Resonance

The Missing Phenomenon in Hemodynamics

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To simulate a short segment of the aorta, we studied wave propagation in an elastic tube with a side branch balloon. The small balloon simulated the organ (group of arterioles). Ligation of this side branch would reduce the moduli of the higher harmonics when the length of the side branch was appropriate. Electrical analogy of vessels was used to analyze this phenomenon. This simulation can explain the ligation results we found in rats. It may also clarify the discrepancies between the prediction of the Womersley equation and the experimental results. We suggest that the aorta and the closely attached organ can produce coupled oscillation; theoretically, this structure is equivalent to a resonance circuit. (Circulation Research 1991;69:246–249)

The pressure wave in an artery is accepted as the summation of an incident pressure wave and a series of reflected waves originating from peripheral systems.1,2 However, several phenomena in hemodynamics, such as the amplification of the high-frequency components of the pressure wave in some large arteries and the radically different shapes of the flow and pressure pulses in the ascending aorta, cannot be fully understood by current theories.

In addition, measurements conducted by Milnor and Bertram,3 Atabek et al,4 Ling et al,5 and many others found that the ratio of the reactive and resistive terms cannot be fitted by linearized equations such as the Womersley equations. All of these linearized equations greatly underestimate resistance for the small Womersley number $\alpha$ ($\alpha^2 = R_0^2 \omega^2 / \eta$, where $R$ is the radius of the vessel, $\omega$ is the angular frequency, $\rho$ is the density of the fluid, and $\eta$ is the viscosity coefficient).

Because all linearized models had essentially the same defect, there have been suggestions that the inconsistency arises from omission of the nonlinear terms in the Navier-Stokes equations.6

We have performed some experiments in rats in vivo, and the results cannot be explained by current theory either.7–9 When we temporarily clamped the left renal artery, the harmonic moduli of the pressure wave taken at the tail artery were significantly reduced. The moduli for components above and including the second harmonic fell by about 40% or more. Superior mesenteric arterial ligation created an entirely different profile; in this case, significant increases, ranging from 17% to 28%, began at the third harmonic. Ligation of the splenic artery caused a significant effect from the third harmonic and above, with decreasing moduli.

In this report, we present an additional linear phenomenon—resonance. It may solve these problems; since resonance effectively brings in a capacitance in the impedance and greatly changes the ratio of the reactive and resistive parts, it would significantly reduce the high-frequency impedance and facilitate the blood pressure wave propagation. It would also help the blood to enter the organ. Therefore, because of the resonance effect, an appropriately located organ may not increase the load of the heart, but reduce it.

Methods

The construction of the model is shown in Figure 1. An elastic tube (0.8 cm i.d., 1.1 cm o.d.) has a side branch (B) to which a small balloon (volume=1.5 cm$^3$) is connected via a hard tube (0.25 cm i.d., 0.4 cm o.d.). The length of the hard tube (X) was the experimental variable; it was varied from 2 to 100 cm. The pump (P) used to simulate the heart was a pulsatile one (Master-flex Digital unified drive from Cole-Parmer Instrument Co., Chicago). We measured the pulse with a pressure transducer (Validyne model DP103 with a frequency response of 0–1,000 Hz [Validyne Engineering Corp., Northridge, Calif.]) at position T marked in Figure 1. This system is a simulation of the experiment performed on rats described previously.7–9 The elas-
tend to decrease. There were some fluctuations in these moduli when X was changed; the variation curve usually became flat when X>30 cm. This phenomenon may be understood through the electrical power line analogy of the vessel (artery).

Theory

From Noordergraaf,\textsuperscript{10} we know that a vessel may be represented by an analogous electric circuit. The equivalent circuit of an artery tube with a side branch organ is obtained by the three steps shown in Figure 3.

The side branch with a balloon attached does not behave only as a pure reflection site; it may induce a coupled oscillation with the main tube as well. The coupling effect of the main distensible tube with the side balloon depends on the size, elasticity, and position of the balloon. When the balloon is at an appropriate distance from the main tube, the resonance property of the system enhances those harmonics in the resonance bands. This coupling will become weaker when the balloon distance X is large and the balloon will again become only a reflection site.

In an electric circuit as shown in step C of Figure 3, the impedance at frequencies \( \omega_0 = 1/\sqrt{LC} \) and \( \omega_2 = 1/\sqrt{L'C} \) will be greatly reduced, and the \( \omega_0 \) and \( \omega_2 \) are called resonance frequencies of this circuit. Because of the existence of resistance in both resonance units, the \( \omega_0 \) and \( \omega_2 \) peaks will be broadened to two bands centered at \( \omega_0 \) and \( \omega_2 \).

The transmission of a viscoelastic tube can be drawn schematically (Figure 4, sketch 1).\textsuperscript{11} (There is a cutoff in transmission at higher frequencies.) The side branch balloon introduces two resonance bands. With these two resonance bands, transmission will be increased by two broad peaks at \( \omega_0 \) and \( \omega_2 \). If \( \omega_0 \) or \( \omega_2 \) is at the higher frequency region (from our observations, \( \omega_2 \) is probably at the higher frequency region), we will see that transmission at the higher frequencies is increased because of the resonance phenomenon (sketch 2).

At strong coupling, \( C^* \), which was the compliance of the balloon, became part of the compliance of the large elastic tube. Therefore, some fluid would actually flow a round-trip through the small tube (to the balloon and then back to the large elastic tube).

The leakage resistance in \( C^* \) was about twice the resistance of the small hard tube. When the balloon was at resonance with the large elastic tube, it was easier for high-frequency components (around \( \omega_2 \)) of the pressure wave to travel along the main elastic tube without entering the small tube. Therefore, the increase of the resistance in this simulation was mainly in the low-frequency components, or small \( \alpha \) (Figure 4, sketch 3).

Discussion

An organ such as a kidney or a group of arterioles behaves like the balloon. When the distance X is appropriate, the resonance effect helps the blood
enter the organ. It also amplifies the high-frequency blood pressure waves traveling along the main artery. If we tie the side branch toward the organ (balloon), some of the high-frequency components are reduced significantly. If we release it, the amplitudes of these high frequencies return to their normal values. This

**Figure 2.** Top panel: The changes in the difference in harmonic proportions with and without the side branch balloon as a function of the side branch tube length (X) are illustrated. \( C_n \) is the \( n \)th harmonic modulus normalized by the modulus of the 0th harmonic; that is, \( C_n = \left( \frac{\text{nth harmonic modulus}}{\text{0th harmonic modulus}} \right) \times 100\% \). Difference of \( C_n = \left( C_n \text{ without the side branch} - C_n \text{ with the side branch} \right) \times 100\% \). With a side branch length less than 10 cm, the attached balloon is similar to the addition of a capacitance. It decreases the low-frequency \( C_n \) and increases the high-frequency \( C_n \); at \( X=10 \) cm the effect is most profound. Bottom panel: The pulse shape for \( X=10 \) cm.

**Figure 3.** Equivalent circuit of an artery tube with a side branch organ obtained by three steps. In step A, a uniform vessel behaves like a low-pass filter. A side branch organ can be treated in the same way (step B). Because of the property of linearity, the analogous representation of the artery tube with a side branch organ is a linear combination of the two (step C). \( L \), equivalent inductance of the uniform vessel; \( C \), equivalent capacitance of the uniform vessel; \( L^* \), equivalent inductance of the side branch organ; \( C^* \), equivalent capacitance of the side branch organ; \( R \), resistance.
is the result we found in the rat kidney experiments and our balloon simulation (Table 1).

In the physical model simulation experiment, we found that variation of the static pressure applied to the system strongly affects the resonance condition. There was also an optimal distance between the attached balloon and the main tube. In this construction it was about 10 cm (Figure 2).

Resonance is very important to high-frequency blood pressure wave propagation; therefore, the diastolic pressure, the position of the attached organ, and the physical properties of the attached organ, all of which influence the resonance condition, are important factors in blood pressure wave propagation.

The effect from the ligation of the mesenteric artery may be explained by reflection, because no organs are closely attached to the aorta by the mesenteric artery. This is similar to a side branch with a large distance where resonance is not so important.

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KEY WORDS • resonance • Womersley • organ • couple
Resonance. The missing phenomenon in hemodynamics.
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doi: 10.1161/01.RES.69.1.246

*Circulation Research* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1991 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/69/1/246

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