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Limitations Using the Vacuum-Assist Venous Drainage Technique During Cardiopulmonary Bypass Procedures

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Abstract: Vacuum-assist venous drainage (VAVD) can increase venous blood return during cardiopulmonary bypass (CPB) procedures. However, the negative pressure created in the closed cardiotomy reservoir can be transmitted to the oxygenator if a nonocclusive or centrifugal arterial pump is used, resulting in bubble transgression (BT) from the gas to blood compartment of the oxygenator. We analyzed the vacuum pressure required to produce BT using an *in vitro* circuit including successively a closed reservoir, a pump (centrifugal or roller), and an oxygenator. A constant hydrostatic pressure was maintained onto the oxygenator. Vacuum was applied on the cardiotomy reservoir, progressively increasing negative pressure from 0 to –80 mmHg and monitoring BT with a bubble detector. Six different oxygenators were compared. A partially occlusive roller pump and a centrifugal pump were compared to a control, which was without any pump. A mean negative pressure of –53 ± 7 mmHg was necessary to produce BT in all the oxygenators in the absence of a pump. The presence of a centrifugal pump between the reservoir and the oxygenator significantly increased the negative pressure required to produce BT compared to the control (–67 ± 7 mmHg, $p < .05$). No bubbles were detected using the roller pump (>–80 mmHg needed for BT), thus statistically significant when compared to the centrifugal pump ($p < .05$). The centrifugal pump offers significant resistance to BT but not as much compared to the roller pump, though BT cannot be prevented if the pump is turned off while the vacuum remains on the reservoir. Therefore, VAVD is a safe technique as long as the perfusionist stops the vacuum when the arterial pump is no longer in use. **Keywords:** cardiopulmonary bypass, centrifugal, hollow fiber membrane oxygenator. *JECT. 2003;35:207–211*

Standard cardiac surgery procedures with cardiopulmonary bypass (CPB) necessitates a median sternotomy and has gained confidence due to its simplicity, safety, and success over many years. In several situations such as minimally invasive surgery and emergency cardiac resuscitation peripheral venous cannulae are needed. These cannulae are longer and have smaller diameters compared to classic cannulae, thus blood drainage is limited. Gravity siphon or passive venous drainage (PVD) may thus provide insufficient blood return for adequate tissue perfusion.

This drawback has lead to the development of active venous drainage (AVD), which can increase venous return to more acceptable levels of perfusion. AVD is generally divided into kinetic-assist venous drainage (KAVD) and vacuum-assist venous drainage (VAVD). KAVD uses a centrifugal pump (CP) placed in the venous line to generate negative pressure and consequently increase venous return. This technique has been shown to guarantee adequate global tissue perfusion for use in minimally invasive CPB procedures (1–3). VAVD involves a constant vacuum pressure, onto an airtight venous reservoir, allowing more blood to be drained from the patient via the venous line. However, it was recently shown that AVD techniques might introduce gaseous microemboli (GME) into the patient undergoing CPB (4). Although many potential causes for gaseous emboli during CPB have been identified (5), the creation of a negative pressure in the venous line facilitates entrapment of air around the venous cannula, possibly increasing GME. However, when a CP is used in the arterial pump position in combination with VAVD it apparently aids in clearing the GME (6).

If the arterial pump is stopped for various reasons and the vacuum source is left on the venous reservoir, microbubble transgression (BT) can occur from the gas compartment to the liquid compartment of the oxygenator, creating another source of GME as soon as the arterial pump is turned on again. We analyzed the nega-

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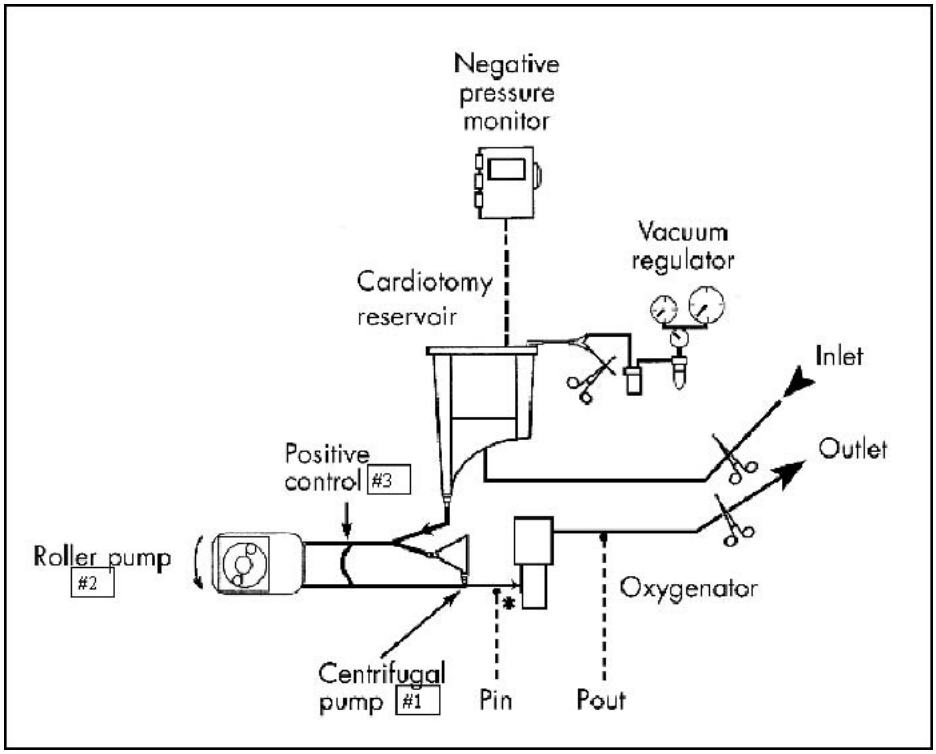

Figure 1. Schematic layout of the experimental circuit with the three test conditions numbered: a centrifugal pump (#1), a partially occlusive roller pump (#2), or no pump = control (#3). The bubble detector is placed between the P_{in} and the oxygenator (*).

tive pressure required to produce this phenomenon in six different commonly used commercially available oxygenators.

MATERIALS AND METHODS

We set up an *in vitro* circuit (Dideco, Mirandola, Italy) containing the routine layout for a classic CPB operation (Figure 1). A vacuum regulator (Baxter Healthcare Corporation, Irvine CA) placed above the venous reservoir allowed one to vary the negative pressure (between 0 and –80 mmHg) onto the reservoir with precision. On the arterial line, we used either a roller pump (RP) (Stockert Instrumente GmbH, Munich, Germany) or a CP (Medtronic Biomedicus BP-80, Eden Prairie, MN). We analyzed the negative pressure required to cause BT across the oxygenators. The technical specifications for the six oxygenators were supplied by the manufacturers (Table 1).

Five adult oxygenators were tested: Dideco703 hollow fiber membrane oxygenator (Dideco, Mirandola, Italy), Quadrox (Jostra Medizintechnik AG, Hirrlingen, Germany), Maxima plus and Maxima plus PRF (Medtronic DLP, Grand Rapids, MI), Cobe CML (Cobe Cardiovascular, Inc, Arvada, CO). One pediatric oxygenator was tested: Liliput 901 (Dideco, Mirandola, Italy).

A venous reservoir was connected to an oxygenator via 3/8 inch tubing incorporating either a CP (Figure.1#1), a partially occlusive RP (Figure.1#2) or no pump (control) (Figure.1#3). The connection to the Liliput 901 was made with 1/4–3/8 inch connectors. All oxygenator ports were 3/8 inches except for the Liliput 901, which had a 1/4 inch one.

The extracorporeal circuit was primed with Ringer's Lactate and deaired. The hydrostatic pressure onto the oxygenator was constant and set at 25 mmHg recorded at the inlet pressure to the oxygenator. This was achieved by keeping the volume in the reservoir constant at the start of each experiment. The gas flow rate was 2l/min at a zero

Table 1. Structural specifications for the six oxygenators supplied by their respective manufacturers. The first five present adult oxygenators and the last column presents the pediatric one. MSA presents membrane surface area.

	Oxygenators					
	Dideco 703	Quadrox	Maxima Plus	Maxima Plus-PRF	Cobe	Dideco-Liliput
MSA (m^2)	2.0	1.8	2.3	2.0	2.6	0.34
Priming volume (ml)	270	250	480	480	260	60
Maximum flow (ml/min)	7500	7000	7000	7000	8000	800
Heat exchanger surface area (m^2)	0.22	0.6	0.11	0.11	0.14	0.02

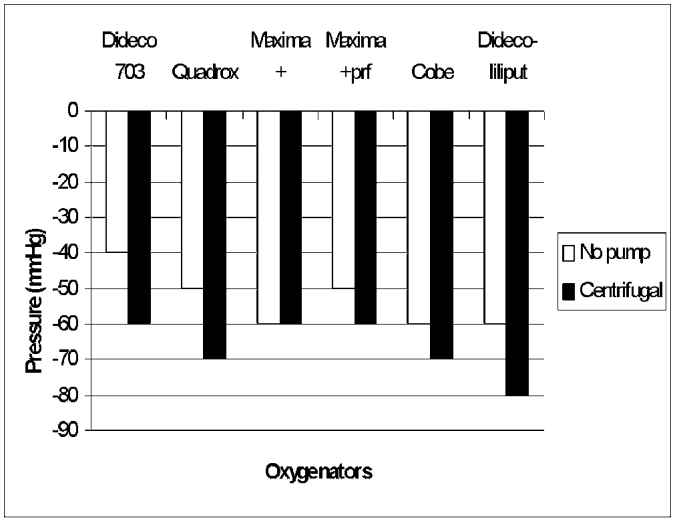

Figure 2. Graphical representation of the negative pressures found during the experiment for the "no pump" and "centrifugal pump" conditions. The values for the roller pump were superior to –80 mmHg, thus were not represented in the figure.

blood flow rate to mimic exceptional clinical conditions. The arterial and venous lines were clamped to mimic off-pump conditions. The negative pressure was then applied to the venous reservoir and adjusted between 0 and –80 mmHg stopping at 10 mmHg intervals for one minute. BT was monitored visually and with a bubble detector (Microbubble detector, Stockert Instrumente GmbH, Munich, Germany), which has a minimum detection size of >300 μm and minimum detection volume of 0.065 cm^3. The bubble detector was placed between the inlet pressure port (P_{in}) and the oxygenator (Figure 1). The value was recorded after one minute. This measure was repeated three times to obtain a mean value.

Results are expressed as mean + standard deviation (SD) and comparison is made using the analysis of variance (ANOVA) test between the three conditions i.e., control, CP, and RP. Differences were considered statistically significant for $p < .05$.

Comparison between the different oxygenators using the RP and the CP were made using the ANOVA test with differences considered statistically significant when $p < .05$.

Table 3. ANOVA test for the control with statistical significance shown in the right hand column.

ANOVA Comparison Test (No Pump)	p value
Dideco 703 vs. Quadrox	$p < 0.001$
Dideco 703 vs. Maxima +	$p < 0.001$
Dideco 703 vs. Maxima +prf	$p < 0.001$
Dideco 703 vs. Cobe	$p < 0.001$
Dideco 703 vs. Dideco-liliput	$p < 0.001$
Quadrox vs. Maxima +	$p < 0.001$
Quadrox vs. Maxima +prf	$p > 0.05$
Quadrox vs. Cobe	$p < 0.001$
Quadrox vs. Dideco-liliput	$p < 0.001$
Maxima + vs. Maxima +prf	$p < 0.001$
Maxima + vs. Cobe	$p > 0.05$
Maxima + vs. Dideco-liliput	$p > 0.05$
Maxima + PRF vs. Cobe	$p < 0.001$
Maxima + PRF vs. Dideco-liliput	$p < 0.001$
Cobe vs. Dideco-liliput	$p > 0.05$

RESULTS

The partially occluded RP completely prevented BT across the oxygenator. This we denoted >–80 mmHg meaning no BT was observed in our experiment (Table 2).

However, in the control with no pump, BT was observed with every oxygenator (Table 2 and Figure 2). BT occurred with a mean vacuum level of –53 ± 7 mmHg. In two adult oxygenators, BT occurred at a high negative pressure (–60 ± 2 mmHg). Interestingly enough, this was also the same value for the pediatric oxygenator (Figure 2).

When the CP was placed in the arterial line, significant increase (21%) in the negative pressure (–67 ± 7 mmHg) was necessary to allow for BT with $p < .05$ compared to the control (* in Table 2).

In the "no pump" condition, the most resistant oxygenators (–60 ± 2 mmHg) were the Maxima+, (Medtronic DLP, Grand Rapids, MI) Cobe (Cobe Cardiovascular, Inc., Arvado, CO) and the Liliput 901 (Dideco, Mirandola, Italy) (Table 2) and statistical significance showed in Table 3 with $p < .001$.

Table 2. Vacuum levels (mmHg) that provoked BT for the six oxygenators tested for the control (no pump), centrifugal pump (CP), and roller pump (RP).

	Oxygenators						
	Dideco 703	Quadrox	Maxima +	Maxima +prf	Cobe	Dideco-liliput	mean ± SD
No pump	–40 ± 2	–50 ± 3	–60 ± 2	–50 ± 3	–60 ± 2	–60 ± 2	–53 ± 7
CP	–60 ± 2	–70 ± 3	–60 ± 2	–60 ± 2	–70 ± 3	–80 ± 3	–67 ± 7*
RP	>–80	>–80	>–80	>–80	>–80	>–80	–80 ± 0**

CP versus control (*$p < 0.05$) and CP versus (**$p < 0.05$).
SD presents standard deviation.

Table 4. ANOVA test for the CP with statistical significance shown in the right hand column.

ANOVA Comparison Test (Centrifugal)	*p* value
Dideco 703 vs. Quadrox	$p < 0.001$
Dideco 703 vs. Maxima +	$p > 0.05$
Dideco 703 vs. Maxima +prf	$p > 0.05$
Dideco 703 vs. Cobe	$p < 0.001$
Dideco 703 vs. Dideco-liliput	$p < 0.001$
Quadrox vs. Maxima +	$p < 0.001$
Quadrox vs. Maxima +prf	$p < 0.001$
Quadrox vs. Cobe	$p > 0.05$
Quadrox vs. Dideco-liliput	$p < 0.001$
Maxima + vs. Maxima +prf	$p > 0.05$
Maxima + vs. Cobe	$p < 0.001$
Maxima + vs. Dideco-liliput	$p < 0.001$
Maxima + PRF vs. Cobe	$p < 0.001$
Maxima + PRF vs. Dideco-liliput	$p < 0.001$
Cobe vs. Dideco-liliput	$p < 0.001$

In the CP condition, the most resistant adult oxygenators were the Quadrox and again the Cobe (−70 ± 3 mmHg) with the Liliput having the strongest resistance of −80 ± 3 mmHg (Table 2) and statistical significance showed in Table 4 with $p < .001$.

DISCUSSION

The partially occluded roller pump completely prevented BT across all six oxygenators. In this situation a negative pressure superior to –80 mmHg would probably be needed to create the phenomenon of BT. A maximum negative pressure of –80 mmHg was chosen as superior values have been reported to create hemolysis. Six oxygenators were chosen due to the fact that many cardiac surgery departments use different oxygenators. The CP was 16% less efficient compared to the roller pump, as a mean vacuum level of −67 ± 7 mmHg was required in order for BT to occur compared to −80 mmHg in the RP (** in Table 2). Among the six oxygenators tested, all showed different levels of resistance to BT when used together with the CP or with the RP (Table 2).

The generation of GME in CPB components has already been extensively documented in the past, including their presence in venous reservoirs (7), arterial pumps (8), arterial filters, and oxygenators (9,10). Tevaearai et al. have used a new aspiration system to reduce blood cell trauma, which may attenuate GME formation (11).

Oxygenators have been found to trap GME up to 10 cm^3, thus offering an additional barrier to air bubbles in the CPB circuit (10), but may also generate GME when used in conjunction with new minimally invasive techniques (5). We know that an increase in membrane surface area improves gas transfer with a limited impact on blood trauma and no increase of blood path resistance (12). However, we could not find a correlation between membrane surface area (MSA) and negative pressure, even though in the adult oxygenators with higher MSA's, more negative pressure was needed to cause BT in our study (Table 1). The converse was observed with the pediatric oxygenator in that more negative pressure was needed despite the smaller MSA, which is approximately one sixth of the other adult oxygenators. It offers a higher resistance to BT, which may be possible because of the structure of the membrane, i.e., pore sizes, densities, and fiber configuration, or other structural specifications listed in Table 1.

The use of a negative pressure in the range specified has been advocated by Shin et al. using values between −35 and −55 mmHg to maintain optimal flow rate index greater than 2.4l/min/m^2 (3). Our data suggest that the use of a CP may provide resistance to BT from the oxygenator into the blood compartment, as the mean negative pressure required for BT was 21% higher compared to the control (Table 2). However, this amount is less than the RP value and might not be sufficient when using the VAVD technique, as the pump may be stopped for several reasons (e.g., surgical maneuvers, clamping of the aorta, emergency procedures, circulatory arrest, weaning) during which the perfusionist could forget to switch off the vacuum. The consequences could be detrimental to the patient as seen in this study. We thus advocate the use of a RP when using the VAVD technique.

In conclusion, the centrifugal pump offers significant resistance to BT compared to the control but not enough compared to the roller pump while using typical negative pressures as seen in VAVD techniques. BT cannot be prevented if the CP is turned off while the vacuum remains on the reservoir. However, the roller pump offers optimal resistance to BT when used in conjunction with the VAVD technique. Therefore, VAVD is a safe technique as long as the perfusionist stops the vacuum when the arterial pump is no longer in use and the use of a roller pump is preferred in the arterial position.

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