THE LIEBAU-EFFECT OR ON THE OPTIMAL USE OF ENERGY FOR THE CIRCULATION OF BLOOD

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A b s t r a c t

Using simple physical and mathematical models we studied the possible role of asymmetry of the cardiovascular system which evolves in early embryonic life. During this phase of life blood circulates in one direction through the system in spite of the complete lack of valves. In our model we were able to show that asymmetry is a precaution for a valveless pumping function of the heart. Besides that it can be shown that the system has to have compliant components. In addition it can be shown that the properties of the pump play an important role: an asymmetric flow source may have different effects than an asymmetric pressure source. An asymmetry of the time source of the pump action may, in addition, have an effect on the effectivity of the pump and on the direction of generated flow. Experiments and model stimulation show that synchronisation between related functions – like the different principles of pumping or like heart beat and respiration- serve the optimization of these functions.

INTRODUCTION

G. Liebau throughout his life was fascinated by the idea that valveless generation of unidirectional flow may play a role in the cardiovascular system (*2*). In fact, it is known that a valveless circulation can be found in Amphioxus and also in early stages of human embryonic life. A summary of earlier literature and of examples and models of valveless fluid propagation was published recently by *Moser et al. (3).* In addition *Kenner et al.* (*1*) and *Tanev et al.* (*4*) have, in scientific meetings, contributed additional information and considerations about modelling of valveless flow.

METHODS

The model

The simplest model, which can be used for the demonstration of valveless unidirectional flow, consists of a water-filled circular tube as shown in *Fig. 1 - (3)*. The upper half of the model is a rigid glass tube. For the other half a flexible and distensible rubber is used.

In our real physical model a Penrose rubber was used. The distensibility is indicated in *Fig. 1* by the outward pointing arrows.

If this tube is compressed rhythmically by a finger at an asymmetric location (arrows at the left side) then the fluid moves in clockwise direction.

If the tube is compressed in the same manner in the symmetric middle of the distensible tube, then no net movement of the fluid can be observed.

If the tube is rhythmically compressed at the right side, net movement starts in counterclockwise direction.

Using simple physical and mathematical models we studied the possible role of asymmetry of the cardiovascular system evolves in early embryonic life. During this phase of life blood circulates in one direction through the system in spite of the complete lack of valves. In our model we were able to show that asymmetry is a precaution for a valveless pumping function of the heart. Beside that it can be shown that the system has to have compliant components. In addition it can be shown that the properties of the pump play an important role: an asymmetric flow source may have different effects then an asymmetric pressure source. An asymmetry of the time course of the pump action may, in addition, have an effect on the effectivity of the pump and an on the direction of generated flow. Experiments and model stimulations show that synchronisation between related functions - like the different principles of pumping or like heart beat and respiration - serve the optimisation of these functions.

RESULTS

An explanation of the pump action

This simple and impressive experiment which, in different modifications, has already been performed by *G. Liebau* himself (*2*), raises the following questions:

1) What are the conditions for unidirectional net motion of fluid?

2) What determines the direction of fluid movement?

3) Is there a possibility that valveless pumping actually may play a role in a living organism?

Ad 1) The observation of the function of the model shown in *Fig. 1* indicates: there must be a source of energy, i.e. a mechanism, which acts as a pump. The tube system must consist of at least two components, which can be described by three parameters: compliance, resistance and inertance. In order to generate net fluid movement the relation between these components and the „pump“ has to be asymmetric.

Ad 2) As discussed by *Kenner et al.* (*1)* and by *Tanev et al.* (*4*) the properties of the pump in relation to the properties of the tubing system play an essential role for the answer to this second question.

DISCUSSION

Wetterer and *Kenner* (*5*) have analysed and explained the difference between a low resistance pressure pump and a high resistance flow pump. As an interesting example of a pump which changes its property during periodic activity the behaviour of the so-called Moen's opening wave and closing wave in an elastic
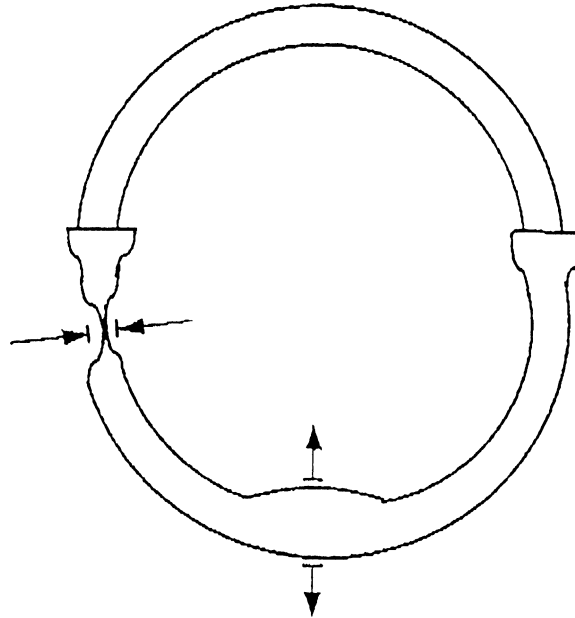
fluid filled tube, which is connected to a constant pressure reservoir, was described. The opening wave is generated by the opening of a valve between reservoir and tube. Therefore, the open reservoir acts as a low resistance pressure pump. After closure of the valve the resistance at the location of the valve becomes infinite.

Although there is no more actual pumping activity, in terms of action on the reflected pressure waves in the elastic tube the closed valve acts as a high resistance location.

This example indicates that quite simple circumstances are able to change the properties of a pump from low resistance pressure source to high resistance flow source and, thus, gives rise to an asymmetry of the time course of the pumping activity.

Under the assumption that, as soon as the local compression by the finger starts, a short and symmetric pressure impulse is generated that acts equally in both directions. During this phase the compressed site of the tube acts as a low resistance pressure pump. This phase of pumping is indicated in the upper part of *Fig. 2*. It is easy to understand that the direction of a net volume displacement depends on the impedance of the adjacent tube segments.
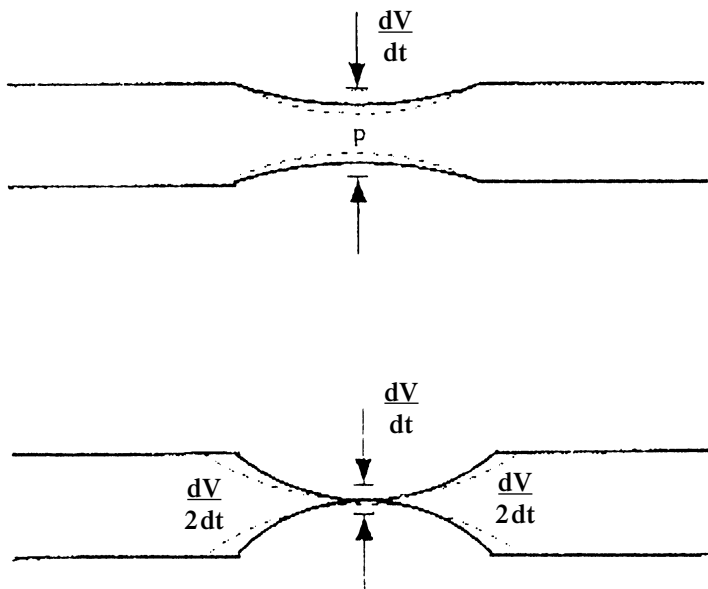
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Fig. 2

The figure demonstrates that at the beginning of the constriction of the elastic tube, the location acts as a low resistance pressure source (p, in the upper part of the figure). As soon as the folds touch, the further compression of the tube leads to the generation of a high resistance flow source, as indicated in the lower part of the figure. This sequence of events is essential for the explanation of the Liebau effect.

In contrast, we can assume, that the further strong and complete compression, as shown in the lower part of *Fig. 2,* generates a more or less symmetric flow pulse. Thus, the compressed site now acts as a high resistance flow pump. It follows that now the same flow, and therefore, the same volume, is pressed in both directions of the compression.

In summary, it can be assumed that during the compression of an elastic tube there is the following sequence of events: in the first instant of compression the „pump" acts as a symmetric pressure source. As soon as the two folds of the compressed tube touch each other, the „pump" changes its property into a symmetric flow source. From the observation of the movements it can be said that the latter part of pump activity plays a more prominent role in the generation of net unidirectional fluid movement.

Immediately after the subsequent release of the compression the pressures on both sides of the „pump" equalise. It appears then, that the backward flow through the tube with the higher inertance starts slower than the forward flow from the more compliant tube with smaller inertance.

The fact that the model system contains elements with compliance and elements with resistance and inertance explains that the following compression and release damped oscillations appear in the tube.

The essential functional asymmetry happens during the compression phase when the second - flow generating - part of the stroke pushes the fluid with force into the part of the tube with high inertance.

In other words: As found in the physical model our simple reasoning indicates that compression of the model in the location at the left side of *Fig. 1* will generate a net flow in clockwise direction.

Ad 3) There are two main final statements.

The physical model, at first chosen by *Moser et al.* (*3*) to analyze the *Liebau* phenomenon, actually demonstrates the fact that in an asymmetric system a net flow can be generated by an asymmetric pump. b) *Tanev et al.* (*4*) have observed the fact that the property (internal resistance) of the „pump" not only changes from compression to release but also during each of both phases. There is, in addition, an asymmetry of function and time course, in particular, if the sequence of compression and release is considered.

There is no question that other asymmetries, including nonlinearities of the system may also add to unidirectional flow effects. Nonlinearities may even play a prominent role.

The overall efficiency of this type of pumping has been estimated by *Moser et al.* (*3*) in comparison of a system without valves and a system with valves. The unidirectional flow without valves in average is less than half compared to the flow generated with valves, in a model of the kind shown in *Fig. 1*.

CONCLUSIONS

In spite of the disadvantage of a rather small efficiency, the Liebau phenomenon of valveless unidirectional flow might well serve as a source of flow in the embryonic circulation or in other valveless biological flow systems, or may act as an additional energy source for a flow in the adult circulation. Therefore, the Liebau effect acts as a contribution to the optimal use of energy in the cardiovascular system.

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OPTIMÁLNÍ VYUŽITÍ ENERGIE KREVNÍM OBĚHEM: LIEBAU-EFEKT

S o u h r n

Za použití jednoduchých fyzikálních a matematických modelů jsme studovali možnou úlohu asymetrie kardiovaskulárního systému, který se vyvíjí v raném embryonálním stadiu života. Během této fáze života krev cirkuluje systémem v jednom směru navzdory kompletní nepřítomnosti chlopně. V našem modelu jsme mohli ukázat, že asymetrie je předpokladem pro čerpací funkci

srdce v nepřítomnosti chlopně. Kromě toho je možno ukázat, že systém musí mít komponenty compliance. Dále je možno ukázat, že vlastnosti pumpy hrají důležitou roli: zdroj asymetrického proudu může mít odlišné účinky než zdroj asymetrického tlaku. Asymetrie časového zdroje činnosti pumpy může kromě toho působit na účinnost pumpy a na směr vytvářeného proudu. Experimenty a modelové stimulace ukazují, že synchronizace mezi spřaženými funkcemi - jako odlišné principy čerpání nebo jako srdeční tepy a dýchání- slouží k optimalizaci těchto funkcí.

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