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STRUCTURAL ASYMMETRY AND THE OPTIMISATION OF TRANSPORT FUNCTION IN THE CIRCULATION. REVIEW

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A b s t r a c t

The question of symmetry and asymmetry plays an important role in physics, physical chemistry as well as physiology. During both the ontogenetic and the phylogenetic development, the structure of the heart and vascular system begins to function as a symmetric line with symmetric branching. At the later and more developed stages of phylogeny and ontogeny, the cardiovascular system becomes more asymmetric. It seems that the effects of blood mixing may also be involved in the process of optimisation. Finally, we suggest that the so-called Liebau effect may be involved in improving vascular fluid transport.

K e y w o r d s

Structural asymmetry, Functional asymmetry, Optimisation of transport, Function of circulation

INTRODUCTION

This paper intends to direct attention to the question of symmetry and asymmetry in physiology and pathophysiology. Symmetries, conditions of symmetry and so-called breaks of symmetry have been studied and discussed much more in physics and chemistry than in physiology, as can be found in the excellent review by *Mainzer* (*1*). As everybody knows „the heart is on the left side of the body". This fact indicates that asymmetry is particularly obvious in the mammalian circulation. During both the ontogenetic and phylogenetic development, the structure of the heart and vascular system begins to function as a symmetric line with symmetric branching. At the later and more developed stages of phylogeny and ontogeny, the cardiovascular system becomes more asymmetric, as reported in our previous work (*2*). *Kilner et al.* (*3*) have published an interesting paper on „asymmetric redirection" of flow through the heart.

There are many ways of how to optimise the function of the cardiovascular system. Of course, it cannot be denied that many ideas about optimisation are just conjectures or some kinds of educated guesses. It is a fact that, besides the heart, additional pumps help to propel blood in a certain direction. If animals of different sizes are compared, proof of optimal function clearly appears from the rules of similarity. Finally, there seems to be a correlation between a high quality of transport function and the degree of asymmetry. One reason for this was known as early as in the 19th century. The pumping effect of the mechanism of the moving plane of valves („Ventilebenenmechanismus“) is well descibed in the article by *Boehme* (*4*). A theoretical model was presented by *Krasny et al.* (*5*). A related mechanism is based on the long axis contraction of the heart and the problem of cylindricality (*6*). These mechanisms are only possible due to the asymmetric, folded and twisted configuration of the heart. It is less clear why, apparently, all highly-efficient fast moving animals have an asymmetric one-sided aorta. It seems that effects of blood mixing may also be involved in the process of optimisation. Finally, we suggest that the so-called Liebau effect may be involved in improving vascular fluid transport, as reported in our recent paper (*7*).

Physiological asymmetry

The word symmetry describes a special morphological and functional condition in physics, chemistry and biology. In both everyday physiology and medical practice, the normal left-to-right symmetry, e.g., that of face and body, has slight deviations which, a at brief glance, are scarcely or not at all recognised. However, more marked deviations such as anisokoria or unequal width of the pupillae are immediately recognised by any observer. From the medical viewpoint the recognition of a marked external asymmetry may be of diagnostic or pathologic significance.

As far as internal organs or systems are concerned, in each normal person there are well known asymmetries. In particular, the anatomical asymmetry of the heart and large arteries and its functional significance will be considered here. Furthermore, asymmetries of the time course of oscillatory functions will be discussed.

The development of cardiovascular asymmetry

In the first weeks of embryonic life, the heart and vascular system are a lateral-symmetric system of elastic and contractile tubes. As shown by *Moore* (*8*) this system is still lateral-symmetric at 35 days of embryonic life. Therefore, contractions of the heart chambers (the heart at that time is situated between the veins and aorta) must occur mainly in a circumferential direction.

As will be discussed below, asymmetry exists in the sense of direction of blood flow from more distensible veins to less distensible arteries. This is a condition as well as a consequence of unidirectional pumping (*9*) that, at this early time of development, is generated without valves.

During this early period of development, the contractile part of tubes, i.e., the early structural state of the heart, folds and twists in a rather complex manner. The aortic-arterial outflow system divides, giving rise to a double outflow aorta and a pulmonary artery. Furthermore, the aorta becomes asymmetric because, from

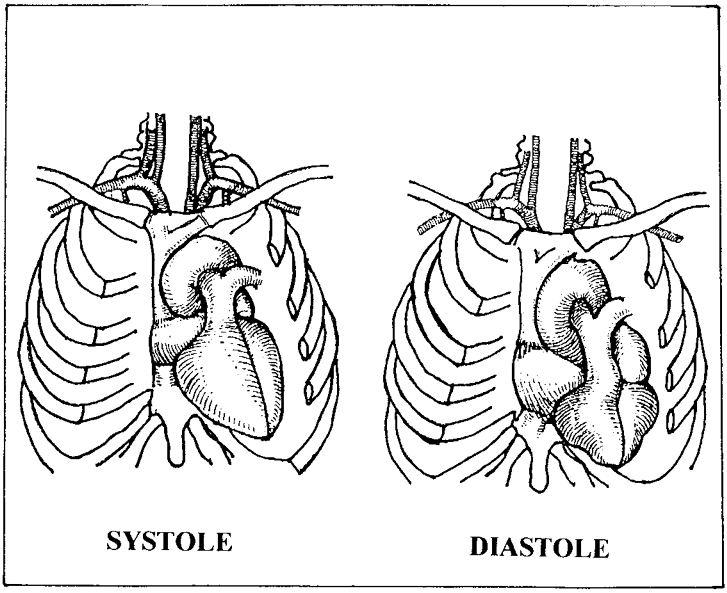

Fig.1
A schematical drawing that shows movement of the plane of the valves. It was first drawn by the anatomist Henke in 1872 and later published by *Boehme* (*1*).

the former symmetric double arch, only the left arch is completely retained. Finally, the left and right pumps are positioned side by side. All these developmental processes are completed before 49 days of embryonic life (*8*). Therefore, the two chambers of the heart are then able to contract in both the circumferential and the lengthwise direction. As indicated in the schematic drawing by Henke from 1872, reproduced in the article by *Boehme* (*4*) and is presented in *Fig. 1*, both ventricles shorten during systole. By this shortening, the atria are extended. From that it follows that, during ventricular ejection, the atria are filled from the veins. This mechanism, which is well described in most of the textbooks on physiology, is called the mechanism of the moving plane of valves (in German it is „Ventilebenenmechanismus“). In the English literature, the longitudinal shortening of ventricles has recently been included in the term long-axis dynamics of the heart (*6*).

Valveless pumping, the Liebau effect

Liebau was a practitioner who was interested in physical curiosities. He published several papers and formulated patents on the principle of valveless pumping (*9*). There are essential conditions for this effect (*7,10*). The first main condition is an energy source. The second condition is a structural asymmetry. An example of a model of the Liebau effect is a circular tube, half of which is made of a rigid tube. The other half is made of a distensible rubber tube. If the distensible tube is compressed periodically (with a finger) in an asymmetric location, fluid moves into the direction of the more closely located rigid tube.

Another model is a straight elastic tube that consists of a wider and of a narrower part. Compression of the wider part of the tube moves fluid in the direction of the narrower (i.e., stiffer) part of the tube. This model was especially studied by Liebau himself and was, as an example of the effectiveness of the mechanism, drawn in one of his patent applications. This model appears to be a possible mechanism of valveless pumping of the early embryonic heart.

Asymmetry of the time course

The time course of biological (input) functions has a marked influence on the output, the effect, the used or generated energy, etc. The term symmetry of the time course is used in a sense that a function $f(T - t) = f(t)$, $t=0$ to $t= T/2$. This description means that the second part of the function $f(t)$ from $t = T/2$ to $t = T$ is a mirror image of the first part from $t = 0$ to $t = T/2$. A half sinus is an example of such a function.

As far as functions in the circulation are concerned, the function describing the ejection of blood from the left ventricle into the aorta is an interesting example of asymmetry. The normal ejection function starts from zero with a steep increase in flow and, from the peak, decreases with a slow declining slope that, in a typical normal example, has a small bump. Kenner and Pfeiffer (*11*) have adapted the contour of ventricular ejection to a “windkessel” model under the condition that, given a certain stroke volume, the energy output of the heart should be minimised. As can be seen from examples in *Fig. 2*, the result of this calculation is fully in agreement with the well known contour of the normal central aortic flow pulse. It can be concluded that the optimal ejection flow is markedly asymmetric.

Conclusions

In addition to the symmetries described, there are still other symmetries and asymmetries that may be important in biological systems. One kind of symmetry is related to periodic functions. One complete 360° cycle of a sinus function can be described by $f(T\text{-}t) = - f(t)$, where T is one period. This means that the second part of the cycle is the inverted mirror image of the first part. In fact, many periodic cycles are not symmetric in the defined sense. The cardiac cycle has a shorter systole and a longer diastole. In respiration, inspiration is shorter than expiration. Finally, in circadian cycles, the night part of the daily period is usually shorter than the day part. Under pathologic conditions, the contour of the function may also acquire a more asymmetric shape.

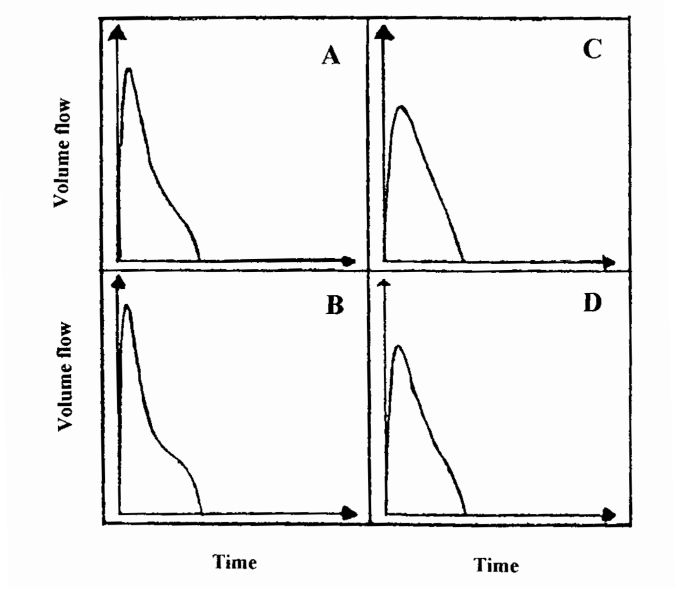

Fig. 2

Four examples of calculated left ventricular ejection flow pulses. In C and D, the compliance of the aortic „windkessel" is twice as high as that in A and B. Peripheral resistance is 1.66–times higher in A and C than resistance in B and D. The calculation is made under the assumption that, in all examples, the same stroke volume is ejected and, in each example, the energy output of the ventricle is minimised (from *Kenner* and *Pfeiffer*; *11*).

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STRUKTURÁLNÍ ASYMETRIE A OPTIMALIZACE TRANSPORTNÍ FUNKCE V OBĚHU

S o u h r n

Otázka symetrie a asymetrie hraje důležitou roli stejně tak ve fyzice, ve fyzikální chemii jako ve fyziologii. Během ontogenetického i fylogenetického vývoje začíná struktura srdce a vaskulárního systému fungovat jako symetrická linie se symetrickými odbočkami. V pozdějších a vyvinutějších stádiích fylogeneze a ontogeneze se kardiovaskulární systém stává asymetričtějším. Zdá se, že v procesu optimalizace může hrát roli i vliv mísení krve. Konečně se domníváme, že ve zlepšování vaskulárního transportu tekutiny se může projevovat tak zvaný efekt Liebau.

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