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IMPEDANCE DEFINED FLOW
GENERALISATION OF WILLIAM HARVEY'S CONCEPT OF THE CIRCULATION - 370 YEARS LATER

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ABSTRACT

William Harvey (1628) attributed the flow of blood through the cardiovascular system to the heart, providing the energy, and to its valves, ensuring the preferential direction of flow. This report presents a flow generating mechanism free of valves, dubbed impedance defined flow. Nature offers examples where impedance defined flow appears to be the sole perfusion mechanism. These include the human foetus by the end of the third week of gestation. It is proposed that addition of valves in specific locations is a later development in evolution and amounts to a special case of impedance defined flow, a suggestion that may profoundly impact our current concept of the circulation. © *1998 Medical and Engineering Publishers, Inc.*

INTRODUCTION

In the Galenic (Galenus of Pergamon, 131-201 AD) theory of the cardiovascular system, blood is formed in the liver and distributed by the veins to nourish all parts of the body. The heart plays a secondary role by drawing a fraction of this venous blood into the right ventricle through its active dilatation. Some of this blood is forced into the pulmonary artery through contraction of the thorax, and some penetrates into the left ventricle via pores in the intraventricular septum. The blood in the left ventricle acquires air from the lungs transported via the pulmonary vein. Blood endowed with air is distributed throughout the body by the arteries, it being drawn from the left ventricle by the pulsatile properties of the arteries [18]. Galenus's exposition was found so lucid and so convincing that, in spite of sporadic criticism, it endured until Harvey (1579-1657).

***Key Words**: Circulation, cardiac valves, impedance defined flow, cardiogenesis*

William Harvey [7] made the heart, consisting of two pumps in series, the exclusive organ that propels blood around a closed circuit. In Harvey's, as well as in contemporary teaching, there is average flow around this circuit with superimposed pulsations, the occurrence of the average component being attributed to the presence of four valves in the heart.

For more than a century, it has been occasionally argued that the heart alone is not capable of sustaining the necessary pumping, but that it is assisted. Thus, Weber [24] stated as early as 1834 that there are other forces (than from the heart) that help support the circulation. Donders proposed in 1856 that the "respiratory pump" assists the circulation of blood through a valveless mechanism [4], an idea that was debated for decades. Ozanam [19] argued the validity of his "law of the circulation by influence" before the (French) Academy of Science by claiming that, on the basis of his experimental observations, pulsating arteries can induce valveless flow in their companion veins.

Liebau [14] argued in favor of valveless flow generation by demonstrating its occurrence in fluid-mechanical models. At first, utilizing an open system as shown in Fig. 1, he demonstrated that periodic compression at the arrows caused outflow at the top, while no compression produced no flow. Proceeding to a closed fluid-filled system (reconstructed and shown in Fig.2A-C) Liebau [13] showed that periodic compression at the location of the fingers in Fig.2A produced pulsatile as well as average clockwise flow in this circuit. Compression at the location of the fingers in Fig.2C reversed the direction of the average flow component, while periodic compression at the point of symmetry generated no average flow (Fig.2B).

In spite of Liebau's long term devotion and his suggestion of several features as playing a role in creating valveless flow, e. g. different elastic properties of the two tubes in Fig. 2, as well as inertial and viscous effects of the fluid [12], he was never able to offer an interpretation of why, and under what conditions, average flow could be generated. Consequently, even viewers of such an operating model reported not to be relieved of their doubts. The basic question remained, why the average value of flow should not be zero when fluid, displaced by compression, could escape in two directions and, upon relaxation, could return from those two directions.

The goal of this report is to identify the responsible mechanism and the conditions under which this mechanism operates.

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EXPERIMENTAL AND THEORETICAL STUDIES

1) A fluid mechanical model demonstrating valveless flow can be easily constructed. A length of glass tubing (for example a semicircular Pyrex glass tube, diameter 15 mm, and a rubber tube (Penrose drainage tubing, diameter 15 mm)), can be fitted together to form a closed loop (diameter 203 mm, Fig. 2). The model is filled with water and a particle of styrofoam is added to visualize flow. All air can be replaced by filling glass tube and rubber tube and connecting them below the surface of a water filled reservoir. The model is operated by rhythmic quick compression and release at a point close to either end of the rubber tube (Fig. 2A, C). The experiment shows clockwise or counterclockwise flow confirming Liebau's claim [13]. Compression at the point of symmetry generates no average flow (Fig. 2B).

2) A conceptually even simpler fluid filled model, free of valves, is drawn in Fig. 3a. In this model two rigid tubes, one narrow (subscript 1) and one wide [2], are connected via distensible reservoirs C_0 and C_1. Reservoir C_0 is periodically compressed and released. For the sake of clarity of the mathematical equations, it will be assumed that channel 1 is narrow enough and channel 2 is wide enough to neglect fluid inertia and fluid friction, respectively. With these assumptions, Fig. 3b depicts Fig. 3a in electrical symbolism. The equations describing pressures (p) and flows (Q) in either loop are during compression of reservoir C_0,

$$Q_0(t) = Q_1(t) + Q_2(t) \tag{1a}$$

$$p_0(t) - p_1(t) = R_1 Q_1(t) \tag{2}$$

$$p_0(t) - p_1(t) = L_2 dQ_2(t)/dt \tag{3}$$

$$Q_1(t) + Q_2(t) = C_1 dp_1(t)/dt \tag{4}$$

When reservoir C_0 is not compressed, eq. (1a) is replaced by

$$Q_1(t) + Q_2(t) = -\, C_0 dp_0(t)/dt \tag{1b}$$

The other equations remain unchanged. The coefficients (parameters) C_0 and C_1 denote the distensible properties of the reservoirs, R_1, the flow resistance of channel 1 and L_2 the inertia of the fluid in channel 2. Both flows and pressures are functions of time t.

With suitable initial conditions and parameter values, both sets of four equations can be solved for the four unknowns: two pressures (p_0 and p_1) and two flows (Q_1 and Q_2). The two volumes, V_0 and V_1, in the reservoirs can be computed from the flows. Applying the parameter values and initial conditions, defined in Fig. 3, the left column of Fig. 4A depicts steady state solutions for the flows through the channels and for pressures and volumes in the reservoirs when C_0 is compressed and relaxed at a rate of 1 Hz. Average flow in clockwise direction is in evidence, but seen more clearly in Fig. 4B (dots). Average flow is a function of the frequency of compression and may reverse direction. Average flow also depends on parameter values (not shown).

In the case of a single compression (Fig. 4A, central column), both reservoirs regain their original volumes eventually (roughly in 2 sec. in the illustrated case). For periodic compressions, there may not be sufficient time for this to occur. Fig. 4C (dots) depicts the volume in reservoir C_0 at the end of the refilling period versus frequency of compression.

Figure 4D shows the efficiency of this system in generating average flow around the loop in Fig. 3. For this purpose, efficiency is defined as the ratio between average flow around the circuit $\bar{Q}_1$ (equal to $-\bar{Q}_2$) normalised by dividing this value by the average value of flow exiting reservoir C_0 as a consequence of it being compressed ($\bar{Q}_0$). The dots indicate an efficiency of around 25% in the lower frequency range.

3) There is an alternative way to generate average flow in the fluid-mechanical model depicted in Fig.2: Instead of compressing the rubber tube in the proximity of either end, the model, fixed to a support, was shaken in its own plane. First, in a direction parallel to the line connecting the points where rubber and glass meet. The model was accelerated and decelerated rapidly and periodically. This resulted in average flow around the circuit. Similar shaking in the direction perpendicular to the first yielded no average flow (not illustrated).

4) An excised segment of bovine thoracic aorta (circa 20 cm in length) was suspended horizontally in a water-filled bath about 10 cm below the surface. The segment was open at both ends and fluid-filled. Periodic compression and relaxation with a selected frequency at an asymmetric proximal site generated average flow in the distal direction through the segment (made visible by inserting a blue dye into the segment). Mathematical analysis of this experiment required treatment of the longer and shorter parts of the segment as two parallel transmission lines. The analysis shows that average flow in the distal direction is generated only at particular frequencies of compression.

DISCUSSION

Analysis of the 4 cases described in the preceding section leads to the conclusion that three conditions must be satisfied if average flow around the circuit is to be generated. These conditions are:

Condition One. Energy must be provided to the system to move the fluid. If no energy is applied, no flow will occur. It turns out that the shape of the energy pulse is critical for the efficiency of the system. Short duration rapid ejection followed by a relatively long relaxation period, appears advantageous.

Condition Two. The circuit must contain a compliant reservoir to allow for storage of the displaced fluid. If no compliant reservoir is available, no storage can occur, owing to the incompressibility of the fluid.

Condition Three. The impedance in the two pathways, Z_1 and Z_2 of the system must be different and at least one of the two must be a complex number. If both are complex numbers, their phases must be different. Where this is not the case the displaced volume through either branch will be equal to the volume returned through that branch, and no average flow will occur. At the point of symmetry, both branches have equal impedance and no average flow can be observed (Fig 2B).

Where all three conditions are satisfied, referring to Fig. 3 and Fig. 4A (left column), compression of reservoir C_0 allows ejected flow to reach reservoir C_1 preferentially through one branch (#1, in this case). During the relaxed phase of C_0 when fluid shifts back from C_1 to C_0, flow occurs preferentially through the other branch (#2 in this case), resulting in average flow (clockwise in this case). Since impedance plays a critical role, the principle will be called impedance-defined flow.

A few earlier investigators have attempted interpretation of Liebau's findings by invoking fluid-dynamics principles [15, 23]. They took as their point of departure Liebau's suggestions in combination with a displacement pump, focused on pressure changes, and failed to arrive at the three conditions developed above.

Evolutionary Aspects

Among the wide diversity of invertebrates and some vertebrates, species with valveless circulatory systems can be found, although valves are common in most species [21] Two especially interesting examples of valveless circulations are found in the Tunicates, primitive settled sea animals which switch the direction of flow in

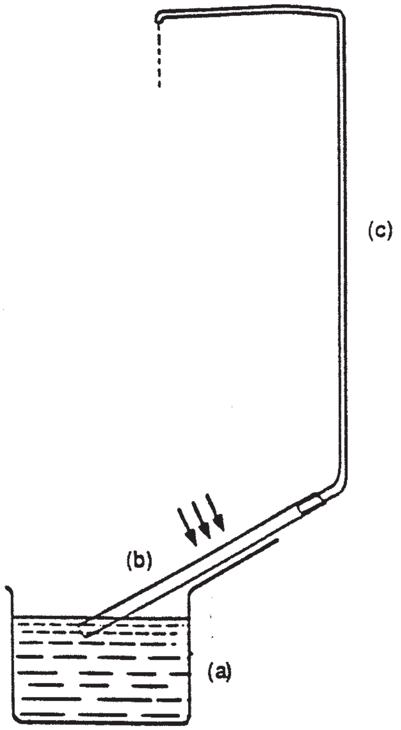


FIGURE. 1

Water reservoir (a), with a rubber tube, length 40 cm, diameter 1 cm (b), partially immersed, and a rubber tube, length 100 cm, diameter 0.2 cm (c) in a vertical plane. In the resting state the water level in the tubes coincides with the water level in the reservoir, but periodic compression of the wider tube at the location of the arrows will gradually fill both tubes with water, eventually causing water to flow out at the upper end of the narrower tube [14].

their circulatory system, and in Amphioxus, a small fishlike relic which is thought to represent an ancestor of the whole vertebrate branch.

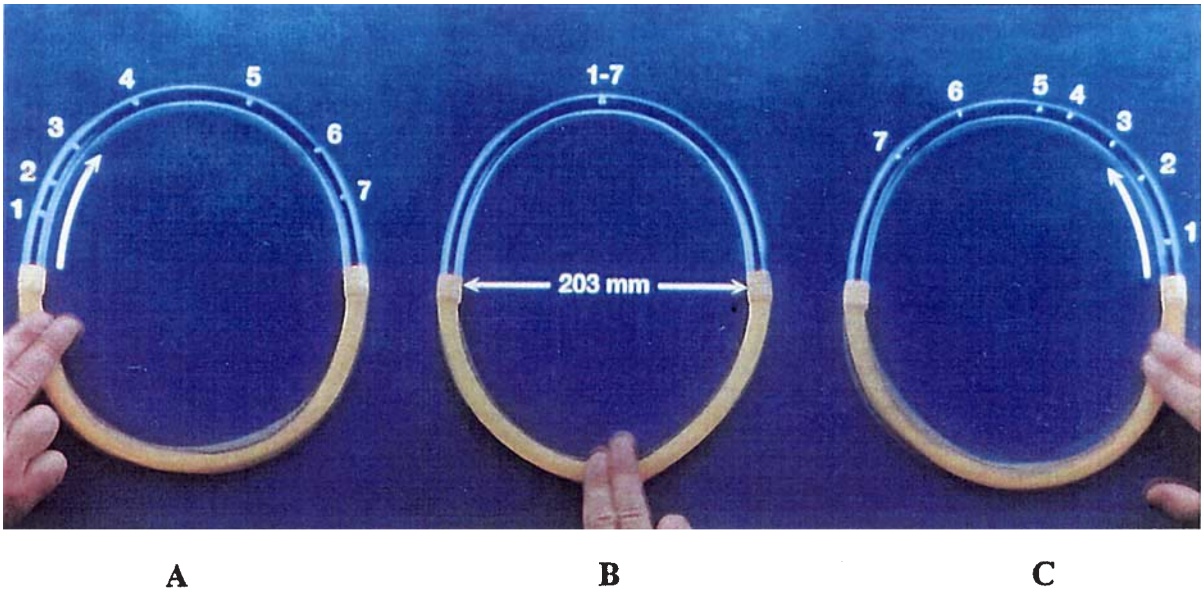
The Tunicates' circulation consists of a simple straight tube with the heart located at its center and can change the direction of flow by the activation of pacemaker cells situated at either end of the heart. The traditional interpretation is that peristaltic waves travel from one end to the other and vice versa and determine the direction of flow. The more logical interpretation, considering the impedance defined flow principle, is the use of the asymmetry of the system imposed by the location of the pacemakers.

In the case of Amphioxus, this species is the cordate that does not have a distinct heart, but rather 3 contractile vessels distributed along the circulation, free of valves. In addition to being valveless, it appears that the three criteria above are fulfilled, therefore generation of average flow should be expected. It has been reported, that the three contracting vessels are not well coordinated in phase of beat [21] which would be difficult to harmonize with the presence of valves but fits easily into the concept of the impedance defined flow principle.

Evidence of blood propulsion by a part of the (valveless) arterial system was discovered in larval bullfrogs (Rana catesbeiana) by Pelster and Burggren [20]. In wintering animals the contractile conus arteriosus was found to be the main propulsive organ primed by the ventricle, while in summer the ventricle retained its function as being the main propulsive pump.

Adding a valve to the system

It seems logical to raise the question whether addition of a valve to the system can make a difference of interest. For a particular case this questions is answered in Fig. 4A (right column), and Fig. 4B-D. In the valveless case the average flow in the circuit is clockwise at low frequencies and reverses at high frequencies. If a valve is inserted channel 1 the magnitude of the average flow becomes larger (4B), relaxation volume changes insignificantly (4C), and efficiency is roughly doubled (4D, squares). In contrast to this, if the valve is placed in channel 2, average flow becomes counterclockwise and



A B C

FIGURE 2

Photograph of a reconstructed [13] fluid filled valveless closed loop. It consists of a semicircular glass tube and a rubber tube with styrofoam marker in the fluid. Shown are three modes of compression, each photographed by repeated exposure at the same frequency the compressions (3 cycles/sec): Panel A demonstrates periodic compression by 2 fingers on the left side of the rubber tube. Sequent numbers indicate the change in position of the styrofoam ball during a sequence of 7 compressions. Panels B and C show the sai sequence for different compression sites. Note that Panel A shows clockwise average flow, while panel C shows counterclockwise avera flow. In Panel B, in which compression is at a symmetric site, no average flow is in evidence.

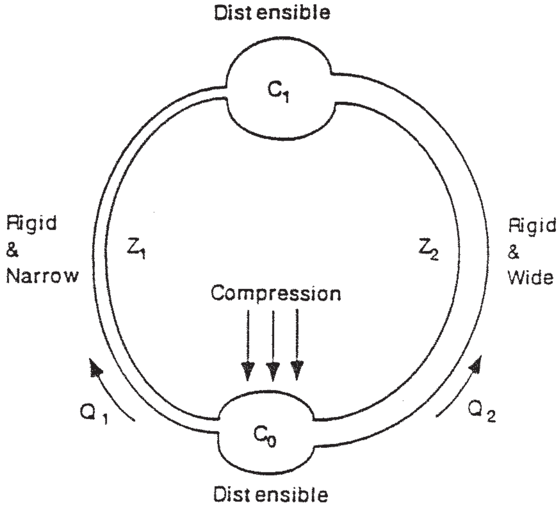


FIGURE 3 (a)

This simple model consists of two distensible reservoirs, C_0 and C_1, connected along two pathways 1 (at left) and 2 (at right). The pathways are made up of rigid tubes, one narrow and one wide. Reservoir C_0 is compressed and relaxed rhythmically with a frequency f, causing flows Q_1 and Q_2 in pathways 1 and 2, respectively. The flow impedances of the pathways are $Z_1=R_1$ and $Z_2=j\omega L_2$, with $j=\sqrt{-1}$, $\omega=2\pi f$, f = frequency; R_1=1mmHg-sec/cm^3 ; L_2=0.1mmHg-sec^2/cm^3. Initial conditions are: Compliant reservoir C_0 contains 100 cm^3 while C_1 contains 5 cm^3 of fluid and pressure is 5 mmHg throughout. Reservoir C_0 is compressed such that all the fluid it contains is forced out at a steady rate during 0.1 sec. It is relaxed otherwise.

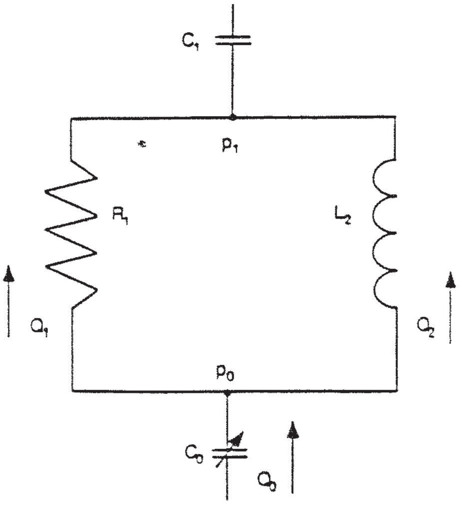


FIGURE 3(b)

Equivalent of the same loop, employing electrical symbols. The flow out of or into reservoir C_0 is denoted Q_0, with $Q_0=Q_1+Q_2$. Arrows define positive directions for flows. These flows vary with time, as do the pressures p_0 and p_1 and the volumes V_0 and V_1 in the reservoirs.

larger at low frequencies (4B), relaxation volume tends to drop (4C) but efficiency remains above 50% (4D, triangles). Placing a valve in channel 2 weakens the performance of the circuit compared to a valve in channel 1. It should be concluded therefore, that both the presence of a valve and its location in the circuit may play a vital role.

Embryological aspects

At the end of the third week in the development of the human fetus, the heart beats in a coordinated fashion [16] and average circulation is concluded from the provison of oxygen necessary for further development. It is even stated that the circulation at this stage is the first functioning system of the embryo [16]. Yet the cardiac valves have not been formed. In conjunction with Fig. 4B-D in the preceeding section, which show that the location of a valve can be critical, a functioning circulation may be required as a source of information where to place the valve. Evidence that blood flow might contribute to the shaping of the heart [10] could be expanded with the suggestion, that the location and formation of valves needs an operating circulation.

Practical application of impedance defined flow to the cardiovascular system

Since the cardiovascular system forms an extensive closed circuit, compression at many sites (Condition 1), in principle, permits blood to choose from two options: flowing upstream or downstream. All chambers of the heart and all vessels have compliant properties (Condition 2). At most sites, the input impedances of the two pathways are different (Condition 3). The main difference with Fig. 3 is the replacement of reservoir C_1 by two or more seperate reservoirs. Their individual compliant properties will affect the magnitude of the generated average flow. To analyse such situations, the set of equations given above must be expanded accordingly. This offers a large new field of research.

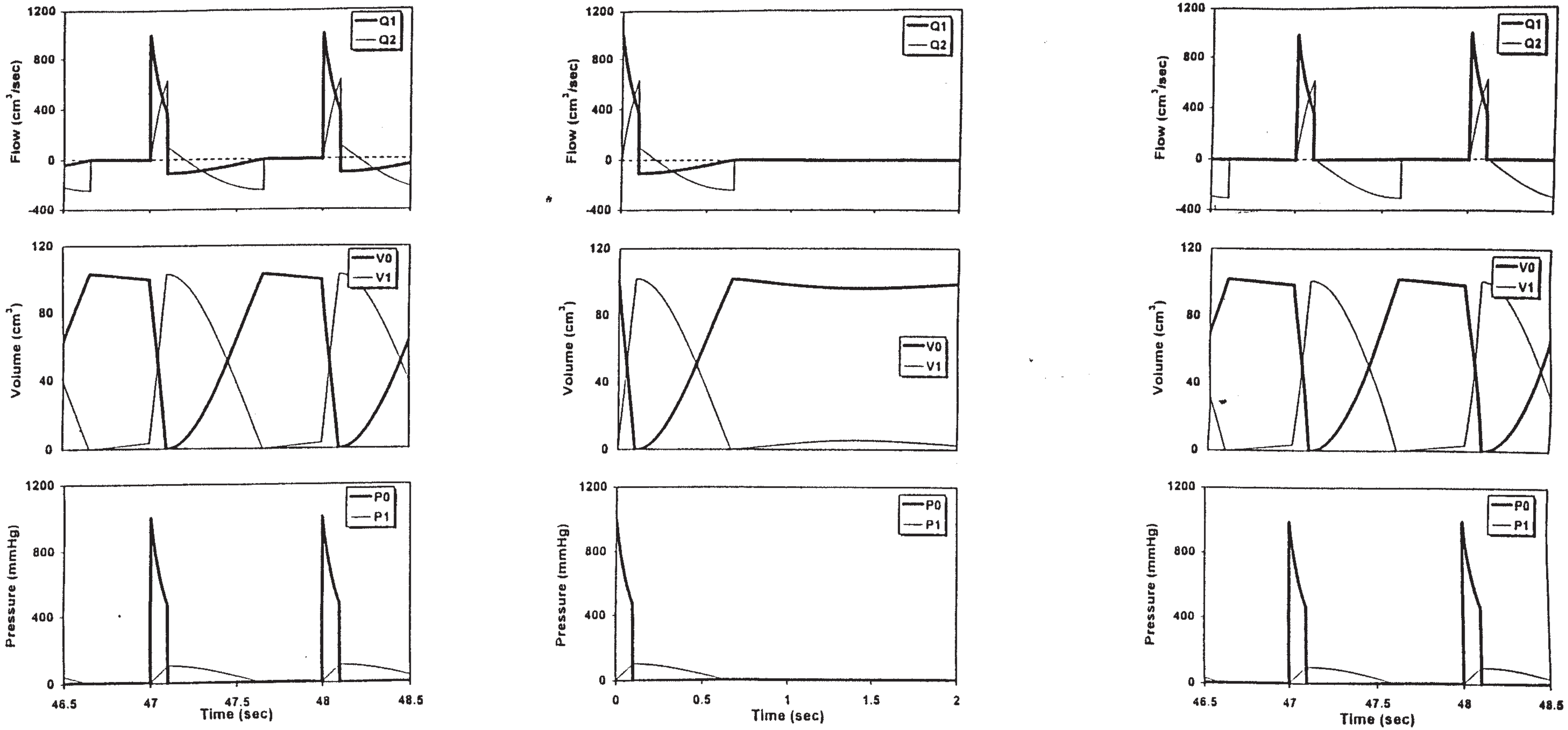
In the fully developed cardiovascular system its complement of valves accounts for a new feature: In addition to higher efficiency it offers the possibility to create high pressure reservoirs.

In a previous section it was demonstrated that shaking a closed system fulfilling the conditions resulted in an average flow around the circuit. Body acceleration in synchrony with the heart beat (BASH) may well be the clinical correlate of the experiment described in the previous section. In 4 terminal cardiogenic shock patients, refractory to the standard treatment, survival of two resulted from treatment with BASH [1]. Inspite of these results no physical basis of BASH had been developed at that time preventing the further development of the method. Since the physical principle is now available the study of BASH should probably be reopened.

The popular temporary cardiac assist device, the intraaortic balloon pump (IABP) can be considered a mirror image of the experiment with a segment of the aorta described in the previous section, although it has never been viewed that way. The IABP operates in a more complex environment since the part of the aorta proximal to the IABP is closed part of the time owing to the presence of the aortic valve. It might be rewarding to restudy the timing imposed on the IABP from the point of view of impedance defined flow.

On the basis of experimental data it has been reported that during cardiopulmonary resuscitation (CPR) the cardiac valves can remain open [2]. Nevertheless, some of the victims of cardiac arrest have survived by chest-compression or by coughing [3]. Although the mechanism of action in both cases has not been satisfactorily explained, the possibility presents itself that the impedance defined flow principle may provide assistance in understanding and improving the procedure.

As another practical application, one could wonder about the value of valveless pumping in the design of artificial hearts, since it has been demonstrated that artificial valves can have damaging effects on the formed elements [11].



4 A (left) 4 A (center) 4 A (right)

FIGURE 4

(A): (Left Column): Computed time courses of flows through channel #1 (Q_1) and #2 (Q_2), volumes V_0 and V_1 and pressures p_0 and p_1 in the two compliant chambers C_0 (20 cm^3/mmHg) and C_1 (1 cm^3/mmHg)for the steady state at a constant compression rate of 1 Hz.

(Center Column): The same quantities for a single cycle. (Right Column) Steady state solution, also at 1 Hz, after addition of a single valve that restricts Q_1 to non-negative values

(B): Steady state average flow, $\overline{Q}_1=(1/T)\int^{T} Q_1(t)dt$, (T = duration of 1 cycle) around the circuit in Fig.3 as a function of compression frequency for three conditions: valveless (dots), a valve that prevents $Q_1(t)$ from going negative (squares) and a valve that prevents $Q_2(t)$ from going negative (triangles). Positive values denote clockwise, negative values counterclockwise average flow.

(C): The volume in compliant chamber C_0 at the end of the relaxed period for three conditions: no valves, $Q_1 \geq 0$, $Q_2 \geq 0$. The maximum possible value is 105 cm^3 in the illustrated example.

(D): Efficiency of the system in Fig.3: Average flow $\overline{Q}_1$ $(= -\overline{Q}_2)$ around the loop (positive clockwise and negative counterclockwise) as a percentage of average flow generated by compression of compliant chamber C_0 periodically vs. frequency. Same three conditions as in Fig. 4B and C.

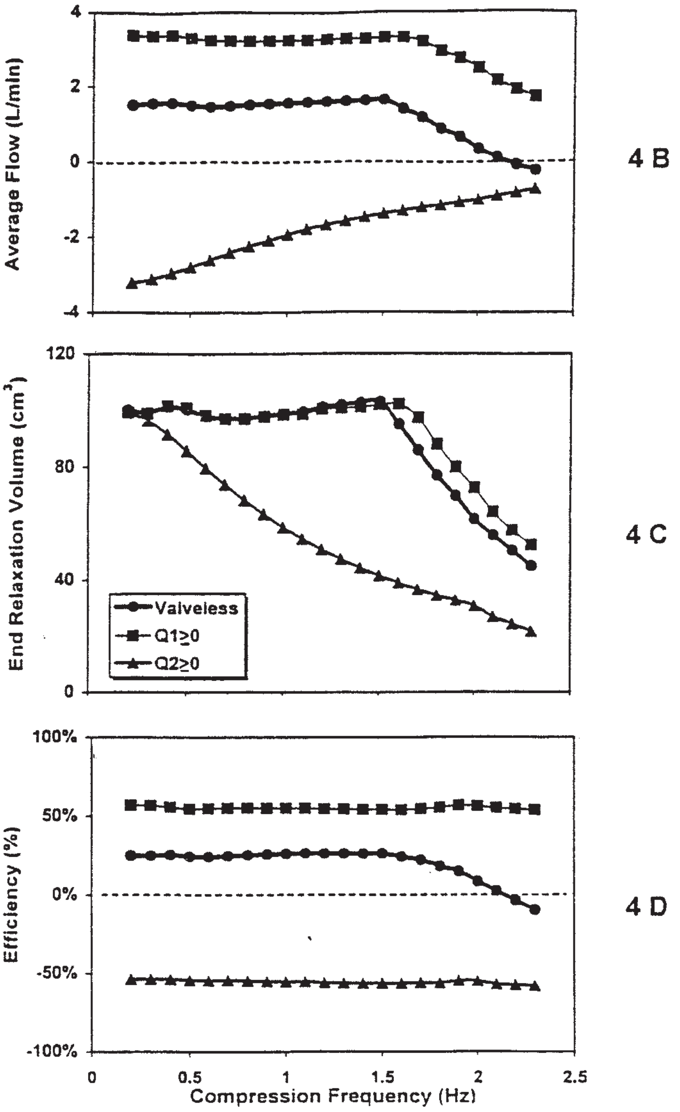


FIGURE 4 CONTINUED

When the valve is open, ventricle and aorta behave like a valveless subsystem for around 30% of the time; with respect to the atrioventricular valve it is valveless for about 60% of the time. The subsystem comprising the central veins and their respective atria is valveless 100% of the time.

The principle of impedance defined flow may provide the key to establish whether or not Donders' claim concerning the respiratory pump mentioned in the introductory section above is actually valid. In the low pressure circulation of the pulmonary veins and central systemic veins the external pressure oscillation imposed by the respiratory system constitutes a driving force (Condition 1). In addition, the other two conditions are satisfied, since the impedance in the central direction is lower than the impedance in the peripheral direction (Condition 3), while the central veins and the left atrium provide storage facility (Condition 2). A similar consideration applies to the central systemic veins.

It has been well established and was used by Harvey [7] in his publication on the movement of blood that veins feature a multitude of valves in the extremities. It has been demonstrated [5, 9] that periodic contraction of the peripheral skeletal musculature promotes venous return in the direction of the heart. The rocking chair may well serve as a long-term substitute for enhancing venous return.

Application of the impedance defined flow outside the cardiovascular system

In view of its fundamental nature, application of the impedance defined flow principle should not be restricted to the cardiovascular system. A suggestion in that direction can be found in a paper about lymph drainage in the eye [6]. Another possible example is the calorically induced nystagmus, which, contrary to expectations, was observed in microgravity [22]. The gravity driven phenomena observed in 1-g conditions might be generated by pulsations induced by regional arteries in microgravity, temperature gradients producing asymmetry in the distribution of viscosity in the endolymph of the semicircular canal.

Tuning the system

From the analysis of the aortic experiment described in the previous section it became evident that selection of the frequency of repetition of the external force is a critical parameter in some circumstances. In other words tuning between the driving force and the parameters of the given system may be an essential feature for successful operation. This is especially relevant under resting conditions, as chronobiological evidence of synchronicity of respiration and heart rate during sleep shows [8, 17].

SUMMARY

It is shown that the impedance defined flow principle, introduced in this paper, is capable of producing average flow. Any compliant fluid conducting system of which a part is subject to pressure oscillation, and which displays asymmetric flow impedances tends to produce unidirectional flow. This constitutes a generalization on Harvey's view that blood moves around the circuit solely by the pumping action of the heart, thereby creating a new field of research within and without the cardiovascular system. Judicial placement of the valve can improve the pumping efficiency of the system. The fact that valveless circulatory systems can be found predominantly in simpler animal species suggests that valves constitute a refinement developed later in the evolutionary process. Also, in early development, valves appear only after the creation of flow in the embryonic circulation giving rise to the suggestion, that flow contributes to the location and formation of valves.

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