Comparison of six pediatric cardiopulmonary bypass pumps during pulsatile and nonpulsatile perfusion

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Several investigators have shown that pulsatile perfusion improves vital-organ recovery after hypothermic cardiopulmonary bypass (CPB) with or without deep hypothermic circulatory arrest (DHCA).¹⁻⁴ Nevertheless, pulsatile perfusion remains controversial, and only a few pediatric centers use it routinely.⁵ The main reason for this controversy is lack of quantification of pulsatile and nonpulsatile pressure-flow waveforms. We propose to end the controversy by quantifying pulsatile flow with Shepard's energy equivalent pressure (EEP) formula, which accounts for both arterial-pressure and pump-flow waveforms and not pressure waveforms alone.⁶⁻⁸ Generation of pulsatile flow depends on an energy gradient rather than on a pressure gradient. The following formula is used to define the EEP:

$$EEP = (f p dt) / (f dt)$$

where f is the pump flow rate (in milliliters per second), p is the arterial pressure, and the time integrals are over one pulse cycle. The EEP, which is expressed in millimeters of mercury, is the ratio of the areas beneath the hemodynamic power curve ($f p dt$) and the pump flow-rate curve ($f dt$) at the end of the flow and pressure cycles.

To determine whether the pulsatile or nonpulsatile perfusion mode yields the greatest hemodynamic energy during CPB, we evaluated 6 pediatric pumps in terms of the EEP before and after DHCA in a neonatal piglet model.

Experimental Design

Thirty-nine piglets (average weight, 3 kg) were subjected to CPB with one of the following: a hydraulically driven physiologic pul-

satile pump ($n = 7$; Medical Engineering Consultants, Bishop, Calif), a Jostra HL-20 pulsatile roller pump ($n = 6$; Jostra USA, Austin, Tex), a Stöckert SIII pulsatile roller pump ($n = 6$; Stöckert, Munich, Germany), a Stöckert SIII mast-mounted pulsatile roller pump with a miniature roller head ($n = 7$), a Stöckert SIII mast-mounted nonpulsatile roller pump with a miniature roller head ($n = 6$), or a Stöckert CAPS nonpulsatile roller pump ($n = 7$). All animals received humane care, as described in the "Guide for the Care and Use of Laboratory Animals" of the National Research Council (National Academy Press, revised 1996).

Each piglet was premedicated with intramuscular ketamine hydrochloride (20 mg/kg) and acepromazine maleate (1 mg/kg). Once an intravenous line was established, a 3-mm endotracheal tube was inserted for mechanical ventilation. Intravenous boluses of fentanyl citrate (100 µg/kg) and pancuronium bromide (0.3 mg/kg) were then given. After a median sternotomy was performed, the ascending aorta and the right atrium were cannulated with a 10F aortic cannula (DLP, Inc, Grand Rapids, Mich) and a 21F single-stage venous cannula (Polystan A/S, Varlose, Denmark), respectively.

The extracorporeal circuit was primed with heparinized fresh blood and lactated Ringer's solution. The priming volume for the whole circuit was approximately 600 mL. During CPB, the hematocrit level was maintained at 20%. In all the experiments, a hollow-fiber membrane oxygenator (Capiiox SX10; Terumo Corp, Tokyo, Japan) and a pediatric arterial filter (Terumo Corp) were used. During pulsatile CPB, the pump rate was maintained at 150 beats/min, and the stroke volume was maintained at 1 mL/kg. Pump flow was maintained at $150 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in all the groups. An ultrasonic flow probe (T109; Transonic Systems, Inc, Ithaca, NY) was placed in the circuit beyond the membrane oxygenator to measure blood flow. During CPB, the mean arterial pressure (MAP) was maintained at approximately 45 mm Hg by adding isoflurane through the oxygenator gas-inflow conduit. At the end of the experiment, the animal was killed with an intravenous bolus of pentobarbital sodium and phenytoin sodium (Beuthanasia-D; 0.22 mg/kg).

Once CPB was begun, each animal underwent 15 minutes of normothermic CPB, 25 minutes of hypothermia, 60 minutes of deep hypothermic circulatory arrest, 10 minutes of cold reperfusion, and 40 minutes of rewarming. After the ascending aorta was crossclamped at 18°C, a 40-mL dose of crystalloid cardioplegic (modified Kirklin) solution was manually administered into the aorta. During cooling and rewarming, alpha-stat acid-base management was used. In all experiments phenoxybenzamine (1 mg/kg), a potent vasodilator and α -adrenergic blocker, was used 5 minutes before the initiation of CPB.

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TABLE 1. Femoral artery pressure: percentage of change from MAP to EEP

Pump	Normothermic CPB (mm Hg)	Hypothermic CPB (mm Hg)	Postrewarming period (mm Hg)
Physiologic pulsatile	12.9 ± 3.2 (50.4 ± 4.9 to 56.9 ± 5.2)††	15.3 ± 4.0 (45.8 ± 8 to 52.6 ± 8.8)††	16.3 ± 4.5 (48.4 ± 18.3 to 56.2 ± 20.8)††
Jostra HL-20 pulsatile roller	5.3 ± 1.2 (39.6 ± 6.9 to 41.6 ± 6.8)*	4.8 ± 0.8 (44.7 ± 6.4 to 46.8 ± 6.3)*	6.2 ± 1.8 (39 ± 3.4 to 41.5 ± 3.6)*
Stöckert SIII pulsatile roller	3.7 ± 1.2 (43.5 ± 10.7 to 45 ± 10.8)*	4.5 ± 0.5 (38.2 ± 6.7 to 39.9 ± 6.8)*	4.2 ± 1.2 (49.2 ± 11.8 to 51.1 ± 12.4)*
Stöckert SIII mast-mounted pulsatile roller	−0.3 ± 1.6 (45.2 ± 8.7 to 45.2 ± 9.1)*††	−0.2 ± 1.4 (43.9 ± 7.4 to 43.7 ± 7.1)*††	−1.8 ± 1.7 (51.6 ± 12.4 to 50.5 ± 11.5)*††
Stöckert SIII mast-mounted nonpulsatile roller	−0.2 ± 1.8 (43 ± 4.8 to 43 ± 5.0)*††	−0.4 ± 0.7 (46.1 ± 3.6 to 45.9 ± 3.6)*††	−0.9 ± 2.2 (51.9 ± 9.2 to 51.4 ± 9.1)*††
Stöckert CAPS nonpulsatile roller	0.7 ± 0.5 (49 ± 5.4 to 49.4 ± 5.3)*††	0.9 ± 0.9 (43.9 ± 12.1 to 44.2 ± 12.0)*††	0.7 ± 0.5 (47.4 ± 14 to 47.8 ± 14.1)*††

Values are given as means ± standard deviation.

* $P < .0001$ versus the Physiologic pulsatile pump.

† $P < .001$ versus the Jostra HL-20 pulsatile roller pump.

†† $P < .01$ versus the Stöckert SIII pulsatile roller pump.

TABLE 2. Preaortic cannula ECCP: Percentage of change from ECCP to EEP

Pump	Normothermic CPB (mm Hg)	Hypothermic CPB (mm Hg)	Postrewarming period (mm Hg)
Physiologic pulsatile	45.9 ± 13.1 (70.4 ± 6.9 to 102.6 ± 12.4)††	46.4 ± 11.3 (65.6 ± 13.7 to 95.7 ± 19.3)††	52.0 ± 10.0 (74.5 ± 17.3 to 112.1 ± 21.0)††
Jostra HL-20 pulsatile roller	14.5 ± 3.9 (59.5 ± 11.9 to 67.9 ± 12.5)*	12.2 ± 2.6 (66.6 ± 6.9 to 74.6 ± 6.6)*	14.8 ± 2.7 (63.1 ± 9.4 to 72.6 ± 11.8)*
Stöckert SIII pulsatile roller	9.2 ± 1.3 (64.1 ± 19.2 to 69.9 ± 20.4)*	11.2 ± 1.8 (54.9 ± 7.8 to 61.0 ± 8.5)*	9.0 ± 2.8 (70.1 ± 15.5 to 76.1 ± 15.5)*
Stöckert SIII mast-mounted pulsatile roller	1.2 ± 3.0 (65.8 ± 14.1 to 66.6 ± 14.6)*††	2.6 ± 2.2 (68.4 ± 19.1 to 69.9 ± 18.4)*††	−0.5 ± 1.4 (69.9 ± 19 to 69.5 ± 18.5)*††
Stöckert SIII mast-mounted nonpulsatile roller	1.3 ± 1.8 (59.1 ± 5.7 to 59.9 ± 6.6)*††	1 ± 0.2 (70.5 ± 6.6 to 71.2 ± 6.6)*††	−0.7 ± 1.3 (73.4 ± 13.6 to 72.9 ± 13.7)*††
Stöckert CAPS nonpulsatile roller	1.9 ± 0.4 (68.2 ± 13.8 to 69.5 ± 13.8)*††	1.7 ± 0.8 (59.4 ± 8.7 to 60.3 ± 8.5)*††	1.9 ± 0.7 (73.9 ± 10.1 to 75.2 ± 10.1)*††

Values are given as means ± standard deviation.

* $P < .0001$ versus the Physiologic pulsatile pump.

† $P < .001$ versus the Jostra HL-20 pulsatile roller pump.

†† $P < .01$ versus the Stöckert SIII pulsatile roller pump.

Waveforms of the femoral artery pressure (MAP), precannula extracorporeal circuit pressure (ECCP), and pump flow were collected during 3 experimental stages: (1) normothermic CPB (after 15 minutes on pump at 36°C); (2) deep hypothermic CPB (immediately before DHCA at 18°C); and (3) the postrewarming period (after 60 minutes of DHCA, 10 minutes of cold reperfusion, and 40 minutes of rewarming).

Analysis of variance with repeated measures was used for statistical analysis among the 6 groups. All results were expressed as means ± standard deviation.

Results

Tables 1 and 2 summarize the results. The physiologic pulsatile pump produced the greatest hemodynamic energy. Compared with all the other pumps except the physiologic pulsatile model, the Jostra and SIII pulsatile roller pumps produced a significantly higher average increase in hemodynamic energy (from MAP to EEP and from ECCP to EEP). This extra energy produced by pulsatile pumps may maintain capillary patency and increase the flow of lymph fluid in the tissues by generating oscillatory movements

at the cellular level.⁹ During deep hypothermic CPB and after rewarming, the results did not differ from those observed during normothermic CPB. The SIII mast-mounted pulsatile roller pump failed to generate higher hemodynamic energy than the nonpulsatile pumps because it had a miniature roller head. None of the nonpulsatile roller pumps produced extra energy. There were no differences between the MAP-EEP or the ECCP-EEP during nonpulsatile perfusion.

The physiologic pulsatile pump used in this study is hydraulically driven and is unique in that it has 2 pump chambers. The first chamber is placed between the venous reservoir and the membrane oxygenator, and the second chamber is positioned after the membrane oxygenator. Therefore, in this set-up the oxygenator does not affect the quality of the pulsatility. A detailed description of this pump is presented elsewhere.¹⁰ All the other pumps used in this study, except the physiologic pulsatile pump, are approved by the Food and Drug Administration for clinical use. The Capiox hollow-fiber membrane oxygenator and the DLP aortic cannula were chosen specifically for this study because of their previous excellent performance with pulsatile flow pumps.^{11,12}

Conclusion

Most of the pediatric pulsatile pumps (hydraulically driven or pulsatile roller) that we tested, but not all of them, generated significantly higher hemodynamic energy than did the conventional, nonpulsatile pumps. On the basis of these results, further studies are warranted to confirm that the extra energy produced by pulsatile flow improves vital-organ function after CPB. For direct comparison of the different perfusion modes, the EEP formula must be used to quantify pulsatile and nonpulsatile pressure-flow waveforms.

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