

Original Article

***Experimental Use of an Ultra-Low Prime Neonatal
Cardiopulmonary Bypass Circuit Utilizing Vacuum-Assisted
Venous Drainage***

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ABSTRACT

In adult cardiopulmonary bypass surgery, vacuum assisted venous drainage has become a popular technique to augment venous return to the bypass circuit. The application of this technique in neonatal cardiopulmonary bypass surgery could be beneficial to the further miniaturization of neonatal circuitry by coupling radical repositioning of the oxygenator and pump console with decreasing line length.

This report communicates the use of an investigational, vacuum assisted venous drainage neonatal circuit that is positioned at patient level utilizing a modified pump console with elevated double head twin roller pumps. The circuit, including the oxygenator, arterial line, venous line, raceway tubing, and a functional level in the venous reservoir has a priming volume of 107 ml. Initial bench and animal tests have demonstrated that this technique may be clinically feasible in CPB applications. With vacuum assisted venous drainage, the goal of asanguinous neonatal cardiac surgery could become a reality. Safety issues must be adequately addressed to ensure that this technique does not impose unacceptable risks.

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INTRODUCTION

In the last decade, there has been a significant increase in neonatal cardiopulmonary bypass (CPB) cases (1). Despite recent improvements in smaller commercially available CPB components, the goal of asanguinous neonatal cardiopulmonary bypass has remained elusive. Significant reduction in circuit prime volume would decrease the amount of hemodilution and minimize or even eliminate the need for bank blood in the prime.

Figure 1: The console used for neonatal VAVD. Note the elevated position of roller pumps and oxygenator.

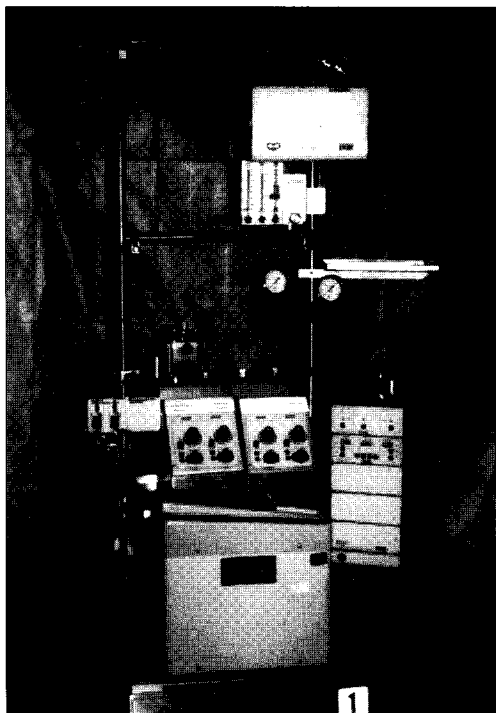
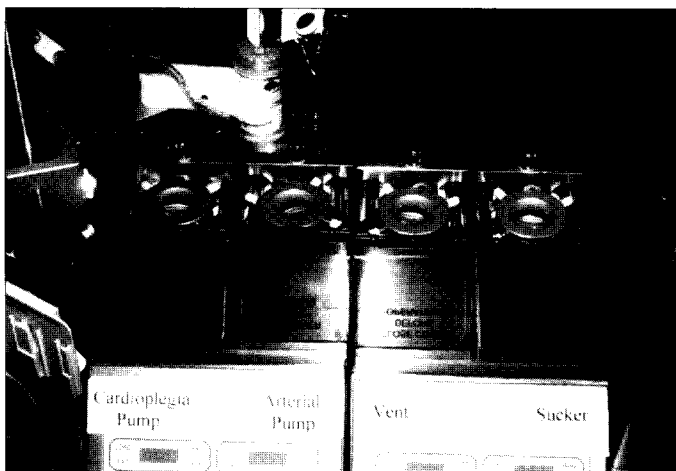


Figure 2: View of the double head roller pumps



Strategies of reducing priming volumes have included: shorter tubing lengths, smaller tubing diameters, the elimination of an arterial line filter, console repositioning, and development of lower prime extracorporeal components (2-8).

In conventional cardiopulmonary bypass, venous drainage is accomplished by gravity, driven by the gradient between the level of the patient and the venous reservoir. In adult cardiac surgery, recent enthusiasm for minimally invasive surgical techniques has led to the use of smaller venous cannulae, which render conventional venous drainage insufficient. To augment venous return, two primary methods of assisted venous drainage have been proposed: kinetic assisted venous drainage (KAVD) and vacuum assisted venous drainage (VAVD). KAVD can be accomplished by the placement of a centrifugal pump into the venous line (9). VAVD is implemented by placing a regulated vacuum into a sealed hard shell venous reservoir.

VAVD may be of use in applications other than adult minimally invasive cardiac surgery. In neonatal CPB, VAVD could be used to dramatically reduce priming volumes by allowing for the reorganization of the pump console and circuit for maximum reduction of tubing dead space. With VAVD, no longer would it be necessary to have the pump modules positioned near the floor with the venous reservoir lower than the patient. The pumps can be elevated, venous reservoir positioned at the patient level, and a smaller diameter venous line can be used to optimize the reduction of circuit dimensions.

Our objective was to construct a clinically relevant neonatal CPB console and circuit around the concept of VAVD. Design requirements included the use of commercially available components, servo-regulation of the arterial pump with low level and air bubble detection, pressure servo-regulation of arterial and cardioplegia pumps, in-line blood gas monitoring, and enough physical space between equipment and patient to allow for a reasonable sterile field.

We report preliminary in-vitro and in-vivo findings that demonstrate the feasibility of using VAVD with a reconfigured neonatal CPB console and circuit. By repositioning the pump console and shortening tubing lengths, priming volume could be greatly reduced using this technique.

MATERIAL AND METHODS

CONSOLE

The console consisted of a Stockert-Shiley^a 3-pump base with two Stockert-Shiley double head roller pumps mounted on a modified that allowed the pumps to be elevated (Figure 1). The double head roller pump houses two completely independent roller heads, with independent controls. These small roller heads have a 3.3 inch raceway. The first double head roller pump was used for the arterial pump and the cardioplegia pump while the

^a Sorin Biomedical, Irvine, CA

second was used for the suction and vent pumps (Figure 2). The console was equipped with the Stockert-Shiley Computer Assisted Perfusion System (CAPS) to allow for servo-regulation of the pumps to pressure, level, and air bubble parameters. A Baxter^b vacuum control system, connected to a hospital grade vacuum source, was used to regulate vacuum in the venous reservoir. A Biomedicus^c Heater-Cooler was positioned beneath the pumps.

VAVD CIRCUIT

The VAVD extracorporeal circuit consisted of a Cobe^d Micro oxygenator. The arterial and venous lines were 3/16 inch I.D. PVC. The raceway tubing segment was 1/4 inch I.D. with 3/16 inch I.D. leading to and from the raceway. A Sorin Vanguard 4:1 blood cardioplegia system and a Minntech^e minifilter hemoconcentrator for modified ultrafiltration (MUF) were customized to reduce all unnecessary tubing. A 3/16 inch I.D. PVC (with 1/4 inch I.D. raceway segment) was used for both pump suction and vent. The vent line contained a Quest^f triple-action vacuum relief valve. A positive pressure relief valve was placed on a venous reservoir luer site. A Transonic^g flowmeter was used to measure venous line flow rates to allow for rapid assessment of venous return during VAVD. A Gish^h Stat Sat monitor was used to measure in-line venous oxygen saturation.

BENCH-TOP EVALUATION

Priming volume was carefully measured by individually filling each component of the circuit and draining contents into a graduated cylinder. The venous reservoir was evaluated for its ability to hold a vacuum. All ports and luer connections on the reservoir were occluded and a set vacuum was applied to the reservoir. Integrity of the seal was analyzed with a DLPⁱ pressure transducer placed on the venous reservoir. To test the performance of the VAVD, a recirculation model was constructed by attaching the venous and arterial lines to an empty 500 ml bag. Venous return was evaluated at a variety of vacuum pressures with the bag at different heights relative to the venous reservoir.

A modified suction line was placed directly into the venous reservoir. In this suction line, there was a push valve which kept the line closed. When suction was desired, the valve on the handle could be manually opened and then used to aspirate volume. The reservoir vacuum pressure was analyzed to evaluate stability of set vacuum in the reservoir.

ANIMAL EXPERIMENTS

Two 1-week-old piglets, weighing 3.5 kg and 2.8 kg, were studied. All animals received humane care as described in the Guide for the Care and Use of Laboratory Animals of the National Academy of Sciences, published by the National Institute of Health (NIH Publication No. 85-23, 1985). The research protocol for this study was approved by the Duke University Animal Care and Use Committee. All experiments were performed at the Thoracic Surgery Research Laboratory, Duke University

Medical Center.

Animals were premedicated with intramuscular ketamine (20 mg/kg), intubated, and mechanically ventilated with a Sechrist^j Infant Ventilator. After a bolus of intravenous fentanyl (100 µg) and pancuronium (0.1 mg/kg), anesthesia was maintained with continuous fentanyl infusion (50 µg/kg-hr-). A femoral artery catheter was placed for measurements of mean arterial blood pressure and arterial blood sampling. A median sternotomy was performed. The aorta was cannulated with an 8 Fr Medtronic DLP aortic cannula and the right atrium was cannulated with a 12 Fr Medtronic DLP venous cannula. These cannulae were attached to the arterial and venous lines of the CPB circuit.

The circuit was primed with Normosol R, albumin (5 grams/dL), heparin (500 units), and the pH was normalized with sodium bicarbonate. After the circuit was primed and completely de-aired, the venous line was drained into the reservoir and then clamped. The venous reservoir level was adjusted to a 25 ml level by draining off excess volume prior to initiation of CPB. Conduct of perfusion was carried out according to institutional protocols. These include activated clotting times > 500 seconds, alpha-stat blood gas management, calculated pump flow rates of 150-200 ml/kg/min, mean arterial pressure range 30-60 mmHg, and blood cardioplegia (30 ml/kg) delivered at 10°C.

The first piglet was used primarily to test the function of the VAVD CPB in vivo. Upon demonstrating the initial feasibility, a more extensive animal trial was done to include most aspects of neonatal CPB. The protocol for this test was as follows:

Time	Initiation of CPB	Cross Clamp On	Cross Clamp Off	Termination of CPB	End
0'	Cool 28°C	10'	25'	45'	60'
		Blood cardioplegia delivery	Re-warm phase	MUF phase	

RESULTS

BENCH-TOP PHASE

The sealed venous reservoir of the Cobe was tested and found capable of holding vacuum. No leaks were present in any of the tested reservoirs. To test the strength of the reservoir to a vacuum pressure, a vacuum of -200 mmHg was applied. The reservoir had no functional problems, though there was visible flexing of the polycarbonate shell.

A breakdown of the priming volumes of the VAVD neona-

- b Baxter Healthcare Corp., Irvine, CA
- c Biomedicus, Eden Prairie, MN
- d Cobe Cardiovascular, Inc., Arvada, CO
- e Minntech Corp., Minneapolis, MN
- f Quest Medical, Inc., Allen, TX
- g Transonic System, Inc., Ithaca, NY
- h Gish Biomedical, Inc., Irvine, CA
- i Medtronic, Inc., Grand Rapids, MI
- j Sechrist Industries, Anaheim, CA

tal circuit is shown in Table 1. Values of our conventional neonatal circuitry are shown for a side by side comparison. Combined priming volume of the arterial line (empty venous line), raceway tubing, and oxygenator/heat exchanger was measured at 107 ml. This included a 25 ml operating level in the venous reservoir. If the venous line was left fully primed, the priming

volume was increased to 125 ml. The addition of a pediatric blood cardioplegia system and a small MUF hemoconcentrator (for use post-CPB) added an additional 84 ml to the overall priming requirements. This yielded an overall total system prime of 191 ml with an empty venous line or 209 ml with a filled venous line. The calculated effects of asanguinous hemodilution of this circuit over a range of patient sizes are shown in Table 2.

Table 1: Breakdown of priming volumes of both the VAVD and conventional neonatal CPB circuits

CPB Component	VAVD Neonatal Circuit	Conventional* Neonatal Circuit
Oxygenator	52 ml	52 ml
Venous Reservoir Level	25 ml	25 ml
Raceway Tubing	15 ml	20 ml
Arterial Line	15 ml	68 ml
Venous Line	0 ml (18 ml)	74 ml
Arterial Line Filter	NA	30 ml
Total Priming Volume	107 ml (125 ml)	269 ml
Cardioplegia System	60 ml	154 ml
Hemoconcentrator	25 ml	60 ml
Combined Volume	192 ml (210 ml)	483 ml

* Duke University Medical Center's current neonatal system
Values in parenthesis represent volume using a filled venous line.

A re-circulation circuit (using a bag to represent the patient) demonstrated that the use of VAVD at vacuums levels up to -80 mmHg produced excellent venous return with the bag at or below the level of the venous reservoir.

ANIMAL PHASE

The first test animal (3.5 kg) was placed on VAVD CPB to test the function of vacuum return on a 3/16 venous line in vivo. Arterial pump flows of 500 ml/min were maintained with a reservoir pressure between -15 and -25 mmHg. Filling or emptying the animal was easily controlled by increasing or decreasing vacuum to the reservoir.

In the second test animal (2.8 kg), cardiopulmonary bypass was initiated with the venous line empty. Similarly to the first test animal, VAVD produced sufficient venous return at vacuum pressures of -10 to -60 mmHg. Venous reservoir vacuum pressure remained stable throughout the bypass run despite the variable use of both the sucker and vent pumps. Arterial pump flow rates were maintained at 150 ml/kg/min and venous saturations >65% throughout the duration of bypass. Arterial blood gases were maintained within accepted standards. No problems were encountered with other aspects of CPB, such as cooling, blood cardioplegia delivery, re-warming, termination of bypass, and MUF.

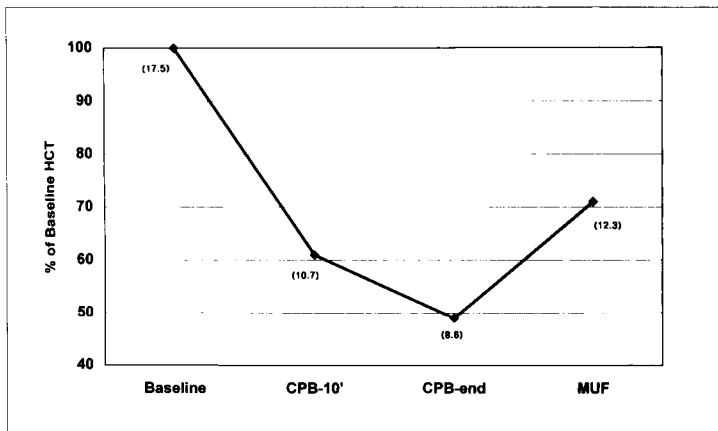
Table 2: Estimated hemodilution on patients starting with a 35% HCT using the VAVD circuit

Patient Weight (Kg)	2.0	3.0	4.0	5.0
Pt. Blood Volume* (ml)	170	255	340	425
Post dilutional HCT ^v (35% baseline)	21.5%	24.7%	26.6%	33.3%
Post dilutional HCT ^z (35% baseline)	16.4%	20.0%	22.4%	24.2%

* based on 85 ml/kg
^v dilution based on circuit without blood cardioplegia/MUF system
^z dilution based on circuit with blood cardioplegia/MUF system

The pre-CPB baseline hematocrit (HCT) was 17.5%. No blood was given during this trial despite HCTs below what we would consider clinically acceptable. There was a 39% reduction in HCT after initiation of VAVD CPB. The use of blood cardioplegia and fluid replacement during the case caused a further 14% reduction from baseline. Following 10 minutes of MUF, final hematocrit levels were restored to within 71% of pre-pump levels (Figure 3). Safety devices operated as intended, with the exception of the air bubble detector, which gave several false positive alarms. This could be attributed to using a detector that was originally intended for 3/8 inch I.D. tubing. Sorin makes a bubble detector specifically for 1/4 inch I.D. tubing that may be less susceptible to false positives on 3/16 inch tubing.

Figure 3: The effects of asanguinous CPB on hematocrit (expressed as % of baseline). Actual % HCT are shown in parenthesis.



DISCUSSION

The concept of using a controlled vacuum pressure to draw venous blood from the patient and into

the extracorporeal circuit has its roots early in the evolution of perfusion technology (10). The technique was abandoned for the simpler gravity drainage system. Although gravity drainage has been the standard technique for the last three decades, the development of minimally invasive techniques for cardiac surgery has resurrected interest in using vacuum to assist venous drainage.

While VAVD has been used primarily in adult cases, the concept (and theoretical advantages) for utilizing the technique in pediatric CPB cases has been outlined previously (11). Murankami et al. extended the use of vacuum for not only venous drainage, but also for suction and venting during CPB (12). This configuration allowed for the elimination of the roller pumps usually used for suction and venting, thereby simplifying and reducing the size of the CPB console. A recent experimental study advanced this concept on 8 mongrel dogs (average weight = 20kg) and demonstrated reduced priming volume, miniaturization, and simplification of the console (13). The authors suggested that this technique could contribute to successful non-transfusion cardiac surgery even for neonates.

In our model, we attempted to build a dedicated neonatal CPB console built around the concept of VAVD. We liked the idea of using the small double roller pumps for this application. These pumps provided the opportunity to save space without sacrificing any features found in the standard size pumps. In the space of two pump modules, we had the capacity of four roller heads. This provided us with an arterial pump head, cardioplegia pump, a suction pump, and a vent with economy of space. The small console "footprint" allows for flexibility in positioning the heart-lung machine close to the patient. The small size of the raceway gave us some initial concerns over the possibility of excessive RPMs in the arterial head. We satisfied that concern by using a 1/4 inch I.D. tubing segment in the raceway. This produced flow rates of ~ 650 ml/min at 100 RPM and ~1000 ml/min at 150 RPMs.

The Baxter vacuum control system worked well in maintaining a constant vacuum pressure in the reservoir. The aggressive use of the pump suction did not affect the set vacuum pressure. A further validation of the ability to maintain a set vacuum level was noted in our experiments using a "pumpless" sucker. This appeared to work well without showing any significant destabilization in venous reservoir vacuum pressure when the valve was opened to atmosphere. While it seems conceivable that the suction pump could be eliminated, we felt that roller pump suction provided more precise control and added safety to the system by allowing "sucker bypass," should the vacuum supply fail. This would be an attractive option to provide additional suction capacity to the operative field.

To utilize VAVD to its full potential for prime reduction, we initiated bypass with the venous line empty. While this may prove to be an overkill, it demonstrated that initiation in this manner could be accomplished without complication. VAVD also eliminates the nuisance of venous air locks often associated with complex cannulation in congenital heart surgery.

The reduction of priming volume from our conventional neonatal circuit was significant and resulted in relatively low hemodilution. Unfortunately, our baseline hematocrit was 17.5% before initiation of CPB, so our HCTs during bypass were below what we would accept clinically. Our intent, however, was to use VAVD in a manner to determine clinical feasibility.

When discussing prime volumes it is important to define what that volume includes. In this report, to avoid confusion, we present priming volume in two ways. The first way is the volume of the basic circuit, which included the volume of the oxygenator, raceway tubing, arterial/venous lines, and amount in the venous reservoir. The second way of expressing priming volume was the basic circuit plus the volume of the blood cardioplegia and MUF system.

We customized our blood cardioplegia system to reduce the amount of volume, yet we were frustrated at the amount of prime required in these systems. This is an area for further component miniaturization. We decided not to use an arterial line filter in our tests because of the relatively large priming volumes that even the smallest filters require. It could be argued, however, that if ever an arterial line filter should be used to remove gaseous micro-emboli (GME), it would be in a compact system such as this. While we currently advocate the use of arterial line filters for all conventional CPB, our intent was to produce the minimal amount of priming volume possible while adhering to generally accepted practices in neonatal perfusion. At this time, the use of arterial line filters in neonatal bypass circuits remains a topic of debate among leading pediatric centers. In addition, because of the vacuum pressure in the venous reservoir, the arterial line filter purge would need to be turned off, thereby limiting the filters' effectiveness at removing GME. Finally, when considering whether to use or not to use arterial line filtration, understanding the air handling characteristics of specific oxygenators may be an important consideration. DeSomers et al. examined the air removal capabilities of two neonatal oxygenators and concluded that oxygenator design can greatly affect the ability of these devices to handle and remove entrained air (14).

In miniaturized systems, safety issues must be satisfactorily addressed. A complication such as air in the arterial line could pose a greater risk in this circuit because of the very short arterial line length. The diminished interventional reaction time makes it essential to have the arterial pump servo-regulated to both blood level and bubble detectors. Other recommended safety devices include pressure servo-regulated on the arterial and cardioplegia pumps.

Despite trying to incorporate as many safety features as possible in this model, we believe that VAVD on small scale circuitry may amplify many of the technical pitfalls seen in larger VAVD applications. The reservoir should be vented both pre and post CPB to prevent over-pressurization during pump suction use. During bypass, the perfusionist must be aware of any arterial line shunts that communicate with the venous reservoir. These shunts should not be opened during VAVD. The Cobe

Micro has two shunts; one from the heat exchanger and another from the membrane bundle. The vacuum pressure in the venous reservoir will not only increase these shunt flows, but could also pull air across the membrane into the blood path if the pressure in the system is low (e.g. trickle flow, circulatory arrest). Arterial line filter purge would be another example of a shunt affected by VAVD and should be turned off when vacuum is applied to the reservoir. The arterial roller pump must be tested to ensure that it is not grossly under-occluded. An under-occluded arterial roller pump will expose the oxygenator to the vacuum pressure in the reservoir, causing air to be drawn across the membrane fibers. We were able to demonstrate this phenomenon by loosening the occlusion of the arterial pump with vacuum pressure applied to the reservoir.

The defining question regarding VAVD in neonatal circuitry design is: Is it really worth the added challenges? Certainly the benefits of avoiding the problems associated with blood transfusion (infection, immunologic, metabolic) could also be afforded the neonate if an asanguinous procedure were possible (15-17). It has been shown in infant cardiac surgery that lowering priming volumes can have a strong influence on the use of blood products such as platelets and FFP (18).

Much work remains to be done, including comparative studies between conventional gravity versus VAVD systems to evaluate a full spectrum of effects that this promising technique may have in neonatal CPB. These initial trials demonstrate that this technique is indeed feasible in a neonatal application and may help usher in the era of non-transfusion neonatal cardiac surgery.

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