Hydraulic Ram Consisting of Collapsible Vessels[1] (34235)

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Since Whitehurst's discovery of the principle of the hydraulic ram two centuries ago, and the automation of this device a few years later by Montgolfier, hydraulic rams have been utilized to lift water above its source wherever the hydrostatic energy of a larger reservoir such as a lake was available. In the conventional hydraulic ram, lake water is permitted to flow out of a pipe under the action of gravity until a maximal momentum of the stream is achieved. The outlet (waste) valve is then closed and the stream is redirected so that its momentum compresses a pocket of air (1). The increased air pressure then lifts a small volume of water to a level higher than the level of the lake.

Examination of the anatomical relationships between vascular (primary) and secretory (secondary) fluid systems in the salivary gland led us to design a new type of hydraulic ram. This device operates without a discharge valve or air chamber, and separates the fluid providing the energy from the fluid being pumped.

Apparatus. The hydraulic ram consisted of two flow systems (Fig. 1). In the *primary* (unshaded) system, fluid from a reservoir at a selected "arterial" level (P_A) flowed through a connecting "artery" (A) and a segment of soft-walled single-dip latex rubber tubing (E–F) of 1 cm diameter and 10 cm length, into a sink (P_V). The *zero reference* was the level of the soft-walled tube. The collapsible tubing was enclosed in a glass cylinder (B) of 7 cm diameter and 20 cm length. The primary stream was connected to the "extra-vascular" space of the cylinder through the side-arm connectors (C,D). The cross sectional area of (D) is less than that of (C). This produces a relative increase in the pressure in the cylinder (B).

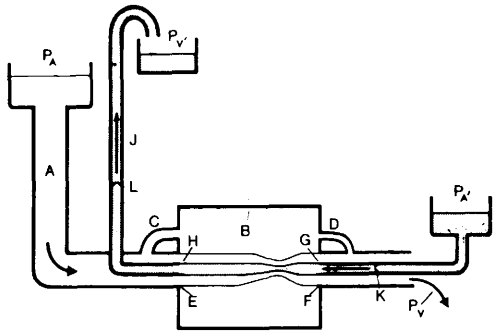

Fig. 1. Hydraulic ram model, described in text.

The *secondary* (shaded) system consisting of a source reservoir (P_A') was connected to a receiving reservoir (P_V'). The tubing connecting P_A' to P_V' consisted of hard latex rubber except for a segment of soft-walled latex tubing (G–H) which was threaded through the corresponding segment (E–F) of the primary system. Valves (K and L) on each side of the secondary soft-walled tube directed flow toward the receiving reservoir P_V'. Stretching of the soft-walled tube of the secondary system modifies the efficiency of the apparatus. This effect was tested in some experiments by using a spring scale to apply a calibrated tensile stress to this soft-walled tube.

We examined the effects of the "arterial" pressure (P_A), the flow rate through the primary system (Q), the "secretory" pressure (P_A'), and the tensile force applied to the soft-walled tube (G–H) on the flow through the secondary system (Q').

The efficiency E = (energy stored/energy expended) of the hydraulic ram, *i.e.*, the ratio of the energy stored in the secondary

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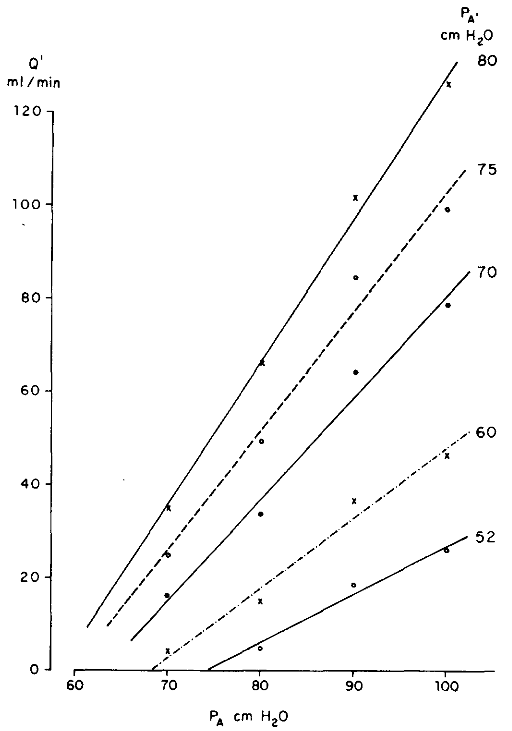

FIG. 2. Relationship between primary "arterial" pressure (P_A) and flow through the secondary system (Q') for the levels of the secondary source reservoir P_A' shown by the number at the right of each line. The receiving reservoir (P_V') was at 100 cm.

system to the energy expended by flow through the primary system, was calculated as $E = [(P_V' - P_A')\, Q'/P_A Q]$.

Results. Flow through the primary system resulted in the pumping of small volumes of fluid through the secondary system from P_A' to P_V'. Experiments were performed with P_A' values ranging from 27 to 80 cm H_2O for each of four P_A values: 70, 80, 90, and 100 cm H_2O. A family of curves (Fig. 2) was obtained in which the individual lines were related by the expression, $Q' = 0.071\, P_A'\, P_A - 2.7\, P_A - 3.6\, P_A' + 112$. The efficiency of the hydraulic ram in these experiments reached a maximum of slightly over 1% as either P_A' or P_A approached P_V'.

The latex tube of the secondary system exhibited a linear relationship between mechanical tension and elongation (Hooke's Law) in the range between 150 and 650 g/cm circumference. The relationship between the tension on the latex tube and the flow through the secondary system was complex. As tension was increased, flow through the secondary system varied widely but not consistently and showed two or more maxima and minima (Fig. 3). The greatest flow (108 ml/min) and efficiency (3%) were obtained as P_A approached 100 cm H_2O and at tensions of 300 to 600 g/cm on the latex tube of the secondary system.

Mechanism. When fluid flows through a segment of soft-walled tubing enclosed in a rigid capsule, the tubing may be caused to close and reopen recurrently (2). The frequency of closure is primarily a function of the transmural pressure across the tube although other factors such as the elastic qualities of the tube also play a role. Our data show that in structures in which discrete soft-walled tubes are enclosed in a capsule the hydraulic ram principle can generate a pressure higher than that of the source. The mechanism of the hydraulic ram principle in the present apparatus depends on frictional energy losses in the soft-walled vessel of the primary system which cause the transmural pressure in this vessel to be at its lowest level at its downstream end. The resulting gradient in transmural pressure in this vessel results in a downstream cross sectional area

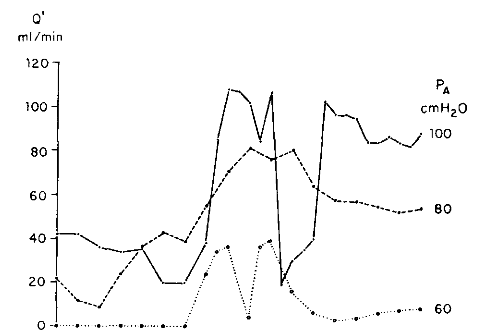

FIG. 3. Relationship between secondary flow (Q') and the tensile stress applied to the soft-walled tube of the secondary system. Each curve represents a different "arterial" pressure (P_A) as indicated by the values at the right of each line. The secondary source reservoir (P_A') was at 60 cm H_2O, and the receiving reservoir (P_V') was at 100 cm.

which is less than that upstream. The velocity of the stream in the downstream segment therefore increases, producing a further fall in intravascular pressure near the outlet of this vessel. The pressure in the surrounding glass cylinder is relatively uniform because of the slow rate of flow through it. The transmural pressure in the downstream segment of the primary soft-walled vessel then falls until a negative transmural pressure collapses the vessel.

The sudden obstruction of the primary system generates a water hammer wave which moves retrograde. The wave collapses the enclosed secondary soft-walled vessel, and milks fluid from P_A' toward P_V'. The rise in pressure in the upstream end of the closed segment of the primary system then forces the vessel walls open, so that flow through the primary system is resumed, and the cycle is repeated.

Discussion. The anatomical arrangement of the blood vessels and ducts in the salivary glands has some similarities to our hydraulic ram model. Thus the systemic arterial system supplies a source of hydrostatic pressure; the arteries, lying immediately adjacent to the secretory ducts, are enclosed within the capsule of the lobe of the gland it supplies; and the arterial blood flows counter-current to the flow of saliva (3). During salivary secretion, blood flow through the gland increases extraordinarily and the blood leaving the gland is red, suggesting that the increased flow rate is not necessarily associated with the oxygen requirements of secretion (4). The high rate of blood flow suggests that a hydraulic ram mechanism could contribute to the development of the suprasystolic pressure (5, 6) sometimes found in the ducts of the submaxillary gland. The peak pressure generated will vary with the compliance of the capsule of the gland. The pressures generated in the submaxillary gland which has a relatively firm capsule, may thus be higher than the pressure generated in the parotid gland, the capsule of which is less well developed (6).

The efficiency of the present system is low. However, efficiency may be increased by factors which modify the resonance and other properties of the system. The present system encloses the secondary vessel in the primary vessel. The system functions similarly when primary and secondary vessels are adjacent to each other and enclosed in the capsule.

Summary. A new type of hydraulic ram is described. The apparatus operates without a discharge valve or air chamber, and the fluid providing the energy is completely separated from the fluid being pumped. Factors affecting the efficiency of the system are discussed. The possibility that similar mechanisms in the body may operate to provide a pressure higher than the source is suggested.

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