PULSE SOLITONS IN BLOOD CIRCULATORY SYSTEMS

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INTRODUCTION

It is generally recognized that the nonlinear effects play important roles in blood circulatory processes (1). One of the major contributing nonlinear factors is the pulse wave itself. The amplitude of pulse waves through the arterial vessels is so significant that neither the propagation of energy nor transport of fluid through the wave action should be ignored. In this study, we propose a conceptual wave tank model to study the energy and fluid transport by means of wave propagation in combination with pressure gradient driven flow in blood circulatory systems. The concept of pulse soliton in blood vessels is proposed to describe the dynamics of blood flow. It explains how the energy and fluid propagate throughout the blood circulatory system by pulse solitons and how the pressure is accumulated. We further discuss the evidences that support the concept of pulse soliton in blood circulatory systems and derive a possible practical application.

THE MODEL

The variation of diameter from pulse wave action stores, transports, and distributes energy and blood flow in blood vessels. The heart's contraction-relaxation combined with the valve's open-closure provide energy source to push blood flow through circulatory systems. The energy from the heart is distributed to the whole circulatory system by means of static pressure buildup and dynamic wave propagation. The following conceptual wave tank model illustrates and resembles the physical process.

Consider a tank with a one-way gate at its inlet experiencing an incoming wave with significant amplitude. If there was an initial depth in the tranquil tank with a fixed level and the tank was longer than the distance over which the wave would attenuate completely, there would be a swell left along the path after the wave disappeared. The volume of the swell, no matter how insignificant it was, should be equal to the volume carried by the incident wave passing through the gate. Since the gate at the inlet end prevents fluid from flowing back, the swell would eventually disperse to flow out to the distant end of the tank given enough time to recover to its original tranquil state. If a train of such waves continuously applied to the inlet of the tank, the waves would continuously attenuate along the same path and the swell would build up as long as the depletion from the dispersion of the swell is slower than that from the accumulative volume by the incoming waves. An uninterrupted supply of such waves would cause the swell to buildup continuously so that the wave transport into the tank decreases while the dispersion of the swell or the pressure gradient driven flow increased until a dynamic equilibrium state was established. In this state, the pressure at the inlet should balance the peak pressure from the incident waves and only top peak portion of the waves would pass through the gate. The fluid transport at the inlet end of the tank should be exclusively from the wave propagation whereas at the distant end the flow from the pressure gradient by wave attenuation would prevail as shown in Figure 1. Specifically, the fluid transport by the waves at the inlet should be equal to the steady flow at the distant end of the tank. Apparently, there would be a transition along the tank between the transport through wave propagation and the pressure driven steady flow and the transition could be smooth or abrupt depends on how the waves were attenuated.

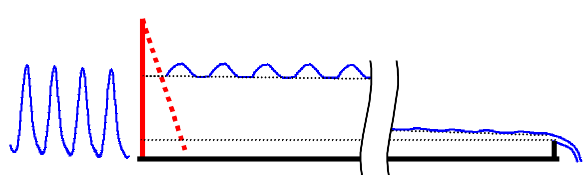

Figure 1. A conceptual wave tank model

There are two major differences between the blood circulatory systems and the above conceptual tank model. Blood vessels accumulate and release elastic potential energy instead of gravitational potential energy as in the tank. Blood vessels branch to smaller vessels. In spite of the differences, the physical features should be similar in wave propagation along with wave attenuation, pressure buildup, and energy transport and dissipation.

At the inlet end, waves not only transport fluid and energy, they also dissipate energy. Pressure gradient driven steady flow at the distant end consumes energy. The longitudinal distribution of the energy and flow is governed by wave attenuation along the path of the waves. A balanced energy transport and dissipation would be naturally achieved for any configuration of such systems described above when experiencing a continuous supply of incident waves. However, if the systems were designed such that the waves have balanced nonlinear and dispersive effects throughout the path, solitary waves would form that makes the whole flow process efficient in volume and energy transport.

Solitary waves were discovered by John Scott Russell in 1934 and has gained renewed attention known as the soliton in telecommunications since the 70th (2). A soliton has a feature of maintaining its shape over a long distance and consumes energy very efficiently, desirable for signal transmission. It is not difficult to find the similarity in pulse waves in blood circulatory in terms of maintaining the shape and minimizing the energy losses.

There are several reasons why a pulse wave in blood circulatory system can be considered as a pulse soliton. First, the nonlinear effect from the blood vessel wall distention is significant that causes the wave at the peak of the pulse travel faster than that at the trough. This is substantiated by the measurements of wave velocity during a cardiac cycle (3) and other published data. However, there has been no breaking wave reported so far (4) and the shape of the pulse waves under normal physiological conditions seem to be stable throughout the arterial systems. A plausible explanation would be that the nonlinear effect is balanced by the dispersive effect. In fact, due to the tapering and changing wall properties of blood vessels, the wave speed seems to increase as the vessels branch, as seen by shortened arrival time intervals of a pulse along the arteries (6) and other published wave speed data for different portion of arteries (4).

DISCUSSIONS

A new method for measuring blood flow is introduced according to the pulse soliton model. The arterial blood flow can be derived through the temporal diameter change and the wave speed measurements by examining the travel of a pulse soliton. In arteries, the flow by wave transport dominates and the pressure slope driven flow is negligible. A one-dimensional continuity equation for the volumetric transport of a soliton in respect to distance x and time t should be written as:

$$Q = a_w (A - A_d)$$

where A is the cross sectional area; Q is the flow rate; a_w is the wave speed; and the subscript d denote the value at the diastole. The equation indicates that the flow at a section is proportional to the increase in cross sectional area as well as the wave speed.

RESULTS

One set of diameter measurement (5) shown in Figure 2 is used to demonstrate how the method can be applied. The figure shows that the change in diameter of the ascending aorta was between 2.2 cm to 2.42 cm in a cardiac cycle. The period of the pulses is about 0.6 seconds that gives the heart rate of 100 per seconds. Both systolic and diastolic pressures of the subject are very high when the measurements were taken suggesting that the blood flow is above normal.

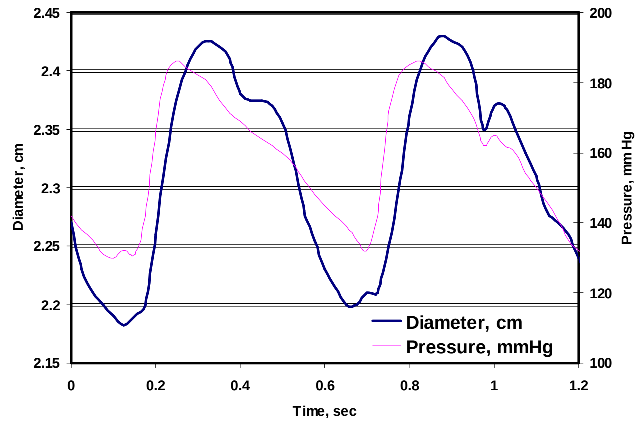

Figure 2. Measurements of Diameter and Blood Pressure (5)

The cardiac output and peak velocity can be estimated using the time series data set. Since the wave speed was not measured in this data set, the diameter and pressure measurements were used to back calculated the wave velocity, which is determined to be in the range between 4.75m/s to 5.35 m/s. Accordingly, the cardiac output of the subject at the time of measurements would have been between 15 liter/min and 16 liter/min. The results of cardiac output of the subject were apparently in the high end of normal physiological range. Apparently, further verifications of the method are necessary to substantiate the method.

REFERENCES

1. Milnor, W.R. 1989 Haemodynamics. 2nd Edition. Williams and Wilkins. Baltimore.
2. E. Infeld and G. Rowlands 1990 Nonlinear Waves, Solitons and Chaos. New York: Cambridge Univ. Press.
3. Anliker, M. and Maxwell, J.A. 1966 The dispersion of waves in blood vessels. In biomechanics (Y.C. Fung, ed.) American Society of Mechanical Engineering, New York. 47-67.
4. Fung, Y.C. 1999 Biomechanics: Circulation. Springer-Verlag New York.
5. Greenfield J.C. Jr. and Patel, D.J. 1962 Relationship between pressure and diameter in the ascending aorta of man. Circulation Research 10:778-781.
6. Olson, R.M. 1968 Aortic blood pressure and velocity as a function of time and position. J. Appl. Physiol. Vol. 24. 563-569.