Received: 24 September 2018 | Accepted: 12 October 2018

DOI: 10.1111/apha.13206

EDITORIAL

ACTA PHYSIOLOGICA

Did you know how the cardiovascular system achieves its high efficiency as a compound irrigation device and why this is relevant to future cardiovascular studies

Historically, some important concepts that help explain the power saving character of the circulatory system have been raised. About 2000 years ago, Greek physician Galen surmised that the arterial pulse propagates directly through the tunics of the arteries. Otto Frank first proposed arterial resonance in 1899. In the introduction of the second edition of McDonald's book,[1] it was stated: “The main developments since 1950 have been in terms of treating the whole arterial system as being in a steady-state oscillation produced by the regularly repeated beat of the heart.” However, these three important findings are neglected in the prevailing hemodynamic models.

Since Euler, most hemodynamic studies have been based on equations associated with the axial motion of the blood; these equations have high dissipation character due to the viscosity of the fluid. The arterial pulse is often described as a transient travelling wave induced by a single heartbeat. The factor of arterial resonance in solving the equations was ignored or unable to be considered since resonance is feasible only for a low dissipative coupled oscillatory system that can reach a steady state by the accumulation result of the repeated inputs.

We have constructed a hemodynamic model containing the three concepts proposed by Galen, Frank and McDonald to describe the ventricular-arterial (VA) system. The VA system was considered to be a compound irrigation device[2] rather than a single flow system. We decomposed it into subsystems with specific ranks and mechanisms.[3] The ventricular power output is first carried by the ejected blood; but after the aortic arch, the arterial wall becomes the primary power carrier and the arterial radial oscillatory motion was governed by a low dissipative PR wave equation.[4] Only in microcirculations, does the blood regain the role of power carrier.

To find the accumulative effect of repeated heartbeats, we[5] do not treat the arterial pulse as a travelling wave, but instead solve the PR wave equation by the Bernoulli's oscillatory method.[6] The solution for the distributed steady-state oscillation of an artery was then used to define two frequency matching rules quantitatively and to analyse how aortic resonance and organ resonance can enhance the efficiency of the VA system.[3,7] Animal[8] and tube simulation[9] experiments were performed to manifest the arterial resonance.

Why is arterial resonance so important? Arterial resonance plays a key role in the high efficiency of the VA system, which uses less than two watts of power to maintain systemic blood circulation. Through arterial resonance, the VA system can quickly reach a steady state. Thereafter, only a small amount of power input is needed to supplement the energy consumed in the viscosity, and the heart no longer needs to initiate the distributed radial oscillation along the whole arterial system, or provide further power to alter existing conservative mechanical energy. This power saving phenomenon is quite similar to push a swing by a small force with the period coinciding with the natural frequency of the swing.

The pulsating input force provided by the left ventricle can be decomposed into various harmonic forces with frequencies to be integer multiples of the heart rate. When the frequency of each harmonic force can coincidence with one of the natural frequencies of the aortic system, the response aortic pulse will be maximized, we call it optimal aortic resonance.

The entire aorta is coupled together as an oscillatory system by the large longitudinal tension in vivo.[10] For a healthy person, the mean arterial pressure is about 100 mm Hg, which makes gravitational force negligible and allows the arteries to maintain circular cross-section in normal body postures. With the rotational symmetry of the aorta, the PR wave equation becomes just as a one-dimensional transverse string wave equation with large longitudinal tension.[4] Hence, the aorta can be described as a one-dimensional oscillator with natural frequencies to be integer multiples of its fundamental frequency.[3]

To achieve power saving through optimal aortic resonance, one should maintain both a stable heartbeat and a good posture that can retain the proper longitudinal stretching and the rotational symmetry along the entire aorta. This hemodynamic model which includes the three missing concepts is realistic and can explain many physiological facts[7,11] such as the similarity of mammalian anatomy; we suggest that it is essential to incorporate this model into future cardiovascular studies.

https://doi.org/10.1111/apha.13206

CONFLICT OF INTEREST

None.

ORCID

Yuh-Ying Lin Wang http://orcid.org/0000-0001-8019-4885

Yuh-Ying Lin Wang[1]
Wei-Kung Wang[2]
[1]*Department of Physics, National Taiwan Normal University, Taipei, Taiwan*
[2]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
Email: yuhying@ntnu.edu.tw

REFERENCES

1. McDonald DA. *Blood flow in arteries*. Arnold, London: Edw; 1974.
2. Lin Wang YY, Wang WK. Why the cardiovascular studies should start with the radial oscillation of arterial wall rather than from axial flow motion of blood. *Int J Cardiol*. 2018. https://doi.org/10.1016/j.ijcard.2018.06.019.
3. Lin Wang YY, Wang WK. A hemodynamics model to study the collective behavior of the ventricular-arterial system. *J Appl Phys*. 2013;113(2):024702.
4. Lin Wang YY, Wang WK. PR wave equation - a primary and realistic arterial pressure wave equation for quantitative and collective study of the cardiovascular system. *Chin J Phys*. 2014;52(2):916-926.
5. Lin Wang YY, Sze WK, Bau JG, et al. The ventricular-arterial coupling system can be analyzed by the eigenwave modes of the whole arterial system. *Appl Phys Lett*. 2008;92(15):153901.
6. Migulin VV, ed. *Basic Theory of Oscillations*. Mir Publishers: Moscow; 1983:320.
7. Lin Wang YY, Wang WK. From a basic principle of evolution to the heart rate of mammals. *J Physiol*. 2015;593(9):2241-2242.
8. Lin Wang YY, Chang SL, Wu YE, Hsu TL, Wang WK. Resonance. The missing phenomenon in hemodynamics. *Circ Res*. 1991;69(1):246-249.
9. Wang Y, Sze WK, Lin CC, et al. Examining the response pressure along a fluid-filled elastic tube to comprehend Frank's arterial resonance model. *J Biomech*. 2015;48(6):907-910.
10. Han HH, Fung YC. Longitudinal strain of canine and porcine aortas. *J Biomech*. 1995;28(5):637-641.
11. Lin Wang YY, Wang WK. Anatomy of arterial systems reveals that the major function of the heart is not to emit waves associated with the axial blood motion. *J Physiol*. 2014;592:409-409.