Water Pressure Drop versus Flow Rate; Its Effect on Rewarming in Infant/Pediatric Heat Exchangers

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Abstract

Four pediatric heat exchangers were tested to determine whether the water pressure gradient through the units, and the related drop in flow, has a significant effect on rewarm time. Varying resistances were noted in each unit, which seemed primarily dependent on heat exchanger design. While the units offering less resistance to water flow would theoretically transfer more heat due to higher water flowrates, they did not demonstrate shorter warm times clinically. The shorter warm times seen clinically were more dependent upon blood flowrates used.

Introduction

The purpose of this study was to determine if the resistance through various pediatric heat exchangers and the related drop in flow has a significant effect on rewarm time.

Methods and Materials

The water source was a standard Sarns[a] Dual Cooler-Heater (model #11160). Water flow was determined using a 3/8″ ID Bio-Medicus[b] in-line flow probe (model #300 AB) connected to a Bio-Console (model #510). Initial calibration of the flowmeter was accomplished using a Cobe/Stockert[c] Roller Pump Module. The pump was made just occlusive and a known flow was pumped through a closed loop of tubing containing the in-line probe. Since the maximum flow reading on the Bio-Console is 10 LPM, it was necessary to reduce the calibration by a factor of four in order to read flows in the expected range (i.e., a reading of 10 LPM on the flowmeter was equaled to an actual flow of 40 LPM). Pressure was measured with a Gould-Statham[d] P23ID transducer connected to a Stockert Pressure Control Module.

The Sarns Cooler-Heater is factory rated at 41 LPM and 11 PSI (569 mm Hg) with no pressure load.[1] In order to determine baseline values, and to ascertain if the tubing resistance significantly affects water flow, the Sarns was operated on each of its control settings through a closed loop of 1/2″ ID tubing containing the flow probe. Water flows and pressures were measured and appear in Table 1.

It was found that in each of its four heating mode settings, the pump speed of the cooler-heater remained constant. It was also noted that in the Recirculate Mode and Cooling Mode 2, the

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[b] Bio-Medicus, Inc., Minnetonka, Minnesota 55343

[c] Cobe Laboratories, Inc., Lakewood, Colorado 80215

[d] Gould-Statham Instrument, Inc., Hato Rey, Puerto Rico 00919

[e] Bentley Laboratories, Inc., Irvine, California 92714

[f] William Harvey, Santa Ana, California 92705

[g] Sci-Med Life Systems, Minneapolis, Minnesota 55441

[h] Shiley Laboratories, Inc., Irvine, California 92714

TABLE 1

Control Water flow (F) and pressures measured proximal (P_p) and distal (P_d) the flowmeter at different cooler-heater settings (S). No heat exchanger in-line

	S	F (LPM)	P_p	P_d	delta P (mmHg)
Cooling Mode	4	29.2	224	108	116
	3	22.8	145	66	79
	2	14.4	64	25	39
	1	12.4	43	14	29
Recirculate		14.4	65	26	39
Heating Mode	30°	29.6	233	116	117
	38°	29.6	233	116	117
	40°	29.6	233	116	117
	42°	29.6	233	116	117

TABLE 2

Water flowrates and pressure determinations utilizing the Bentley Bos-5 heat exchanger. Note maximum flow of 16 LPM

S	F	P_p	P_d	delta P
4	14.0	315	30	285
3	12.0	315	22	293
2	10.8	212	9	203
1	8.8	146	2	144
30°	16.0	316	33	283

TABLE 3

Harvey H-400 heat exchanger in line. Less resistance to flow than Bentley (R = P/F)

S	F	P_p	P_d	delta P
4	24.8	308	79	229
3	21.2	217	55	162
2	15.2	104	20	84
1	12.0	71	12	59
30°	25.2	311	88	223

pump speed was the same; therefore, the collection of subsequent data was accomplished using only all four cooling mode settings and one heating mode setting (30°C).

Four pediatric heat exchangers which had been used clinically were then selected and individually placed in the circuit in accordance with the manufacturer's recommendations for water flow connections. The units used were a Bentley[e] Bos-5, William Harvey[f] H-400, Sci-Med[g] external pediatric unit #P-7-14, and a Shiley[h] S-070. Five sets of data were collected on each unit and the results averaged. Water flow and inlet and outlet pressures were measured on each unit and appear in Tables 2 through 5.

In an effort to determine if our findings were clinically significant in respect to rewarming, the data from eight pediatric perfusions using these heat exchangers were compared. These cases were chosen for similarity in patient weight, blood flow-rate, esophageal temperature at initiation of rewarming, and rewarm time. The cases appear in Table 6.

TABLE 4

Sci-Med P-7-14 in line. Demonstrates flow characteristics similar to H-400

S	F	P_p	P_d	delta P
4	27.2	273	94	179
3	22.4	184	62	122
2	15.2	84	23	61
1	12.8	59	14	45
30°	31.6	280	104	176

TABLE 5

Shiley S-070. Highest resistance of all four units tested. Maximum flow 6.4 LPM

S	F	P_p	P_d	delta P
4	6.4	>350	10	>340
3	5.6	>350	6	>344
2	4.4	327	2	325
1	4.0	217	11	216
30°	6.4	>350	12	>338

TABLE 6
Eight clinical perfusions utilizing pediatric heat exchangers, chosen for similarity in perfusion data

Oxygenator	Bos-5	Bos-5	H-400	H-400	P-7-14	P-7-14	S-070	S-070
Weight (kg)	12.75	11.93	12.2	9.4	10.5	10.2	10.45	9.8
BSA (m^2)	.613	.566	.538	.454	.459	.460	.467	.450
Max blood flow	1420	1010	1010	970	1200	900	930	940
Esophageal T° at rewarm	23.7	29.6	21.0	26.9	24.2	24.7	23.5	21.3
Esophageal T° after bypass	36.1	35.4	34.7	36.0	35.5	35.0	36.0	36.3
Rewarm time (min)	28	15	40	20	22	31	37	37
delta T° (°C)	12.4	6.2	13.7	9.1	11.3	10.3	12.5	15.0

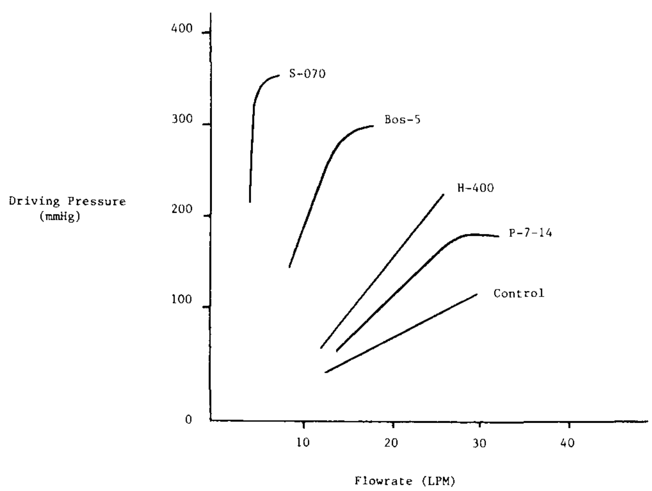
Results

With the collection of this data, it was found that the Sci-Med unit yielded the highest water flowrates (31.6 LPM in the Heating Mode) with the least pressure drop across the unit (176 mmHg). The next best flow characteristics were demonstrated by the Harvey heat exchanger, then the Bentley and Shiley units. The Shiley unit yielded a maximum flow of only 6.4 LPM at the highest flow setting on the cooler-heater, demonstrating a relatively large resistance across the heat exchanger. In fact Shiley's maximum achievable flowrate was less than Bentley's minimum flowrate. This can be seen pictorially in Graph 1.

If we calculate a rewarm factor as described by Page[2] et al, as RF = Wt (kg) × delta T (°C) / Time (min), then the following results are obtained:

HEAT EXCHANGER	REWARM FACTOR		AVERAGE
Bos 5	5.58	4.93	5.29
H-400	4.18	4.23	4.21
P-7-14	5.39	3.39	4.39
S-070	3.53	3.97	3.75

These results do not show an obvious correlation with the ranking in Tables 2 through 5. The Sci-Med, which displayed the best water flow characteristics, ranks third here. The Bentley shows the best rewarm factor, yet ranked third in maximum water flow.



GRAPH ONE
A delineation of Tables 2 through 5. Average pressure drop across each unit at varying water flow rates.

If one considers the blood flow at which the units were operated clinically, we find the following:

HEAT EXCHANGER	AVERAGE FLOWRATE	AVERAGE RF
Bos-5	1410	5.29
H-400	940	4.21
P-7-14	1050	4.39
S-070	935	3.75

Here, the units operated at the higher blood flowrates display the higher rewarming factors.

Discussion

What we see as heat exchange efficiency and rewarm time in the operating room is a summation of many factors. Patient size and temperature, the location of the heat exchanger in the circuit, the presence of counter-current exchange and the material of the heat exchanger surface, as well as the effective blood-to-water flowrates must be considered. Blood flowrates play an obvious role in rewarming but need to be met with sufficient water flowrates. Galetti[3] refers to a satisfactory water flowrate, and estimates it to be 15–20 LPM through the heat exchanger. Altered blood viscosity at lower temperatures limits blood flowrate, as can vascular tone or cannula size. Maximum allowable water pressure through the heat exchanger causes water flow limitations, especially when utilizing a wall water source. Although today's manufacturing techniques have made water-to-blood leaks an infrequent occurrence, varying water path resistance offered by pediatric heat exchangers should be recognized when there exists a concern for water pressure limitation within the extracorporeal circuit.

Each of these pediatric heat exchangers offers resistance to water flow which is characteristic of its size and configuration. The concomitant reduction in water flowrate, however, did not significantly effect clinical rewarm time.

References

1. Sarns Operator's Manual, Dual Cooler-Heater, Form No. 12283001, Revision B, June 1979.
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3. Galetti, P. M. and Brecher, G. A.: *Heart lung bypass: Principles and techniques of extracorporeal circulation*. New York: Grune and Stratton, 1962, page 166.