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The siphon controversy counterpoint: the brain need not be “baffling”

The application of siphon principles to the cerebral circulation has engendered a surprising amount of controversy (1–3, 11, 19, 22, 23). The reluctance to apply siphon principles to the cerebral circulation probably stems more from its inescapable, but counterintuitive, corollary: if the circulation to the brain is a closed loop, then the heart does no extra work in pumping blood “up hill” to the brain. However, no better evidence of the appropriateness of applying siphon principles to the brain can be cited than the observation that the intracranial sinuses and veins of the upright human maintain negative pressure. This is evident from the well-documented phenomenon of venous air embolism when these structures are accidentally perforated at surgery in the sitting position (7, 18). Here, we introduce these clinical observations into the discussion and into our response to the position, staked out by Gisolf et al., that siphon principles do not apply to the brain. We also briefly review the fundamental physical principles that apply (11) and revisit the “natural experiments” provided by comparative physiology.

GRAVITATIONAL EFFECTS ON BLOOD PRESSURE: A BRIEF OVERVIEW

The flow of liquids in a system of tubes is subject to three possible forces: 1) gravitational, 2) accelerative, and 3) viscous. The physical laws describing the first two forces were elucidated by Swiss mathematician Daniel Bernoulli (1700–1782) in *Hydrodynamica* (4) and is described by the following equation:

$$E_{\text{tot}} = (P + \rho gh + \rho v^2/2)\Delta V \quad (1)$$

where E_{tot} equals the total energy of the fluid, $P\Delta V$ represents pressure energy per unit volume, ρgh is gravitational potential (elevational) energy per unit volume ($\rho gh\Delta V$), and $(1/2\rho v^2\Delta V)$ is kinetic energy per unit volume. Although a powerful equation, an additional factor that influences the flow of liquids, the role of viscous resistance, must be considered.

In 1840, the French physician J. L. M. Poiseuille (1799–1869) empirically determined the variables that described steady laminar flow of viscous liquids within narrow tubes (20), which is expressed by the relationship:

$$P_1 - P_2 = (8L\eta/\pi r^2)\Delta V \quad (2)$$

where L is the distance between any two points, η is the viscosity of the liquid, r is the radius of the tube, and ΔV is the

flow rate. The pressure gradient ($P_1 - P_2$) expressed by the Poiseuille equation is related to the frictional or viscous resistance when flow is induced and is termed the viscous flow pressure gradient (P_{viscous}).

It is evident that neither the Bernoulli nor the Poiseuille equation alone adequately describes real viscous flow under gravitational stress and acceleration. For this purpose, a combined equation called the Bernoulli-Poiseuille equation has been proposed (26) and is given by

$$E_{\text{total}} = P_{\text{viscous}} \Delta V + \left(\rho gh \Delta V_{\alpha} + \frac{1}{2} \rho v^2 \Delta V \right) + (\rho gh \Delta V)_{\beta} + \frac{1}{2} \rho v^2 \Delta V + U \quad (3)$$

where $(\rho gh \Delta V)_{\alpha}$ is the pressure energy due to the weight of the liquid and the $(\rho gh \Delta V)_{\beta}$ is the potential energy due to the vertical elevation of the liquid, and U equals frictional heat.

The Bernoulli-Poiseuille equation describes the relationship between viscous and gravitational pressure in an “open system”. Here, an open system is defined as one in which liquid is raised from a lower to a higher gravitational potential energy and is discharged or stored at the high potential. As the liquid is pumped against a gravitational pressure $(\rho gh \Delta V)_{\alpha}$, the gravitational potential energy $(\rho gh \Delta V)_{\beta}$ must increase, and, in addition, the pump must generate enough pressure to overcome the viscous resistance of the tubes (P_{viscous}). Consequently, the total pressure generated by the pump, as it lifts the fluid to a higher level, is expressed as

$$P = P_{\text{viscous}} + \rho gh_{\alpha} \quad (4)$$

If the circulation, in vivo, is analogous to an open system, then the pressure generated by the heart must overcome both the resistance to blood flow and the vertical distance above the heart (11). However, the circulatory system is not an open system, but rather is best described as a closed system, in which liquid is driven and returned to its original level through a series of tubes, without being exposed to the atmosphere above the original level (11).

THE SIPHON PRINCIPLE

The physical principles describing a closed system are fundamentally different from an open system. In a closed loop

system, as the fluid flows up the ascending limb, the decrease in $(\rho gh)_\alpha$ is counterbalanced by the increase in $(\rho gh)_\beta$, and the energy generated by the pump (heart) is determined by the viscous resistance of the entire circuit and the output of the pump (ΔV). Thus the hydraulic work of the pump ($P\Delta V$) will be independent of the orientation of the circuit, and in the vertical orientation, the pump does not develop additional pressure energy to raise the liquid. The mechanical advantage of a closed system is similar to the operation of a siphon loop. However, as previously suggested (3), within the circulatory system, siphon flow is not occurring, but rather the counterbalancing of $(\rho gh)_\alpha$ and $(\rho gh)_\beta$ within the ascending and descending limbs of the vertically oriented circulatory loop eliminates the additional energy required to overcome gravity. A variety of hydraulic models (11, 12) support the siphon principle.

VASCULAR WATERFALL: IS THE ANALOGY JUSTIFIED?

Opponents of the closed system model often cite the assertion made that the siphon principle cannot be reconciled with compliant, or collapsible tubing and that in vivo the descending limb (the jugular vein) cannot support a negative gravitational pressure (12–15). Although the argument is intuitively appealing, simply stating that collapsible vessels do not support negative gravitational pressures is not very convincing. This position has been adequately refuted by both empiric results (12) and reference to basic physical principles. The Bernoulli-Poiseuille equation indicates that the only requirement for the siphon principle is a continuous fluid circuit, with each fluid element surrounded by neighboring elements in direct contact with the surface of the flow channel (excluding any gases or compressible elements). It follows that the ascending and descending limb of a siphon circuit can have any cross-sectional shape, area, or length and that regardless of the vessel compliance, a negative gravitational pressure is supported whether the blood is flowing or static—in other words, the collapsibility of the descending limb does not, a priori, negate the effect. The observation that cerebral sinus and venous pressures are subatmospheric, and, in fact, entrain air when opened to the atmosphere in a sitting human (see below), provides empirical refutation of the notion that “collapsible” vessels cannot support negative pressure.

The notion that a collapsible vessel cannot support negative pressures persists (19, 22, 23), and both theoretical and empirical hydraulic models have been used to argue against the operation of a siphon principle (19, 22, 23). Hydraulic models, however, are often based on an open system, which is not a simple analog of the closed circulation. Within open systems, in which the descending limb discharges the fluid into the open air, the fluid accelerates down the descending limb, resulting in significant contributions of kinetic energy. For example, it has been suggested that within the descending limb of a vertically orient loop, “Fluid simply falls through the partially collapsed conduit” (27). However, within the intact circulation, blood flow from the brain does not “fall” to the right atrium (2, 3). Consequently, open system models are not simple analogs of the in vivo circulation.

THE BAFFLE MECHANISM AND BRAIN-BLOOD FLOW

Using a rearrangement of *Eq. 2*, Gisolf et al. calculate a high cerebral vascular resistance and suggest that, combined with

extensive branching structure of the blood vessels in the brain, a “baffle”, or throttle, mechanism exists within the cerebral circulation. This baffle is said to produce a “discontinuity” across the cerebral vasculature, and although this idea is interesting, the precise physical mechanism for disrupting negative gravitational pressures is not obvious. A negative gravitational pressure within the venous circulation should be present whether or not the veins are collapsible or rigid and whether or not a baffle system exists. The only requirement for the siphon principle is fluid continuity.

The frequent occurrence of venous air embolism (VAE) during sitting neurosurgical procedures (5, 7, 17, 25) implies a substantially negative transmural pressure in the cerebral sinuses and/or cerebral veins when the head is elevated. Because these patients are mechanically ventilated, their intrathoracic pressures are always at or above atmospheric pressure during each phase of the respiratory cycle. The coincident observation of positive pressure ventilation in the thorax and subatmospheric venous pressure in the head can be accounted for by a “closed” circulatory, or “siphon” model, but is inconsistent with a vascular waterfall or “baffle” model. In fact, it is difficult to posit any model other than a closed circulation or siphon model that adequately explains the phenomenon of VAE in mechanically ventilated patients who are in the sitting position. This is further buttressed by the long-standing clinical observation that the tendency for VAE increases with elevation of the operative site above the heart. The “baffle” or vascular waterfall model cannot account for this observation, since upstream pressure in a vascular waterfall is not influenced by downstream pressure or elevation above a downstream reference point (in this case, the heart). In a siphon model, however, it is predictable that the tendency for VAE will increase with elevation of the operative site above the heart. It is difficult to reconcile these observations with a “baffle” or vascular waterfall model, and to our knowledge, proponents of such models have not addressed these fundamental observations from the clinical literature.

With regard to considerations of anatomic complexity, Gisolf et al. assert that “In the siphon controversy, the role of the brain itself has been curiously overlooked.” However, at least one model of the cerebral circulation has been published that takes into account the variety of cerebrovascular components and compliances, the influence of surrounding intracranial pressure, as well as the effect of position on hydrostatic pressure (18). That model also emphasizes the too-often overlooked distinction between local transmural pressure (which is captive to each of the variables just cited and which does not directly affect blood flow except through changes in resistance) and global cerebral perfusion pressure (which is determined only by the difference between inlet and outlet pressures, and does affect blood flow).

THE SIPHON PRINCIPLE AND THE COMPARATIVE APPROACH

The principle of a siphon should apply to any closed circulatory system, and thus comparative physiology provides an alternative approach to investigate this fundamental hemodynamic principle of the circulation. As noted by August Krogh in 1929, “for a large number of problems, there will be some animal of choice or a few such animals on which it can be most conveniently studied” (14). Gisolf et al. note results of several

comparative studies that indicate a siphon principle does not apply to the intact circulation. However, these results are sometimes contradictory, may be incomplete, and in some cases, may have alternative explanations.

The giraffe represents an ideal animal to reveal the general principles that influence blood pressure and blood flow in a normal gravitational field. Simply by virtue of its stature, giraffes operate a cardiovascular system under gravitational pressures that are higher than any living vertebrate. For example, an adult at a height of 5 m has a total gravitational pressure gradient of 370 mmHg from head to foot. In the upright position, the head can be more than 1.5 m above the heart, and when these animals lower their head to drink, the venous pressure in the head can exceed 100 mmHg. These large gravitational pressure gradients result in a significant physiological challenge for regulating blood flow to the brain as the giraffe raises and lowers its head through a natural range of motion (1, 10, 11, 18, 23).

Pressure measurements within the jugular vein of quietly standing giraffes indicate a pressure gradient over a distance of 1 m, from the upper neck toward the heart, of 13 to 4 mmHg. This gradient is one-tenth and is opposite the direction predicted by gravity alone (10). It has been suggested that these pressure gradients result from venous collapse and therefore negate the operation of a siphon mechanism in vivo (10).

In contrast arterial blood pressures, as a function of head position in giraffes support the notion that a siphon principle may be operating in vivo. In the giraffe, blood pressure at the root of the aorta was measured with the head of the animal in the horizontal position and when the head was raised 1.5 m above heart level (9). In the horizontal position, the aortic root blood pressure was ~ 170 mmHg. As the head was elevated, the mean aortic pressure increased to ~ 210 mmHg. If a siphon mechanism was not operating, the aortic blood pressure should have increased, as predicted by Eq. 4, to 280 mmHg (11). The fact that pressure only increased by half the amount predicted by gravity alone, suggests that the giraffe heart, in vivo, may not have to overcome the gravitational pressure related to the weight of the blood in the arterial system above the heart (e.g., a siphon mechanism is operating) (11). However, it is possible that blood flow to the brain may have been reduced during this maneuver (9), and, consequently, P_{viscous} was lowered. Unfortunately, blood flow to the brain was not measured in these experiments.

The high arterial blood pressure of giraffes is often provided as evidence that the heart must "lift" blood to the brain and that a siphon principle does not exist in vivo (10, 21, 22). Allometric analyses, examining the relationship between body mass and blood pressure in mammals tend to support this notion (21). From mouse to elephant, systolic blood pressure scales with body mass ($P_{\text{systolic}} = 115.2 M_b^{.05}$) (21), though the systolic blood pressure in giraffes is notably different from the values predicted by this equation (predicted $P_{\text{systolic}} = 159$ mmHg vs. actual $P_{\text{systolic}} = 235$ mmHg). Consequently, it is assumed that the siphon principle cannot apply to the circulation in these long-necked animals (10, 21, 22). However, systolic and diastolic arterial blood pressures are influenced by several physiological parameters such as cardiac output and total peripheral resistance, which, in turn, are influenced by a variety of physiological states. Arterial blood pressures alone

do not provide convincing evidence against the siphon principle. For example, in birds, the systolic blood pressure of a house sparrow is 180 mmHg, while the systolic pressure of two long-necked birds, the ostrich and emu, are 191 mmHg and 149 mmHg, respectively (21). Clearly, if the heart must work against gravity, the blood pressure in the long-necked birds would be significantly higher than that of the house sparrow (21).

Comparative analyses within a single group of animals can be a useful approach to inferring physiological or morphological adaptations (8). Gisolf et al. report that previous studies investigating cardiovascular adaptations in snakes from diverse habitats (aquatic, terrestrerial, and arboreal) (15, 16, 24) supports the notion that the siphon principle does not apply in these long-bodied reptiles. In these analyses, it was assumed that the heart must work against gravity, and therefore, the greater the vertical distance between heart and head, the greater the gravitational stress. Consequently, natural selection would favor a heart position that reduces cardiac work. In aquatic species, which are less affected by gravity, the heart would be located near the midbody, while in arboreal snakes, in which the animals spend significant time in a vertical orientation, the heart would be located closer to the head (15, 16). An analysis of head-to-heart distances and arterial blood pressure in a variety of snake species, as a function of different ecological niches (aquatic, arboreal, and terrestrial) found that these variables were correlated (15, 16, 24). However, direct correlational analyses between multiple species, using standard statistical tests, are inappropriate, and the use of such a test can be misleading (8). Multispecies comparison, which attempts to infer the adaptive significance of a phenotypic trait (in this case heart position as influenced by gravitational stress), must take into account the genetic relatedness (phylogeny) between species (8). The statistical method for such analyses, called phylogenetic independent contrast, was developed in the mid-1980s (6), and an analysis of the original snake data set, which appropriately accounts for species relatedness, needs to be conducted.

CONCLUSION

The baffle mechanism is intriguing, although the process by which it disrupts gravitational pressures is unclear. Even more troubling is the failure of such models to reconcile with the well-established observation that the upright human brain contains negative pressure in its veins and sinuses. To our knowledge, the principle of the siphon stands alone in accounting for this negative pressure. The principle of the siphon is not species specific and should be a fundamental principle of closed circulatory systems. Therefore, the controversy surrounding the role of the siphon principle may best be resolved by a comparative approach. Analyses of blood pressure on a variety of long-necked and long-bodied animals, which take into account phylogenetic relatedness, will be important. In addition experimental studies that combined measurements of arterial and venous blood pressures, with cerebral blood flow, under a variety of gravitational stresses (different head positions), will ultimately resolve this controversy.

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