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An In Vitro Comparison of the Effects of Temperature on the Stroke Volume and Occlusion Setting of Various Tubing Types in a Roller Pump

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INTRODUCTION

It is the purpose of this paper to compare the effect of temperature change on flow rate and roller occlusion setting in several manufactured tubing types. Wright[1] in 1962, first studied the effects of altering the perfusate temperature on roller pump flow output with various tubing type ventricles. Since 1968, studying the variables that alter roller pump outflow has been a basic and early experience in the Circulation Technology (CT) Division Curriculum in the Ohio State University School of Allied Medicine. This study is an extension of a CT IN VITRO lab employing eleven tubing types presently available on the market. Accurate knowledge of the roller pump blood flow rate by the perfusionist during bypass is imperative to aid in predicting the adequacy of perfusion. Recording an accurate blood flow rate is also important if reproducible research is to be conducted and calculations such as total body oxygen consumption employing cardiac output are to be performed.

The analogy to flow output by the heart may be drawn to a roller pump:

Cardiac Output = Stroke Volume × Heart Rate

or

$$\text{Roller Pump Flow Output} = \text{Pump Tubing Ventricle Stroke Volume} \times \text{Revolution per minute}$$

with the units

$$\text{milliliters/minute} = \text{milliliter/revolution} \times \text{revolution/minute}$$

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The variables that effect roller pump outflow are easily studied if RPM's are held constant. Roller pump inflow pressure gradient, pump outflow gradient and roller occlusion are initially fixed in this method as perfusate temperature is altered.

Pump ventricle tubing must withstand stress and strain with use of a positive displacement roller pump to obtain the desired stroke output, produce a linear output by accurate rapid filling, and maintain the proper occlusion setting throughout the duration of extracorporeal circulation (E.C.C.) and the ranges of temperatures employed. According to Peirce,[2] blood temperature during bypass with hypothermia can range safely from 4.3°C to 42°C.

Eleven tubing types all 3/8″ i.d. × 1/16″ wall thickness* are ranked according to the flow output change as temperature is varied. The variables of occlusion change with temperature and changes in tubing segment due to exposure to several temperatures are isolated in this method.

MATERIALS AND METHODS

A Travenol modular positive displacement roller pump S.N. 2378 set at 100% voltage maximum yielding 340 mean RPM's is used to circulate 25% aqueous glycerol solution from a reservoir fluid level located 40.6 cm below the pump head.

The solution passes through the pump head, through a Sarns 125 ml external heat exchanger and returns to the reservoir. A 200 mmHg roller pump afterload to simulate patient afterload and pressure gradient across the arterial line and cannula during bypass is attained and closely monitored by tightening a Hoffman clamp placed on the positive side of the pump ventricle. Pressure proximal to the clamp is measured with a calibrated Statham P23Ib pressure transducer S.N. 25330 connected to an Electronics for Medicine DR-8 Recorder Monitor.

Mean roller occlusion is set for each roller at a single position on the race by allowing a 30 inch vertical column of glycerol above the reservoir in parallel with the arterial line, drop 1 inch (in) in 1 minute (min) through the roller to attain a barely nonocclusive roller setting.

Three calibrated YSI Series 400 Thermisters are used to measure the temperature of water to the heat exchanger, the temperature of the glycerol solution in the reservoir, and the temperature of the glycerol solution just prior to the pump ventricle. Water temperature is precisely set to maintain the glycerol solution at the desired temperature monitored by the two thermistors to an accuracy of 1/10°C. Flow rate is measured and recorded for three consecutive 15 second fluid collections in a graduated cylinder.

MULTIPLE TEMPERATURE EXPOSED TUBING

Initial mean roller occlusion is set at 37°C after a 10 minute temperature equilibrium period, then the solution is warmed to 45°C and the temperature is changed at 5°C intervals from 45°C to 15°C for a multiple temperature exposure. Flow rate is measured after a 10 minute temperature equilibrium period at each temperature. Three flow rate

* Except Dow Corning Silastic 3/8″ i.d. × 1/8″ wall

TABLE I

Multiple temperature exposure: eleven tubing types are ranked according to increasing ln (ml/min)/°C. Mean % of the initial occlusion setting at each temperature and the temperature calibration line equation for each tubing type are included

Tubing Type	Mean Flow ± 1 S.D. (ml/min)	Flow Range (ml/min)	Mean Occlusion (inch/min/30in)	Mean % of Initial Occlusion Setting, Temperature (°C) 15	20	25	30	35	40	45	Equation of line for multiple temp. exposure $y=e^{(mx+b)}$	Correlation Coefficient (r)
Natural Latex	5811.84 ± 307.52	890.89	.97 ± .18	-35.29	+3.36	-35.29	-12.60	-33.61	-17.65	-16.81	$y=e^{(.0048x+8.522)}$	.961
Harvey PVC/PUL	6472.70 ± 389.98	1077.78	.93 ± .13	+15.08	+2.17	+10.87	-2.17	+4.35	-7.61	-22.83	$y=e^{(.0056x+8.607)}$	.993
Dow Corning Silastic**	5450.03 ± 346.72	893.34	1.51 ± .28	+26.78	+35.71	-3.57	+58.04	+56.25	+56.25	+50.89	$y=e^{(.0057x+8.431)}$	.969
Harvey PVC	6016.10 ± 478.64	1364.44	1.21 ± .19	+27.27	+46.59	+61.36	+63.64	+25.00	+48.86	+27.27	$y=e^{(.0074x+8.478)}$	.982
Bentley PVC	5550.86 ± 441.84	1228.88	1.11 ± .43	+69.72	+37.61	-44.95	-22.02	-44.95	+10.09	+6.42	$y=e^{(.0074x+8.397)}$	.997
Tygon S-50-HL PVC	5745.65 ± 595.49	1657.78	.74 ± .09	+32.81	+26.56	+12.50	+29.69	+23.44	-4.69	+1.56	$y=e^{(.0097x+8.361)}$	.987
Gics Mediflex PVC	5726.35 ± 608.72	1628.89	.61 ± .19	-21.52	-35.44	-46.84	-51.90	-35.44	-6.33	+13.92	$y=e^{(.0099x+8.352)}$	.984
Travenol PVC	5812.70 ± 622.95	1695.56	.66 ± .11	-14.12	-36.47	-35.29	-11.76	-30.59	-20.00	-34.12	$y=e^{(.0099x+8.365)}$	.967
Tygon M-60 PVC	5516.19 ± 695.10	1828.89	.56 ± .31	-66.07	-70.54	-66.07	-61.61	-66.07	-11.61	-58.93	$y=e^{(.0116x+8.261)}$	.947
Cobe PVC***	5997.14 ± 756.23	2086.67	1.32 ± .23	+16.67	+2.50	+10.00	-.83	+21.67	+2.50	+50.83	$y=e^{(.0117x+8.339)}$	.989
Tygon M-70 PVC	5686.98 ± 897.08	2437.77	.76 ± .21	-60.87	-46.96	-48.09	-29.56	-32.17	-23.48	-33.04	$y=e^{(.0149x+8.188)}$	.969

* Travenol modular roller pump S.N. 2378 @ constant rpm, tubing 3/8" i.d. x 1/16" wall
** 3/8" i.d. x 1/8" wall
*** Tygon Product

TABLE II

Single temperature exposure: eleven tubing types are ranked according to increasing ln (ml/min)/°C. Mean % of the initial occlusion setting at each temperature and the temperature calibration line equation for each tubing type are included

Tubing Type	Mean flow ± 1 S.D. (ml/min)	Mean % change of initial occlusion setting @ temperature (°C)			Equation of line for single temperature exposure $y=e^{(mx+b)}$	Correlation Coefficient (r)
		15	30	45		
Harvey PVC/PUL	6848.89 ± 244.56	-11.96	+8.33	+30.21	$y=e^{(.0011x + 8.811)}$	.926
Bentley PVC	5782.22 ± 161.07	+2.22	-10.71	-13.21	$y=e^{(.0027x + 8.646)}$	.700
Tygon S-50 HL PVC	6153.33 ± 93.27	+25.98	-33.33	+14.28	$y=e^{(.0028x + 8.706)}$	.726
Gics Mediflex PVC	6111.11 ± 107.29	+107.29	-8.33	-24.79	$y=e^{(.0028x + 8.678)}$	.995
Harvey PVC	6204.44 ± 130.68	+6.12	-21.05	-17.86	$y=e^{(.0032x + 8.700)}$	.870
Natural Latex	5431.11 ± 95.45	+10.84	-13.26	+10.84	$y=e^{(.0032x + 8.557)}$	.979
Cobe PVC ***	5820.00 ± 164.52	+16.04	-21.57	+84.30	$y=e^{(.0038x + 8.631)}$	.866
Travenol PVC	6080.00 ± 12.25	+8.89	-30.68	-8.33	$y=e^{(.0043x + 8.654)}$	.992
Dow Corning Silastic**	5172.89 ± 113.63	+3.75	-15.97	+4.00	$y=e^{(.0044x + 8.489)}$	.995
Tygon M-60 PVC	5428.89 ± 234.97	-9.57	+5.26	-11.32	$y=e^{(.0050x + 8.550)}$	.854
Tygon M-70 PVC	5215.56 ± 158.04	-2.31	-19.66	-2.17	$y=e^{(.0082x + 8.461)}$	.942

* Travenol modular roller pump S.N. 2378 @ constant rpm, tubing 3/8" i.d. x 1/16" wall
** 3/8" i.d. x 1/8" wall
*** Tygon Product

measurements are made and recorded at each temperature and subsequently the occlusion is checked and recorded. Three pieces of each manufacturer's sample are randomly selected and tested for multiple temperature exposure. The mean and standard deviation for flow rate and occlusion at each temperature and tubing sample are calculated and recorded. The mean percent change of initial occlusion setting is calculated for each tubing type at each temperature.

SINGLE TEMPERATURE EXPOSED TUBING

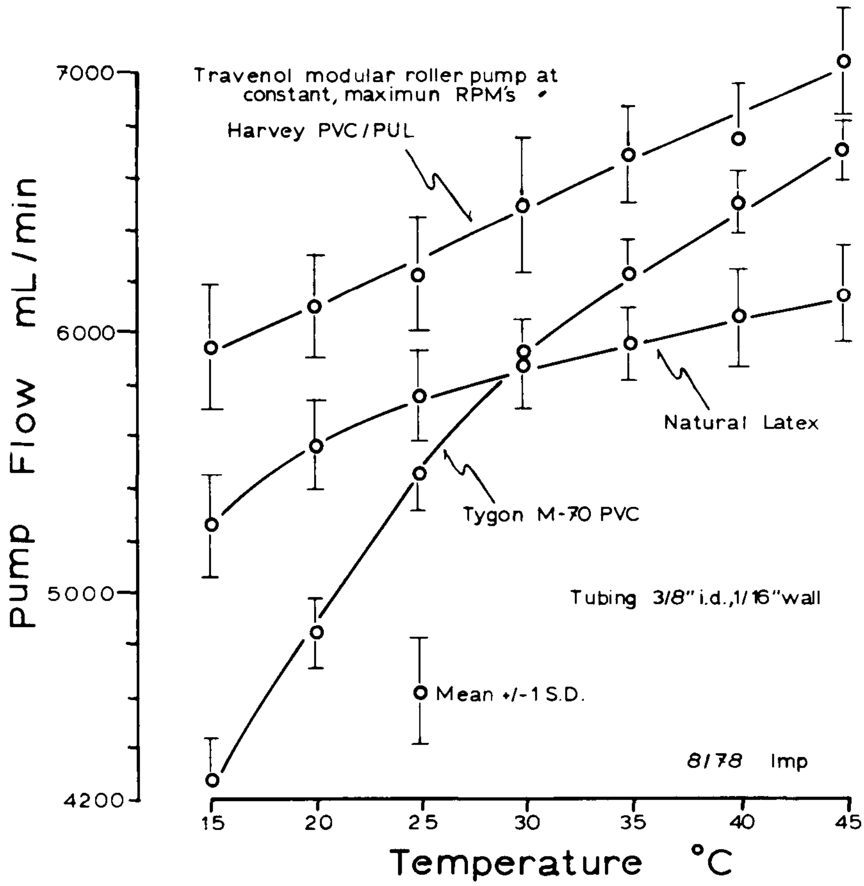
To isolate possible flow rate change due to occlusion shift and tubing physical property change as a result of multiple temperature exposure, three tubing samples of each type are evaluated at three temperatures, 15°C, 30°C, and 45°C, using a different randomly selected manufacturer's tubing sample for each temperature for single temperature exposure. (Personal communication with Don Siddall, Norton Company, Inc.) Pump occlusion is set for 1 inch drop/min/30 inches for each tubing at each temperature and three consecutive 15 second flow rate determinations are measured and recorded after a 10 minute temperature equilibrium period. Occlusion setting is checked and recorded after the flow rate measurement and the mean and standard deviation of both at each temperature is calculated for all tubing segments. Mean percent change of initial pump occlusion setting for each tubing type is calculated and recorded.

RESULTS

The eleven tubing types tested are listed in Table 1 and Table 2 and rated according to increasing natural log (ln) of the change in flow per °C for both multiple and single temperature exposed tubing, respectively. The mean flow (ml/min) ± 1 standard deviation (S.D.) and mean percent change of the initial occlusion setting at each temperature for the multiple and single temperature exposed tubing are also listed on the respective tables. Included in Table 1 is both the mean occlusion (inch/min/30 inches), and the mean % change of the initial occlusion setting at each temperature for the multiple temperature exposed tubing. In addition, the equation of the straight line plotted from flow versus temperature on semilog paper, and the corresponding linear regression correlation coefficient (r) are included in Table 1 and 2. The excursion of flow for the multiple temperature exposed tubing is listed in Table 1 under flow range.

The Polyvinyl Chloride (PVC) tubing with the greatest and least change in mean flow per °C along with natural latex are linearly plotted on Graph 1, and are logarithmically plotted on Graph 2. A straight line results when flow is plotted against temperature on semilog paper. The slopes of these example lines on Graph 2 are the criterion for the tubing ratings on Table 1 and 2.

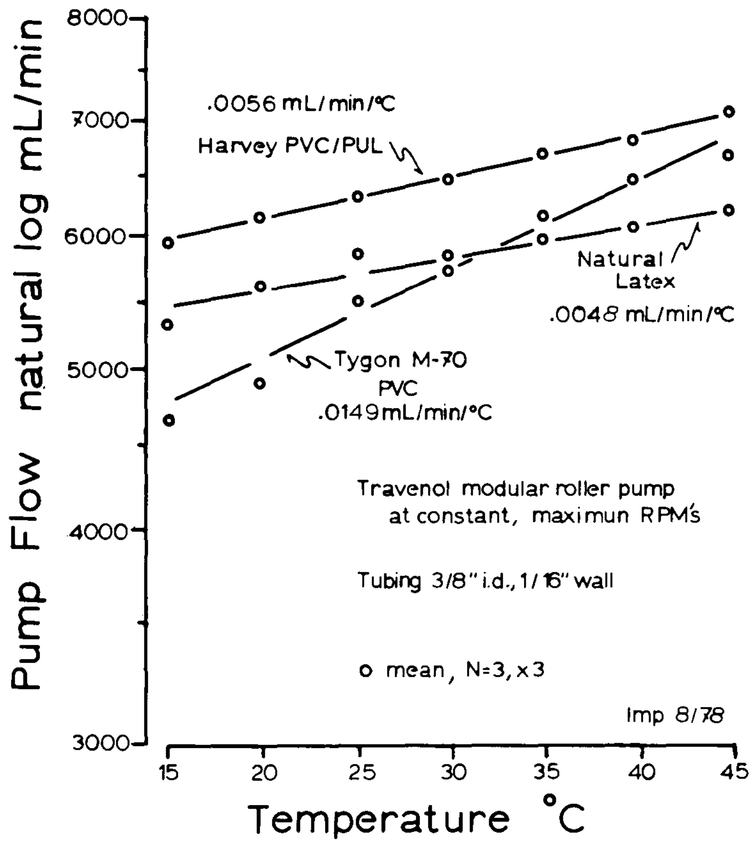
Natural Latex incurred the smallest change in mean flow per temperature (ml/min/°C) shown on Table 1, and is rated first with a slope of .0048 ln (ml/min)/°C. The equation of the line for natural latex is $y = e^{(.0048x + 8.552)}$ where .0048 is the slope (m) and 8.552 is the y-intercept (b). Harvey Polyvinyl Chloride/Polyurethane lined tubing (PVC/PUL) has the smallest change in the ln of flow per °C of the Polyvinyl Chloride tubings with a slope of .0056 ln (ml/min)/°C where $y = e^{(.0056x + 8.607)}$. Dow Corning Silastic is rated next with an ln (ml/min)/°C of .0057 and an equation of the line of y



Graph 1. Multiple temperature exposure: the effect of altering perfusate temperature on the flow output of three tubing types at constant RPM's.

$= e^{(.0057x + 8.431)}$. Tygon M-70 PVC tubing is ranked last with a slope of .0149 ln (ml/min)/°C.

Average % change of initial occlusion setting (inch/min) ± 1 S.D. versus temperature (°C) for multiple temperature exposed tubing is plotted on Graph 3. Average occlusion setting does not change from the initial setting as temperature is varied from 45°C to 15°C, however at 25–30°C fewer tubing types demonstrate a positive change in occlusion. The occlusion variance for each tubing type is often as much as ±35% of the initial occlusion setting. The same trend in occlusion setting is also seen on Graph 4, for Gics Mediflex PVC tubing. Flow rates do not appear to be affected by the average dip in occlusion setting at 30°C. Mean flow at each temperature for both the single and multiple temperature exposed tubing along with the respective equation of the line is shown in Graph 4.



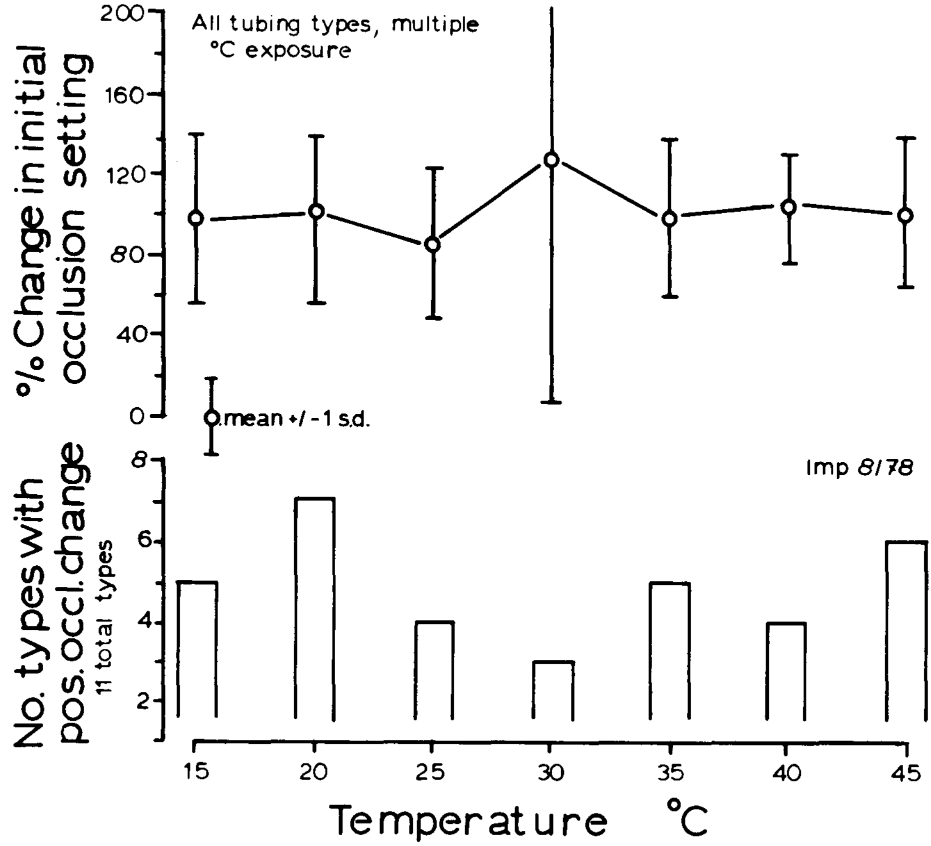
Graph 2. Multiple temperature exposure: the effect of altering perfusate temperature on the natural log of flow output of three tubing types at constant RPM's.

DISCUSSION

The test exposing each tubing sample to a multiple temperature range simulates a commonly used perfusion technique for extracorporeal circulation with hypothermia. Exposure of the test tubing sample to a single temperature with occlusion set at each temperature isolates flow rate changes due to occlusion change and tubing physical characteristics that change with multiple temperature exposures.

Stroke output increases exponentially as perfusate temperature increases with constant mean RPM's and constant input and output pressure for all tubing types tested, evident from Graph 1, 2, and 4 and Table 1, 2, and 3. According to Wright[1] Latex is unaffected by temperature however in this protocol Latex flow rate ranges 890 ml/min from 45°C to 15°C.

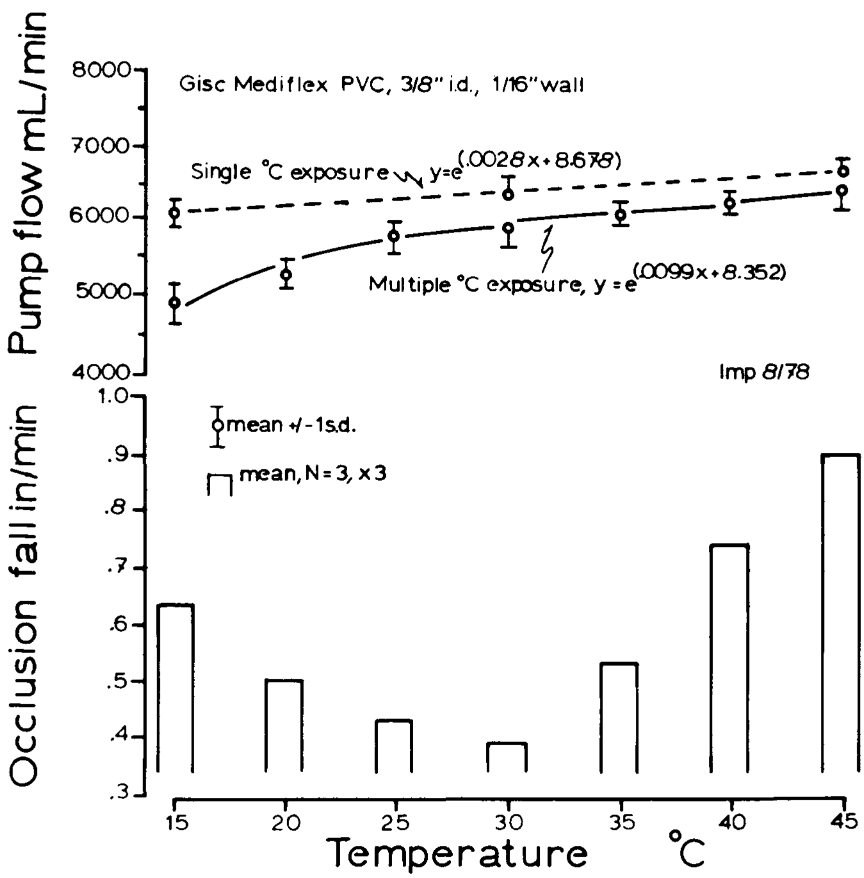
The slope of the line (m) of the natural log of flow rate versus temperature is shown in the equation of the line in Table 1 and 2 for the multiple and single temperature exposed



Graph 3. Multiple temperature exposure: the effect of temperature on the average % change in occlusion for all tubing types grouped together and the number of tubing types that exhibited positive occlusion change versus temperature are plotted.

tubing respectively. Clinical ramifications can be derived from the multiple temperature exposed tubing results (Table 1) due to protocol simulation of the conditions of heart-lung bypass with hypothermia. The tubing order in Table 1 is ranked according to increasing semilog-plot slope value. The smallest slope, correlating to the lowest flow range over the temperature range tested is considered a higher confidence tubing. In general, as the durometer (Shore A Hardness) increases, the slope and the tubing's rank in this method increase. Tubing types in Table 2 are also rated according to increasing slope value determined from the single temperature exposed tubing data showing the effects of isolating multiple temperature exposure and occlusion change with temperature.

The equation of the lines determined by linear regression of the natural log of flow versus temperature found in Table 1 and 2 for the multiple and single temperature exposed tubing respectively, can be used to determine flow rate for a tubing type in this preparation when perfusate temperature is known. The basic equation is $y = e^{(mx+b)}$, where m is the slope of the line, b the y-intercept, x the temperature and y the flow rate.



Graph 4. Multiple and single temperature exposure: Gics Mediflex PVC flow output versus temperature for both single and multiple temperature exposures and the % change in occlusion versus temperature for multiple temperature exposure are plotted.

Multiple temperature exposed tubing equations of the line (Table 1) can also be used to determine flow during extracorporeal circulation with hypothermia. For example, flow rate for Tygon S-50-HL PVC tubing $^3/_8''$ i.d. × $^1/_{16}''$ wall at maximum RPM's and an input pressure of −40.6 cm and output pressure of 200 mmHg with 25% glycerol solution at 20°C is calculated by inserting m, x, and b from Table 1 in the following equation:

$$y = e^{(mx+b)}$$

$$= e^{(.0097\ ml/min/°C \times 20°C\ +\ 8.361\ ml/min)}$$

$$= e^{8.555}$$

$$= 5192\ ml/min$$

TABLE III

Multiple temperature exposure: the mean flow ± one standard deviation at each temperature for each tubing type are presented.

Tubing Type	Temperature (°C)*						
	15	20	25	30	35	40	45
Dow Corning Silastic**	4922.22 ± 80.28	5074.00 ± 109.16	5351.11 ± 87.24	5582.22 ± 79.65	5622.22 ± 121.84	5782.89 ± 117.32	5815.56 ± 142.40
Natural Latex	5278.00 ± 159.01	5560.00 ± 143.88	5755.56 ± 123.20	5913.33 ± 77.46	5956.00 ± 178.84	6051.11 ± 212.86	6168.89 ± 165.26
Harvey PVC/P U L	5957.78 ± 245.45	6122.22 ± 206.26	6224.45 ± 215.36	6486.87 ± 245.36	6711.11 ± 149.37	6771.11 ± 218.20	7035.56 ± 162.72
Bentley PVC	4915.56 ± 153.88	5128.89 ± 140.40	5396.00 ± 165.14	5542.22 ± 215.28	5773.33 ± 211.42	5955.56 ± 300.96	6144.44 ± 302.78
Harvey PVC	5257.78 ± 196.07	5568.89 ± 178.64	5911.11 ± 182.51	6097.78 ± 125.87	6226.00 ± 166.28	6428.89 ± 126.14	6622.22 ± 97.70
Tygon S-50-HL PVC	4833.33 ± 176.07	5184.00 ± 224.06	5548.89 ± 134.20	5813.33 ± 137.11	6093.33 ± 158.11	6255.56 ± 170.52	6491.11 ± 131.57
Gics Mediflex PVC	4806.67 ± 137.21	5124.44 ± 130.30	5553.33 ± 119.16	5757.78 ± 199.11	6088.89 ± 149.70	6317.78 ± 184.78	6435.56 ± 258.80
Travenol PVC	4804.44 ± 131.82	5206.67 ± 150.66	5673.33 ± 198.24	5962.22 ± 163.54	6200.00 ± 199.56	6342.22 ± 203.82	6500.00 ± 168.52
Tygon M-60 PVC	4366.67 ± 147.65	4840.00 ± 156.20	5342.22 ± 144.38	5840.00 ± 171.17	5897.78 ± 137.28	6131.11 ± 166.77	6195.56 ± 166.67
Cobe PVC ***	4893.33 ± 100.00	5237.78 ± 104.14	5737.78 ± 162.62	6055.56 ± 129.91	6451.11 ± 237.72	6624.44 ± 221.08	6980.00 ± 292.40
Tygon M-70 PVC	4255.56 ± 88.19	4820.00 ± 89.44	5453.33 ± 135.28	5875.56 ± 136.67	6231.11 ± 105.88	6480.00 ± 94.34	6693.33 ± 135.28

* Travenol modular roller pump S.N. 2378 @ constant rpm, tubing 3/8" i.d. x 1/16" wall
** 3/8 " i.d. x 1/8 " wall
*** Tygon Product

5192 ml/min is in agreement with Table 3, where the mean observed flow at 20°C is 5184 +/− 224 ml/min for the Tygon S-50-HL PVC tubing.

The exponential equation of the line to determine flow should only be employed in situations with similar initial occlusion setting, input and output pressures, and 340 mean maximum RPM's for any one tubing type. Decreasing the RPM's will decrease the y-intercept of the flow calibration line and probably decrease the slope of the line. Generation of a detailed flow calibration chart relating flow, temperature, occlusion setting, and input and output pressures at all RPM settings is necessary to accurately determine flow rates during E.C.C.

Graph 4 is a comparison of flow versus temperature for Gics Mediflex PVC for both single and multiple temperature exposure. Both testing protocols result in flow curves that are substantially different especially at lower temperatures for all tubing types.

Flow rate change due to temperature change during extracorporeal circulation may become critical with the resulting effect of hypoperfusion as flow rate decrease due to temperature decrease becomes a greater percent of the initial calculated flow rate. Lower initial flow rates from calculated cardiac indices, for small adult patients, and pediatric and infant perfusion may constitute acid base problems if flow rate is manually decreased concurrently with the flow output fall at constant RPM's that accompanies moderate hypothermia or more often in the latter case, profound hypothermia. Conversely, flow rate, if increased by the perfusionist upon warming from hypothermia to overcome any metabolic debt incurred, may overcorrect any acid base imbalance as ventricle stroke output tends to return to and exceed the initial value with increasing perfusate temperature. Also, unassuming flow rate change with temperature will affect any clinical or research oriented calculations where cardiac output is employed.

CONCLUSIONS

1. Holding RPM's constant, pump flow output is a direct exponential function of temperature.

2. In the eleven tubing types studied in this protocol, the tubing type with the least range of flow rate change from 45°C to 15°C is natural latex (890 ml/min) and the greatest, is Tygon M-70 PVC (2437 ml/min).

3. On the average, occlusion did not vary from the initial setting as temperature is changed, however the occlusion variance for each tubing sample tested is often as great as +/−35.% of the initial occlusion setting.

4. Accurate prediction of roller pump output for E.C.C. requires more than a simple RPM versus flow calibration graph when hypothermia is employed.

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