. This structure was a simulation of a short segment of the aorta with a closely attached organ. The transient response was measured by DP103 differential pressure transducer (Validyne, U.S.A.). The response in the time domain was digitized by ADC, then through a Fourier transform we got the response in the frequency domain.

The shape of the generated impulse was measured at about 3 cm from the stepping motor outlet

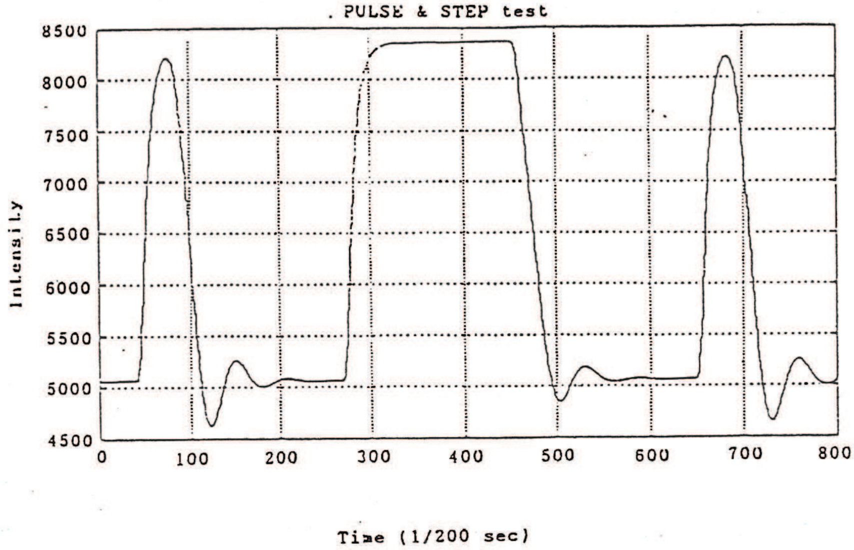


Fig. 1. The shape of the impulses generated by the stepping motor measured near the outlet of the stepping motor. There are two impulses with different durations. In the following experiments we used the impulse of the shorter duration.

with the catheter that led to the transducer sitting at the center of the tube and parallel to the direction of the flow so as to measure the end pressure. The exponential increase and exponential decrease of this impulse measured could be due to the Windkessel-like property of this measuring arrangement.

There is a peak at $\omega = 3.3$ Hz. This is the peak of a single elastic tube, which behaves like a low pass filter and cuts off the higher components [11].

From the impulse response of the uniform elastic tube with the attached balloon, we may conclude that there are two resonance frequencies centered at ω_1 and ω_2 due to the coupled oscillation between

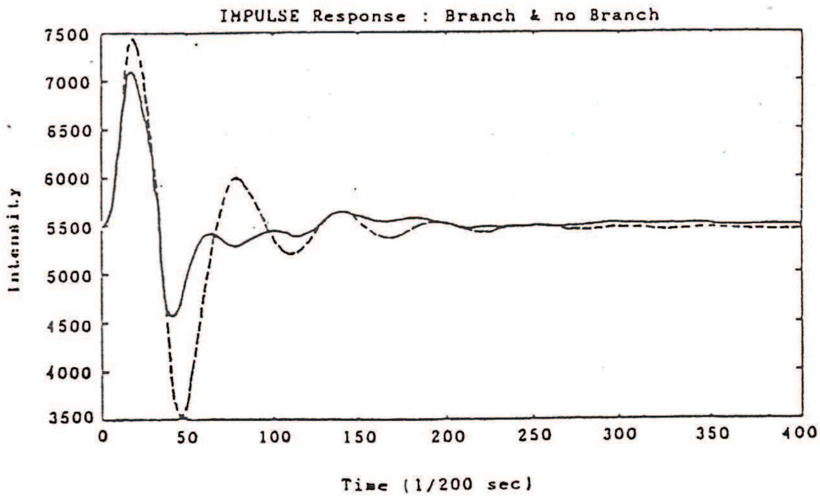


Fig. 2. The impulse response of the elastic tube (dashed line) and the impulse response of the elastic tube with a side branch balloon (solid line) in a time domain.

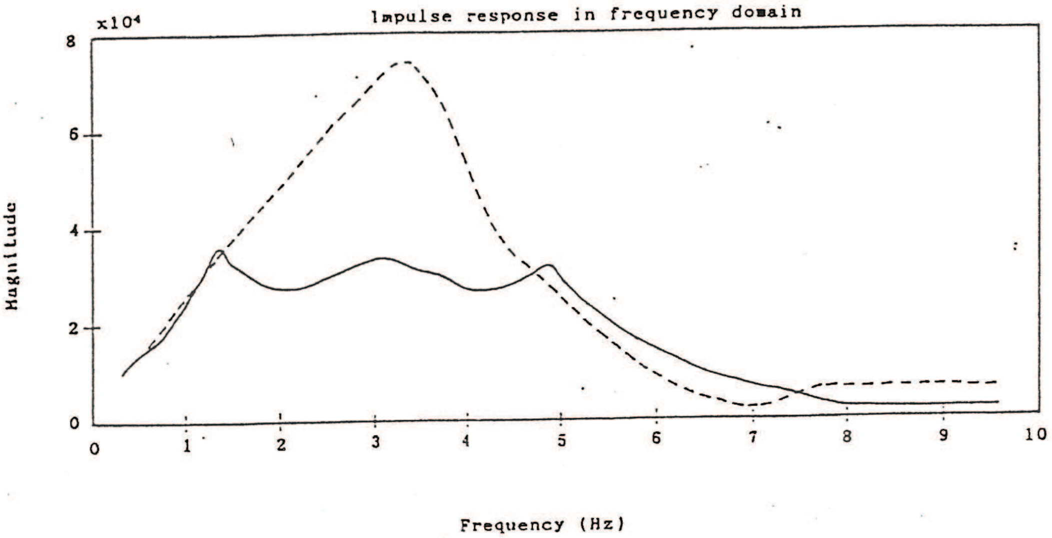


Fig. 3. The dashed line shows the impulse response of the uniform elastic tube without the attached balloon. There is a peak at $\omega = 3.3$ Hz. The solid line shows the impulse responses of the uniform elastic tube with the attached balloon. There are clearly two resonance peaks; one appears at $\omega_1 = 1.3$ Hz, and the other at $\omega_2 = 4.8$ Hz.

the long elastic tube and the side branch balloon. By replacing the balloon with a harder one (less elastic), ω_1 was shifted to a higher frequency (C^* became smaller). We also see ω_2 as well as ω_1 changed to somewhat lower frequencies, due to increases in L^* and L.

From the equivalent circuit, C^* is the compliance of the side branch balloon; the leakage resistance is equivalent to the resistance of the small hard tube which connects the balloon with the main elastic tube. Therefore, some fluid may flow across C^* through the leakage resistance. This is equivalent to flowing from the main tube through the side

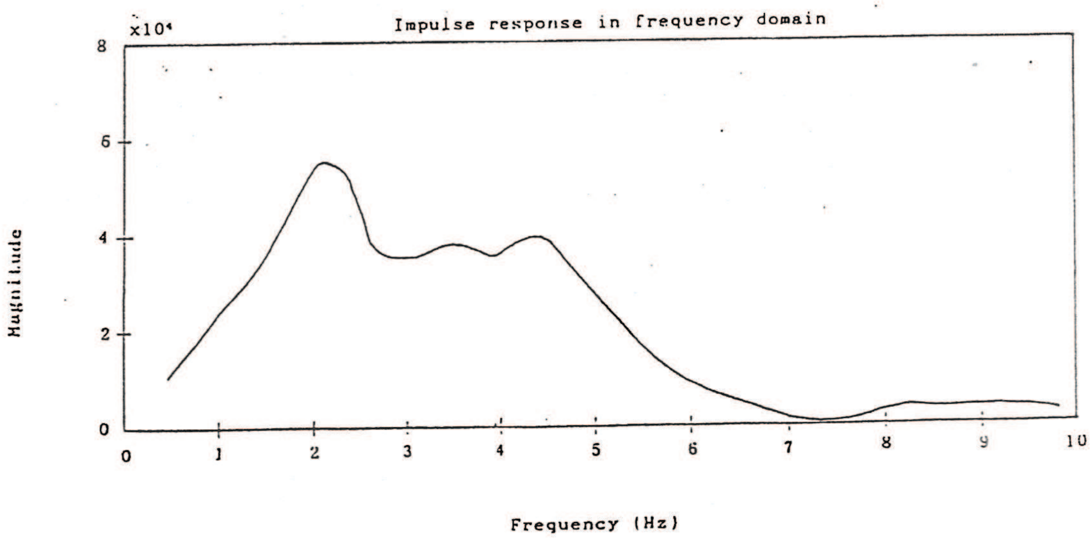


Fig. 4. The line shows the impulse response of the same elastic tube with an attached balloon which has a smaller C^* (less elastic). The resonance peak $\omega_1 = \frac{1}{\sqrt{LC^*}}$ becomes larger and shifts to about 2.1 Hz, ω_2 is a little lower.

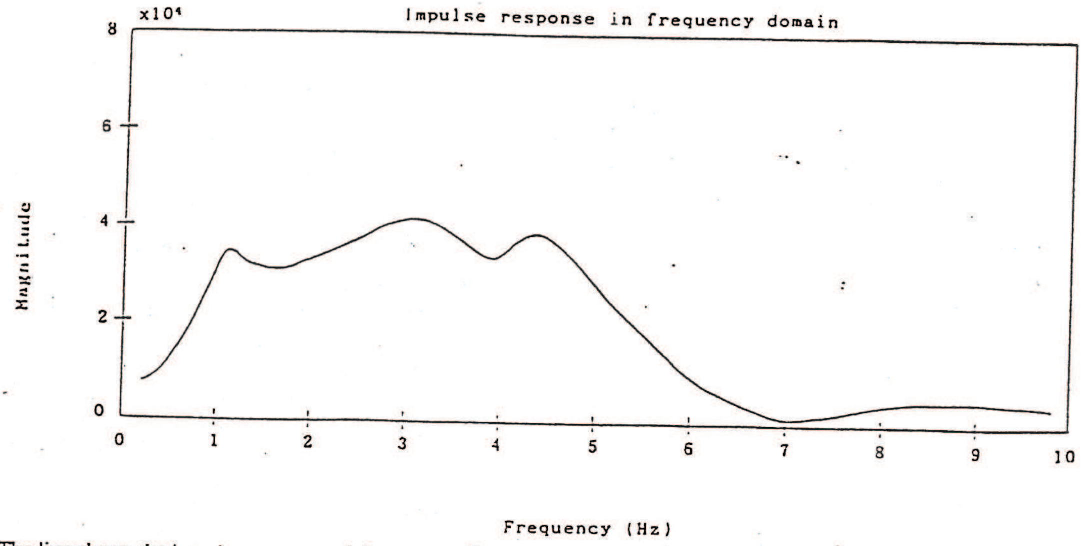


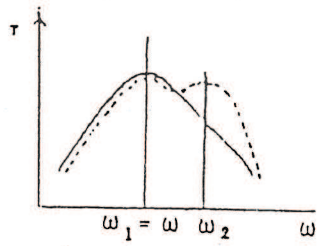
Fig. 5. The line shows the impulse response of the same uniform elastic tube with an attached balloon, the same as A. but filled with NaCl solution with density 1.2; the resonance peaks ($\omega_1 = 1.2$ Hz, $\omega_2 = 4.3$ Hz) both shift to smaller values due to the increase in L* and L.

branch hard tube toward the balloon, then flowing through the hard tube again back to the main tube.

The linearity of this preparation was checked by generating a pure sinusoidal wave of different frequencies from the stepping motor and measuring the frequency composition of this wave after it propagated to the end of the tube. The frequency composition checked near the output of the stepping motor was more than 97% single frequency. After the wave propagated through the elastic tube with the attached balloon, it was more than 92% the same single frequency (we checked from 0.5 Hz to 7 Hz). This means that this simulation was more than 90% linear, which is comparable to the real artery system tested [19].

Implications of Chinese medicine

In Fig. 5, there are actually three peaks in the simulated aorta. If the elastic balloon becomes even less elastic, ω_1 will shift to a higher value. If the main elastic tube becomes longer, the peak frequency ω of the dashed line in Fig. 5 will shift to a lower value. Therefore, somewhere around 3 Hz. the peak ω_1 in Fig. 6, and the peak ω in Fig. 5 may merge into one peak. Thus we may have



If we tie the side branch, we will see the solid line. If we release it, we will see the dotted line. There is only one additional peak in the dotted line. In other words, more high-frequency components are propagating along the aorta due to the resonance effect of the organ. These were the experimental results we found by tying an organ such as the kidney or spleen.

Actually this phenomena has been described in an ancient Chinese medicine Bible *Nei-Ching* (HS3,6C) 清陽發腠理，濁陰走五臟
清陽實四肢，濁陰歸六腑

It means 'The higher frequency waves propagate to the body surface and the lower frequency waves propagate to the five solid organs. Higher frequency components nourish the hands and legs, while lower frequency waves enter the six hollow organs.'

If each organ is oscillating with a specific frequency, the amplitude of this frequency will be a good indicator of the health condition of this organ. The change of this specific amplitude can be felt at the surface artery.

The artery web behaves like a fancy musical instrument. Each organ has its own tune. If every organ is in healthy condition, the music is wonderful. If some organ is out of order, the music will not be in harmony, and we may figure out the problem by listening to it. We may then tune it up by needles or herbs.

This is the art of 'Chi' in Chinese medicine. It has dominated the diagnostic and therapeutic theory in Oriental medicine for more than three thousand years.

References

1. Fung YC, editor. Biomechanics. New York: ASME, 1966.
2. Fung YC. Biodynamics. New York: Springer Verlag, 1984.
3. Milnor WR. Hemodynamics. Baltimore: William & Wilkins. 1989.
4. Womersley JR. Method for calculation of velocity, rate of flow and viscous drag in arteries when the pressure gradient is known. J Physiol 1955; 127: 553–63.
5. Womersley JR. Oscillatory motions of a viscous liquid in a thin-walled elastic tube. I. The linear approximation for long waves. Phil Mag 1955; 46: 199–221.
6. Womersley JR. Oscillatory flow in arteries: The constrained elastic tube as amodel of arterial flow and pulse transmission. Phys Med Biol 1957; 2: 178–87.
7. Ling SC, Atabek HB, Letzing WG, Patel DJ. Non-linear analysis of aortic flow in living dogs. Circ Res 1973; 33: 198–212.
8. Milnor WR, Bertram CD. The relation between arterial viscoelasticity and wave propagation in the canine femoral arterial *in vivo*. Circ Res 1978; 43: 870–9.
9. Atabek HB, Ling SC, Patel DJ. Analysis of coronary flow field in thoracotomized dogs. Circ Res 1975; 37: 752–61.
10. Noordergraaf. Hemodynamics in Biological Engineering. Inter. University Electronics series. Schwam HP, editor. Mcgraw-Hill, 1969; 9.
11. Taylor MG. An experimental determination of the propagation of fluid oscillation in a tube with viscoelastic wall together with an analysis of the characteristics required in an electrical analog. Physics Med Biol 1954; 4: 63–82.
12. Wang WK, Lo YY, Chieng Y, Hsu TL, Wang Lin YY. Resonance of organs with the heart. In Biomedical Engineering, an international symposium; Young WJ, editor. Hemisphere, 1989; 259: 97.
13. Young ST, Wang WK, Chang LS, Kao TS. Specific frequency properties of renal and superior mesenteric arterial beds in rats. Cardiovas Res 1989; 23: 465–7.
14. Wang Lin YY, Chang SL, Wu YE, Hsu TL, Wang WK. Resonance – The missing phenomenon in hemodynamics. Circ Res 1991; 69: 246–9.
15. Wang WK, Wang Lin YY. From hemodynamics to Chinese Medicine. Chin J of Med Biol Eng 1991; 11: 1–14.
16. Solodovnikov VV. Introduction to the statistical dynamics of automatic control systems. Dover. New York: 1960.
17. Blesser WB. A system approach to Biomedicine. New York: Mcgraw – Hill, 1969.
18. Basar E. Biophysics and physiological system analysis. Addison – Wesley, 1976.
19. Dick De, Kendrick Je, Matson GL, Rideout VC. Measurement of non-linearity in the arterial system of the dog by a new method. Circ Res 1968; 22: 101–10.

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