Pump Flow Dynamics of the Roller Pump and Constrained Vortex Pump

Gregory H. Landis, B. A.; Joseph P. Mandl, M. S.; and David W. Holt

The Ohio State University, Circulation TechnologyDivision, School of Allied
Medical Professions, 1583 Perry Street, Columbus OH 43210

INTRODUCTION

The roller pump and the more recently developed constrained vortex pump are clinical devices for pumping blood through an extracorporeal circuit. Using conventional, *in vitro* calibrating procedures to determing pump flow rates may yield inaccurate results due to uncontrolled physical factors present clinically, i.e. temperature, viscosity, occlusion (roller pump), tubing wall thickness and resistance. The effects of these factors may result in an actual flow rate which is significantly different than the calibrated flow rate.

The purpose of this study is to investigate the effects of temperature, viscosity, occlusion, and tubing wall thickness on flow rate and the effects of applied resistance to both the roller and constrained vortex pump systems *in vitro*. The roller pump was further analyzed with the use of a "clicker" device.[1] This simple voltage divider provides a means to record the position of the individual roller head as it passes through the pump racing.

MATERIALS and METHODS

Temperature and Viscosity—The circuit consisted of a pump (roller or constrained vortex), main reservoir, heat exchanger, polyvinyl chloride (PVC) tubing (3/8″ I.D., 1/16″ and 3/32″ wall thickness), and a cylindrical reservoir. Flows were measured with this reservoir using three electrodes in the following manner (Fig. 1). Electrode C was the reference point. The fluid entered the cylinder at the base, became stabilized, and continued flowing up the cylinder at a steady rate. As the fluid reached Electrode B the electrical circuit was complete and the green light came on. At that point a stopwatch was started. The fluid continued up the cylinder to Electrode A at which point the red light turned on and the stopwatch was stopped. The volume between Electrodes A and B was known, therefore flow could be calculated.

The fluid used for the temperature study was .9% normal saline at temperatures of 13, 20, 30, 37 and 45°C. The fluid used for the viscosity study was a mixture of normal saline and ethylene glycol at 20°C. Viscosities of 5.6, 4, 3, 2 and 1 centipoise (cp) were used.[2,3]

The tubing used for both experiments was 3/8″ I.D. PVC of 1/16″ and 3/32″ wall thicknesses. The length of tubing used was the same for both types of pumps. Pump

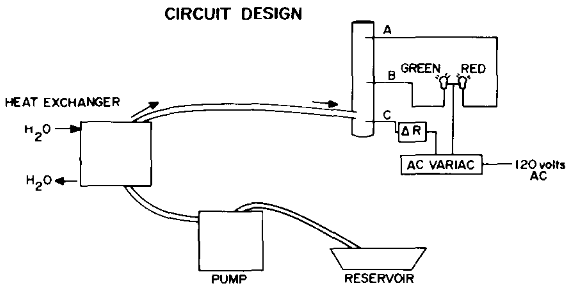


Figure 1. Circuit design for the temperature and viscosity experiments.

occlusion for the roller pump was set as "just occluded" (0 ml fluid level drop per minute at a column height of 30 cm). Roller pump settings of 30, 60 and 90% voltages were used. Pump settings of 900, 1600 and 2300 RPM (non-pulsatile) were set for the constrained vortex pump.

Occlusion—The circuit for the occlusion study consisted of a roller pump, main reservoir, and graduated cylinder (Fig. 2). Water was pumped from the main reservoir into the graduated cylinder for specified periods of time at room temperature. Pump occlusions were set at under occluded, just non-occluded (1 cm/min drop at a 30 cm height), just occluded (no drop), and over-occluded.[4] Tubing was a PVC type with a 3/8″ I.D. and 1/13″ wall thickness. Pump settings of 10, 20, 30, 40, 50, 60, 70, 80 and 90% voltages were used.

Resistance—The circuit consisted of a pump, main reservoir, inflow and outflow pressure monitoring ports, a 3/8″ in-line magnetic flow probe, and tubing clamps (Fig. 3). The tubing was PVC 3/8″ I.D. and 3/32″ wall thickness. Inflow and outflow pressures were monitored using pressure transducers and were simultaneously recorded with flow on an eight-channel thermal recorder. When the roller pump was used, the occlusion was set for just occluded.

The resistance was increased on the outflow side of the pump by occluding the tubing with a tubing clamp. The same procedure was performed on the inflow side.

Roller Head Position—The same circuit was used as shown in Figure 3 except for the tubing clamps. A "clicker" device was mounted on the roller pump (Fig. 4). The clicker element is attached to the roller assembly. The contact of the clicker is aligned with one of the rollers. As the roller head rotates, the clicker touches the contacts at positions X_1, X_2 and X_3, thus completing the electrical circuit at these points. Since the resistances are in series, the voltage drop at position X_1 is more than at position X_3. The

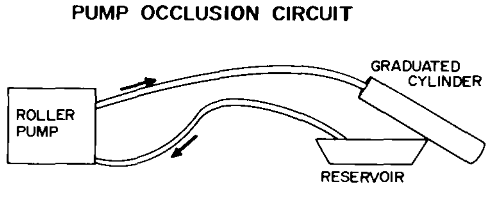


Figure 2. Circuit design for the occlusion study.

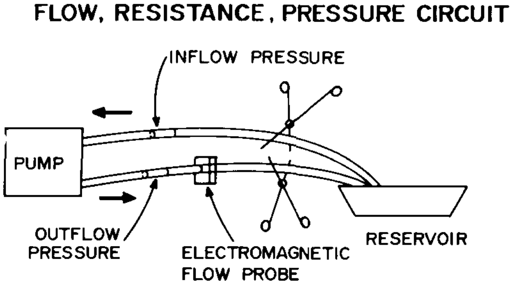


Figure 3. Circuit design for the resistance experiment and roller head position study.

voltage drops were monitored with an ECG preamplifier (DC input). Simultaneous recordings of voltage drops, flow and pressure (inflow and outflow) were obtained using an eight-channel thermal recorder.

RESULTS

Temperature and Viscosity—Graph 1 shows the effects of temperature on flow using the roller pump at three pump settings, 30, 60 and 90% voltages. The flow rate increased linearly for the 3/32″ tubing (dotted line) as the temperature increased. All three flow setting conditions for the 3/32″ tubing had correlation coefficients greater than .98 for linearity.

The 1/16″ tubing (solid line) had higher flows for each pump setting than the 3/32″ tubing. The flow decreased at the 45°C level for the 60 and 90% voltage settings. The points between the range of 13 and 37°C, at the 30% voltage setting, were linear with a correlation coefficient greater than .99. The correlation coefficient for the line, with the 45°C point included, decreased to .96. Smaller variations in numbers have a greater

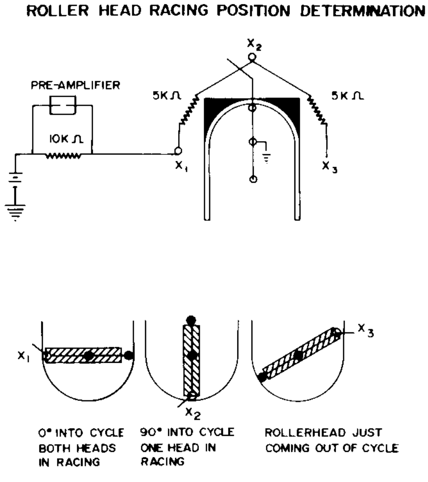
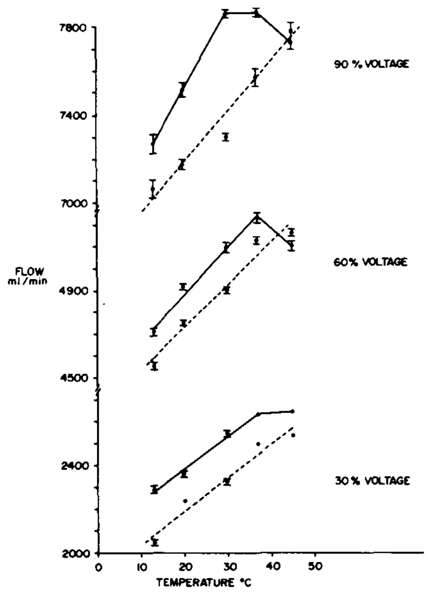


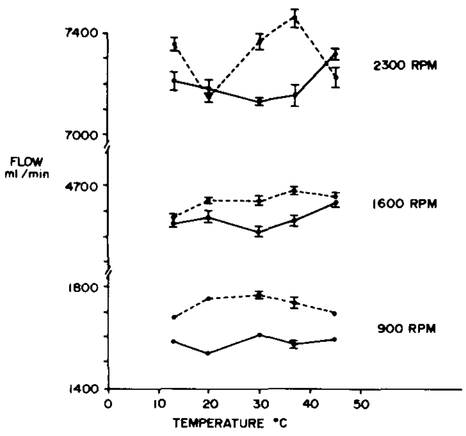
Figure 4. Diagram of the "clicker" device and the relationship of roller head position to fixed electrode contacts, X_1, X_2, X_3.



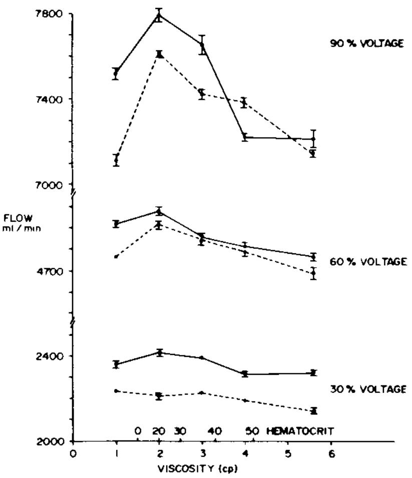
Graph 1. The effects of temperature on flow using the roller pump at 30, 60, and 90% voltage pump settings. Dotted line indicates $^{3}/_{32}''$ thick tubing and the solid line represents $^{1}/_{16}''$ thick tubing. (S.E.M., n = 4).

effect since this condition is of lower flows. The line through all five points has been determined to be non-linear which is partially based upon the data observed at the other two pump setting conditions.

Graph 2 shows the effects of temperature on flow using the constrained vortex pump.

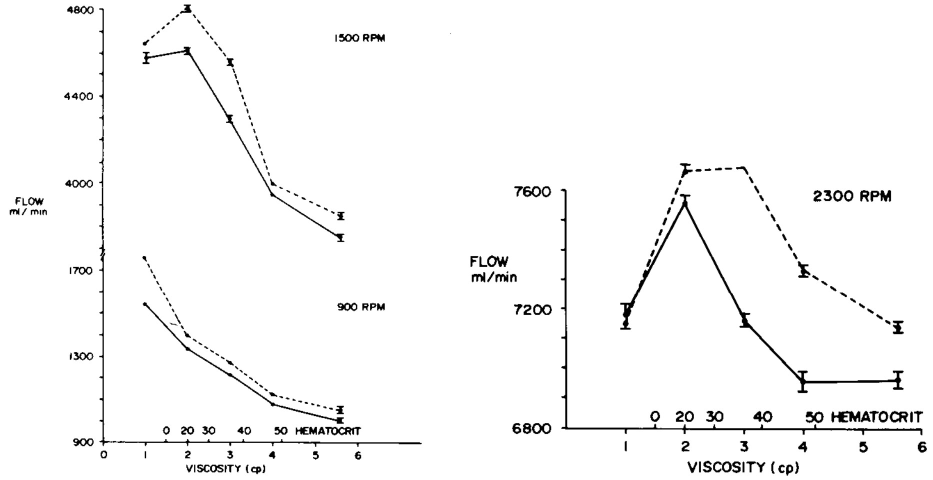


Graph 2. The effects of temperature on flow using the constrained vortex pump at pump settings of 900, 1600, and 2300 RPM. Dotted line represents the $^{3}/_{32}''$ thick tubing and the solid line represents the $^{1}/_{16}''$ thick tubing. (S.E.M., n = 4).

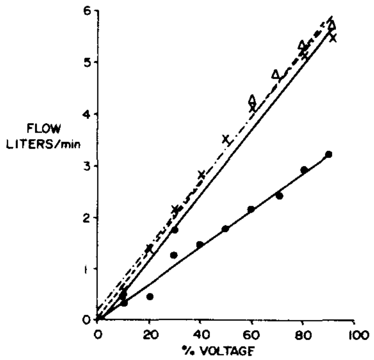


Graph 3. The effects of viscosity on flow using the roller pump at pump settings of 30, 60, and 90% voltages. Dotted line represents $^{3}/_{32}$″ thick tubing and the solid line represents $^{1}/_{16}$″ thick tubing. (S.E.M., n = 4).

In general, the 3/32″ tubing exhibits higher flows than the 1/16″ tubing. Temperature has little effect on flow for pump settings of 900 and 1600 RPM. The flow differences between the two tubing thicknesses is small. Both the flow differences of the two tubing thicknesses and the general slope of the points were small. The 3/32″ tubing has a higher flow rate at temperatures between 25 and 37°C at the 2300 RPM setting than the thinner tubing. The 3/32″ tubing dropped to a lower flow rate at 45°C and the 1/16″ tubing flow increased remarkably.



Graphs 4 and 5. The effects of viscosity on flow using the constrained vortex pump at pump settings of 900, 1600, and 2300 RPM. Dotted line represents the $^{3}/_{32}$″ thick tubing and the solid line represents the $^{1}/_{16}$″ thick tubing. (S.E.M., n = 4).



Graph 6. The effects of occlusion setting on flow using the roller pump. At pump settings of 10, 20, 30, 40, 50, 60, 70, 80, and 90% voltages. Legend: under occluded (dark circles and solid line), over occluded (solid line), just-occluded (triangles and dotted line), and just non-occluded (X's and dot-dash line). (S.E.M., n = 3).

It should be noted that the roller pump settings, expressed in percent voltage, may not correlate with the same RPM for all of the temperature and viscosity conditions.

Graph 3 shows the effects of viscosity on flow for the roller pump at each pump setting. Flow decreased slightly with increasing viscosity at the 30% pump setting. There was an initial increase in flow followed by a decrease with increasing viscosity at the 60% pump setting. The same phenomenon occurred at both the 60 and 90% pump settings except that the effects with the 90% were more remarkable. Generally, the 1/16″ thick tubing had higher flows than the 3/32″ tubing but the difference between the two tubing types was relatively small.

Graphs 4 and 5 show the effects of viscosity on flow using the constrained vortex pump. The 3/32″ tubing yielded a higher flow rate at each pump setting than the 1/16″ tubing. The flow decreased with increasing viscosity at the 900 RPM pump setting. There was an increase in flow between 1 and 2 cp at the 1600 and 2300 RPM pump settings. The 2300 RPM flow setting displays this phenomenon more remarkably. Flow decreased as the viscosity increased past 2 cp. The vortex pump was affected more by the increasing viscosity than was the roller pump at their respective low and medium pump settings. At the respective high pump setting, the effects are relatively similar.

The hematocrit scale was labeled on the same axis with the viscosity levels. The relationship between increasing viscosity and increasing hematocrit is not linear.[5,6] It should not be inferred from the graphs that blood was used in the circuit.

A statistical sign test was used to test the hypothesis that the distribution of the flow data for both tubing thicknesses (1/16″ and 3/32″) and all experimental conditions were identical. The calculated $|Z|$ was greater than 1.96 ($\alpha = .05$) which indicates the flow data distributions are not identical. ($P < .025$ for all cases.) It does appear from this statistical analysis that tubing thickness may effect flow in both pump types and experimental conditions.

Occlusion—Graph 6 shows the results of the effects of occlusion on flow rate using the roller pump. The under occluded condition had the greatest effect. Flow was decreased significantly. The over-occluded condition (solid line with dark circles) also resulted in

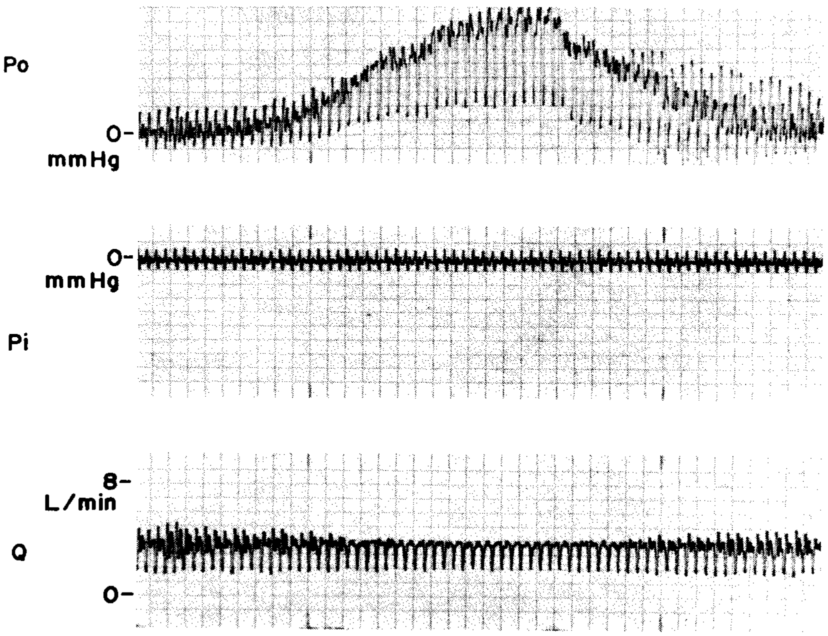


Figure 5. The effect of increasing the resistance on the outflow side of the roller pump. Legend: Po = outflow pressure (mmHg), Pi = inflow pressure (mmHg), Q = flow (liters/minute).

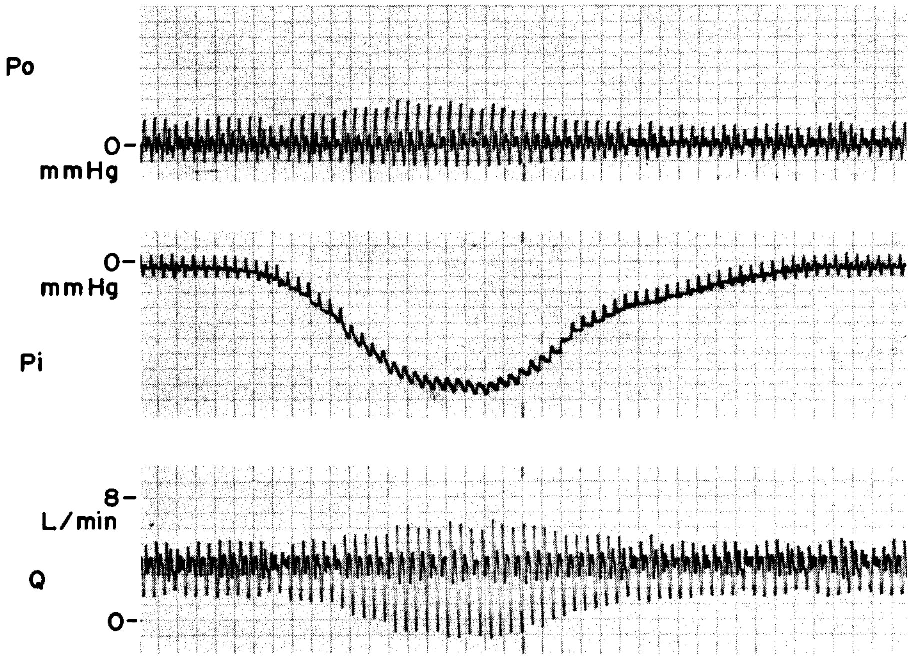


Figure 6. The effect of increasing the applied resistance to the inflow side of the roller pump. Legend: Po = outflow pressure, Pi = inflow pressure, and O = flow.

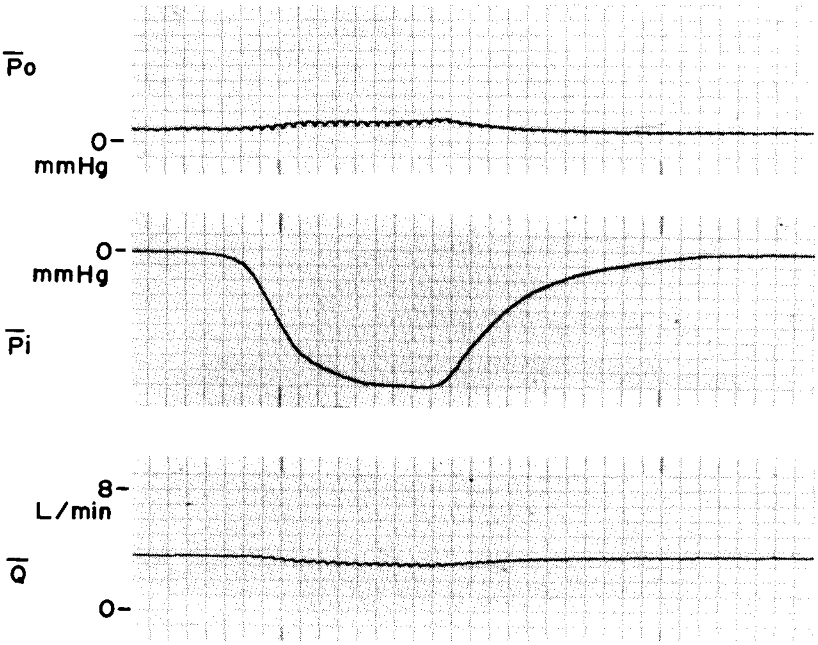


Figure 7. The effects of applied resistance to the inflow side of the roller pump in the mean mode.

decreased flow. The conditions of just-occluded (triangles and dotted line) and just non-occluded (Xs and dot-dash line) gave the highest flow rates. The extremes of over occluded and under occluded resulted in a decreased flow output.

Resistance—Figure 5 shows the results of increasing the resistance on the outflow side of the roller pump. The outflow pressure increased as the resistance was increased, the inflow pressure remained unchanged, and the positive peaks of the flow waveform were diminished. The mean flow, however, remained the same.

In Figure 6, the resistance was increased on the inflow side of the roller pump. The inflow pressure decreased, the outflow pressure increased slightly, and the mean flow rate decreased slightly. Figure 7 displays the recordings in the mean mode. The flow waveform increased its peaks both positively and negatively in phasic mode. The clamp on the inflow side was near total occlusion.

The same conditions were performed on the constrained vortex pump. Figure 8 shows the effect of increasing the resistance on the outflow side. In this case, the tubing clamp is totally occluding the circuit. The outflow pressure increased and then reached a plateau, the inflow pressure went to zero and the flow rate decreased to zero. It should also be noted that the pump was in the pulsatile mode. Figure 9 shows the condition of increasing the resistance on the inflow side of the vortex pump. Outflow pressure decreased towards zero, inflow pressure further decreased and the flow rate went to zero. Again, the circuit was totally clamped.

Roller Head Position—Figure 10 shows results of the roller head position with re-

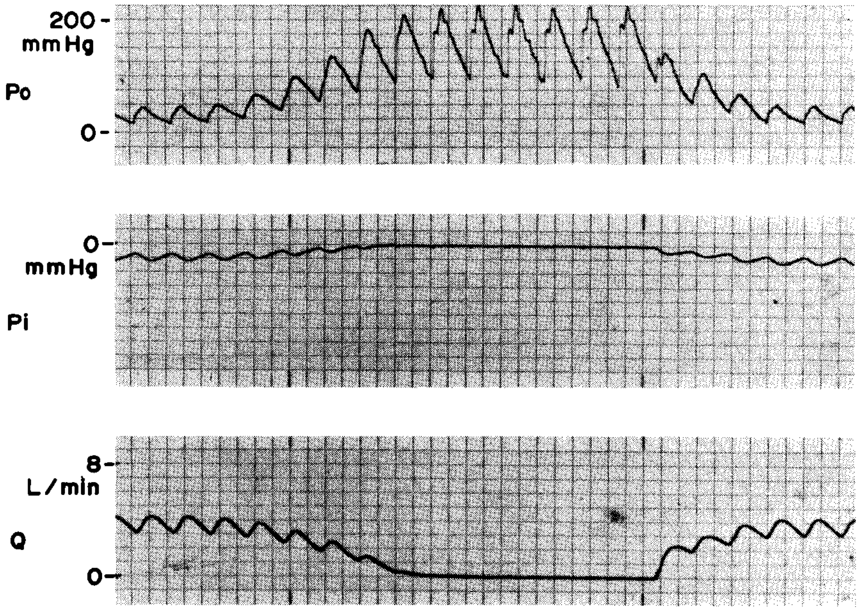


Figure 8. The effect of applied resistance to the outflow side of the constrained vortex pump.

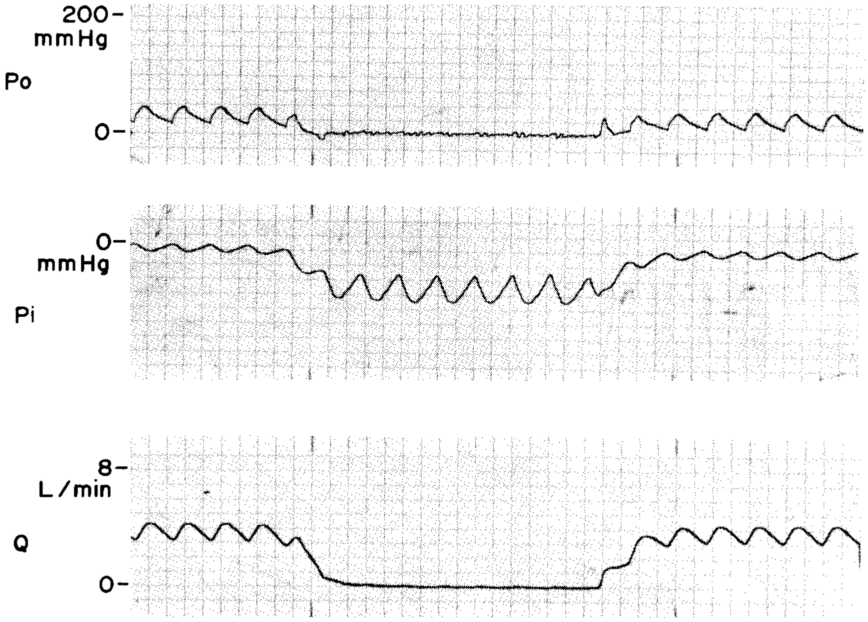


Figure 9. The effects of applied resistance to the inflow side of the constrained vortex pump.

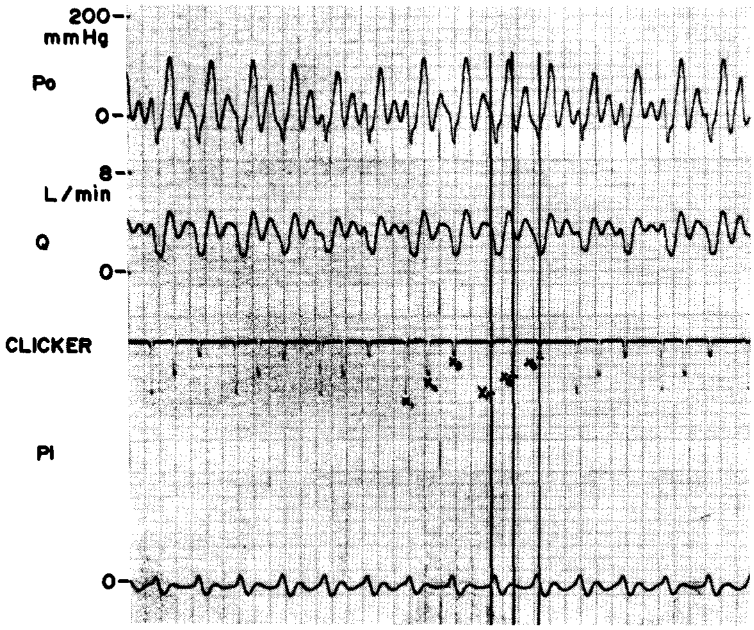


Figure 10. The relationship of roller head position to outflow pressure (Po), inflow pressure (Pi), and flow (O), utilizing the "clicker" device.

spect to the clicker, inflow and outflow pressures, and flow. At position X_1, the roller head is beginning its revolution through the racing. The opposite roller head is just about to leave the racing. One roller head is in the racing between positions X_1 and X_2. The outflow pressure and the inflow pressure dropped below zero. The flow waveform also decreased indicating reduced flow. Just prior to position X_2 the outflow pressure reached its maximum, the inflow was just rising from its minimum pressure, and the flow waveform was near its maximum positive point. At position X_2, the outflow pressure dropped significantly, the inflow pressure was near zero, and the flow waveform was decreasing. The outflow pressure was negative but was closer to zero than at position X_1. The inflow pressure remained slightly negative at a constant level and the flow was decreased. The outflow pressure increased as the roller head moved a little further. The opposite roller head was at that point beginning its revolution through the racing. At position X_3 the roller head had about left the racing. The pressures and flow waveforms were the same as displayed immediately after the roller head passed position X_1. This completed the cycle for the roller head through the pump racing.

It would be noted that the pressure and flow waveforms reflected another rhythmic cycle which may or may not be the result of the pump itself.

DISCUSSION

Temperature and Viscosity—Temperature affected the flow from the roller pump more than the flow from the vortex pump. Some possible reasons for this result are the factors of tubing compliance and memory. Cooler temperatures result in stiffer tubing, decreased compliance and memory capability.[7] Together, these factors could decrease the stroke volume and cause a decrease in flow. Another variable which may have affected the flow was the resistance of the roller head to tubing and to the racing. The colder solutions increase the resistance and may decrease the RPM's of the pump head even though the pump setting is the same. The other phenomenon observed from the roller pump experiment was that the thinner walled tubing (1/16″) had a decrease in flow at 45°C for the 60 and 90% pump settings. There appeared to be a trend of decreasing flow for the 30% pump setting. The PVC tubing becomes more pliable and the viscosity of the fluid decreases at the warmer temperatures. The stroke volume may be decreased as a result of the effects of the warmer temperatures due to increased pliability or decreased viscosity.

The vortex pump was affected by viscosity more than the roller pump. However, the roller pump was affected at the high pump setting. The flow was less at 1 cp than at 2 cp. A possible reason for this result is that the decrease in roller head resistance passing through the racing at 1 cp might have resulted in an increase in RPM. The fluid is at 20°C so the memory of the PVC tubing is depressed which may decrease the stroke volume and thus result in decreased flow. The viscosity of the fluid is doubled at 2 cp. The viscosity of the fluid may cause an increase in memory return in the tubing because of its denser quality. However, at greater viscosities the flow is decreased which may indicate that the resistance to the roller head overrides the increased memory return of the tubing.

The principle of the constrained vortex pump is that the acceleration from the rotator walls is transmitted to the adjacent fluid layer (due to shear forces) which imparts this acceleration and force to neighboring fluid layers. Therefore, due to the shear forces of the adjacent fluid layers, the fluid essentially is its own prime mover.[8,9] These shear forces between the fluid layers are crucial in transmitting the acceleration applied by the pump rotator.

Shear forces are also closely related to the elements of viscosity. Viscosity is defined as tangential forces between the laminae which are proportional to the area of contact between the laminae and to the velocity gradient.[5]

$$\eta = \frac{\text{shearing stress}}{\text{velocity gradient}} = \frac{F/A}{v/l}$$

where: η = viscosity
F = tangential force
A = area of contact between laminae
v = velocity
l = length of velocity gradient

Increasing the shear stress results in an increased viscosity for a given velocity gradient.[10] The greater the velocity gradient, the greater the energy transfer.[5] Depending upon the amount of energy from the pump rotator, the transfer of accelerating forces would be more efficient with increased viscosity and thus result in a higher flow rate. This assumption has been supported by data (Olsen *et al.*) which indicated that increasing viscosity resulted in an increase in flow at a particular pump setting.[8] The results obtained in the present study did not fully support the assumption that increasing viscosity results in an increase in flow.

Two variables may account for the results observed at the 1 and 2 cp viscosities (Graphs 4 and 5). These variables are: 1) the force of the pump rotator, and, 2) the shear forces at the respective viscosity levels. At the 1 cp viscosity level, flow was higher compared to the flow rate at 2 cp for the 900 RPM pump setting. For the other pump settings (1600 and 2300 RPM) the flow was lower at the 1 cp level compared to the 2 cp level. The force from the pump rotator was sufficient at the low pump setting but it appears that there may be turbulent conditions due to the greater force applied at the 1600 and 2300 RPM pump settings. The shear stress is less at the 1 cp viscosity level than at the 2 cp level. Turbulent conditions occur more readily in lower viscosity fluids than in higher viscosity fluids.[10] Although it cannot be determined if the fluid was turbulent in the pump rotator housing the data at the 2 cp viscosity level seems to support this assumption. The increased viscosity has greater shear stress which can more efficiently transfer the acceleration of the pump rotator at higher pump settings (1600 and 2300 RPM). The result is an increase in flow and possibly the reduction of turbulence in the adjacent fluid layers due to the increased viscosity.

The flow decreased at the 1600 and 2300 RPM pump settings with viscosities greater than 2 cp. At the 900 RPM pump setting, the flow decreased with increasing viscosity after 1 cp. This result is contrary to the assumption that increasing viscosity should result in higher flows. A possible reason for the differing results is that the resistance of the circuit increased with increasing viscosity. The total increased resistance is greater than the net efficiency obtained from the increased viscosity since the constrained vortex pump is "load sensitive." If the resistance is great enough, the flow rate will decrease at a given pump setting. Similar results were demonstrated in the resistance experiment. The viscous resistance in the circuit apparently is greater than the output force of the pump which resulted in lower flows with increasing viscosity.

Occlusion—The effects of pump occlusion on flow are reported.[4] A basic fact of an occluded pump is that it is "load insensitive." Within the ranges of outflow pressures commonly used in clinical perfusion, the occluded roller pump will continue to deliver the same flow regardless of the resistance.[7] An unoccluded pump is affected by various pressures and resistances, which have to be compensated for by increasing the stroke rate. The vortex pump, however, is load sensitive as shown in the viscosity and resistance experiments.

Resistance—The basic variables of Poiseuille's Law, flow, pressure and resistance, were analyzed. Poiseuille defines resistance as follows:

$$R = \frac{8\,L\,\eta}{\pi\, r^4}$$

where: $8/\pi$ = a constant
η = viscosity
L = length
r = radius

The effects of viscosity were discussed previously. In the resistance experiments the viscosity and the length of the circuit were both kept constant. The radius, "r", is the most influential variable since decreasing the radius by one-half can increase the resistance by a factor of sixteen.

Increasing the resistance on the outflow side of the roller pump was restricted since total occlusion would result in a circuit rupture. This condition is primarily caused by the total occlusion of the roller head which makes the system load insensitive as previously described. Even though the resistance increased remarkably, the roller pump was able to maintain the flow rate with an appropriate change in pressure. It should be emphasized that if the diameter of the tubing is decreased more than 80%, the flow rate from the roller pump will also decrease. The resulting outflow pressures, however, would be quite high and roller head movement probably impeded.

The constrained vortex pump was affected differently since this pump system is load sensitive. The tubing could be totally occluded with a tubing clamp. The result was an initial increase in outflow pressures which leveled off and a decreased of flow towards zero. The same results occurred on the inflow side. The constrained vortex pump could not handle the resistance placed on the system. An increase of pump RPM's is needed to produce adequate pressure to compensate for the increased resistance.

Roller Head Position—Negative pressure, as demonstrated on the outflow pressure waveform, occurs twice in the roller head cycle. This negative pressure has the potential of bringing gas out of solution.[11] This phenomenon is due to the occlusion of the roller head. If the roller head was not occlusive, the regurgitation which occurs when the roller head leaves the racing would be diminished. This regurgitation can be identified as rapid negative deflection of the outflow pressure waveform.

SUMMARY

Flow was demonstrated to be affected by several physical factors which are present in the clinical environment. The perfusionist should be aware of these factors for both types of pumps. Ideally, the perfusionist should use an in-line flow probe to account for the changing physical factors.

The roller head position was effectively analyzed with a simple voltage divider. It appears that when the roller pump is occluded, negative pressures occur. The perfusionist should analyze and compare the pros and cons of pump efficiency to patient welfare.

Although it has been shown that flow is affected by several physical factors, it is clear that more work is needed to analyze the reasons why these results occurred.

REFERENCES

1. Betts, Robert, Unpublished data, The Ohio State University, 1978.
2. *Handbook of Physics and Chemistry,* Weast, R. C., ed., 49th Edition, Chemical Rubber Publishing Co., 1968.
3. Giles, R. N., "A Study of the Viscosities of Binary Liquid Mixtures Containing Glycerol, Glycols, and Alcohols." Dissertation, Ohio State University, 1930.
4. Meyer, M. M., "Blood Pump Occlusion." *J.E.C.T.* (4): 8, 1978.
5. Burton, A. C., *Physiology and Biophysics of the Circulation.* Yearbook Medical Publishers Inc., Chicago, 1975.
6. Guyton, A. L., *Textbook of Medical Physiology.* 3rd Ed., Saunders, Philadelphia, 1960.
7. Galletti, P. M. and Brecher, G. A., *Heart-Lung Bypass, Principles and Techniques of Extracorporeal Circulation.* Grune and Stratton, Inc., New York, 1962.
8. Olsen, D. A., Kletschka, H. D., Rafferty, E. H., Clausen, E. W. and Laison, W. H., "Design Considerations for a Non-pulsatile Blood Pump." Presented at the 27th ACEMB Leamington Hotel, 9/30–10/4, 1973.
9. Rafferty, E. H., Kletschka, H. D., Wynard, M., Larkin, J. T., Smith, L. V., and Cheathem, B., "Application of Non-pulsatile Force-Vortex Principle." *Minnesota Medicine,* 51: 11–16, January, 1968.
10. Sears, F. W. and Zamansky, M. W., *University Physics.* Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1970.
11. Mandl, J. P. "Comparison of emboli production between a constrained force vortex pump and a roller pump. *AmSECT Proc. V:* 27, 1977.