JECT. 2013;45:122–127
The Journal of ExtraCorporeal Technology

Pro Con Debate

Vacuum-Assisted Venous Drainage, Angel or Demon: PRO?

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Presented at the Perfusion Down Under Winter Meeting 2012, Queenstown, New Zealand, Perfusion Downunder, Queenstown, New Zealand, August 2–4, 2012.

Abstract: Vacuum-assisted venous drainage (VAVD) was proposed to optimize venous drainage during bypass through femoral venous cannulation. It is currently used in both adult and pediatric surgery when siphon gravity venous drainage is suboptimal. In pediatric surgery, the major advantages of VAVD are a significant decrease in cardiopulmonary bypass prime volume and an improved drainage with all collateral benefits. To limit gravity drainage, we use a two-level heart–lung machine dedicated to pediatric perfusion. The top level of the cardiotomy reservoir is positioned at the patient atrial level, making it possible to downsize the length and diameter of venous and arterial lines. Since 2008, a negative pressure of approximately –30 mmHg has been used for all patients. Initiation of bypass is performed in a classical way with a cardiotomy reservoir open; vacuum is added as soon as the maximal gravity drainage is reached. During bypass, when the blood level in the reservoir decreases to the safety limit level, a small increase in negative pressure is used to improve venous drainage. For weaning from bypass, the negative pressure is gradually decreased to zero, then the reservoir is opened and the venous line progressively closed. Prime volumes were significantly reduced to 100 mL for small neonates, 125 mL for infants, and 175 mL for older children with flow up to 1.5 L/min^{-1}. A low prime volume is expected to improve blood conservation and decrease donor exposure, prevent drawbacks of transfusion (immunomodulation, infection), increase the incidence of blood-free surgery in smaller babies, and decrease whole body systemic inflammation by decreasing surface of foreign material in contact with blood and inflammation associated with blood transfusion. The main drawbacks described have been retrograde flow in the venous line with cerebral air embolus and an increased incidence of gaseous microemboli. These drawbacks are avoidable through appropriate training of perfusionists. When negative pressure is "reasonable," complications are more theoretical than significant in clinical practice. A technique with a benefit/drawback ratio of 1:0 is utopian, but the advantages of VAVD far outweigh any potential drawbacks when applied properly. **Keywords:** vacuum-assisted venous drainage, cardiopulmonary bypass, miniaturized cardiopulmonary bypass, low priming volume. *JECT. 2013;45:122–127*

At the beginning of cardiac surgery, vacuum-assisted venous drainage (VAVD) was used in the Gibbon heart–lung console (1). Several years later, it was proposed as a solution to optimize venous drainage for performing total bypass flow through femoral venous cannulation in adult surgery (2) and extensively used for minimally invasive surgery in adults (3). It is today applied in both adult and pediatric surgery, when siphon gravity venous drainage is suboptimal. Like in any alteration in the conduct of cardiopulmonary bypass, there are positive and negative side effects and the perfusionist should weigh advantages and drawbacks before deciding to shift to a new protocol. In many instances, several refinements can also be added to a technique and the way the technique is applied may have a significant impact on its tolerability.

Received for publication December 30, 2012; accepted June 6, 2013.
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The author has stated that he has reported no material, financial, or other relationship with any healthcare-related business or other entity whose products or services are discussed in this paper.

RATIONALE FOR USE OF VACUUM-ASSISTED VENOUS DRAINAGE

Before introducing VAVD in clinical practice, we performed in vitro tests to verify very simple physical laws and to measure the maximal flow for tubing of different diameter. For an optimal in vitro condition, with a hematocrit of 24% in a 3/16-inch silicone tubing with

a height gradient of 6 cm and a negative pressure of –40 mmHg, we measured a maximal blood flow of 1280 mL/min^{-1}. The effective negative pressure is defined as the sum of vacuum contribution and siphon contribution. The siphon contribution is related to the height gradient defined as the distance between right atrial/vena cava level and blood level in the venous reservoir. This height gradient increases when the blood level decreases in the venous reservoir and conversely decreases when the blood level rises in the venous reservoir. Maximal variation is equivalent to the distance between the top of the reservoir and the minimal operating level and depends on the shape of the reservoir (Figure 1). This variation is likely to significantly affect venous drainage. Assuming a height gradient of 40–50 cm, a 10-cm variation in blood level is equivalent to a 20–25% variation in effective negative pressure. VAVD is one way to maintain the effective negative pressure to a constant level by modifying negative pressure in accordance with the modification of the venous reservoir blood level.

When we decided to use VAVD, our primary goal was not to add it on top of siphon gravity drainage, but rather to replace the gravity drainage by vacuum drainage. The major advantage linked with VAVD use in pediatric surgery is the significant decrease of cardiopulmonary bypass (CPB) prime volume and the improved venous drainage with all collateral beneficial effects.

We believe that there are two different ways of applying VAVD. The "wrong way" is to add vacuum to conventional siphon gravity drainage (i.e., without modifying the declivity of the oxygenator) because:

- You do not modify your prime volume;
- You may easily reach dangerous levels of effective negative pressure;
- You may increase entrainment of air in the venous and arterial lines;
- You may increase blood trauma and hemolysis; and
- You may decrease bypass flow (a high negative pressure impairs head pump filling and theoretically may reverse flow if it exceeds the positive pressure generated by the pump).

The "right way" is to use it in lieu of siphon gravity drainage (i.e., with a limited gravity drainage), because:

- You may significantly decrease your prime volume; and
- You can determine the maximal and minimal levels of effective negative pressure, avoiding dangerous levels

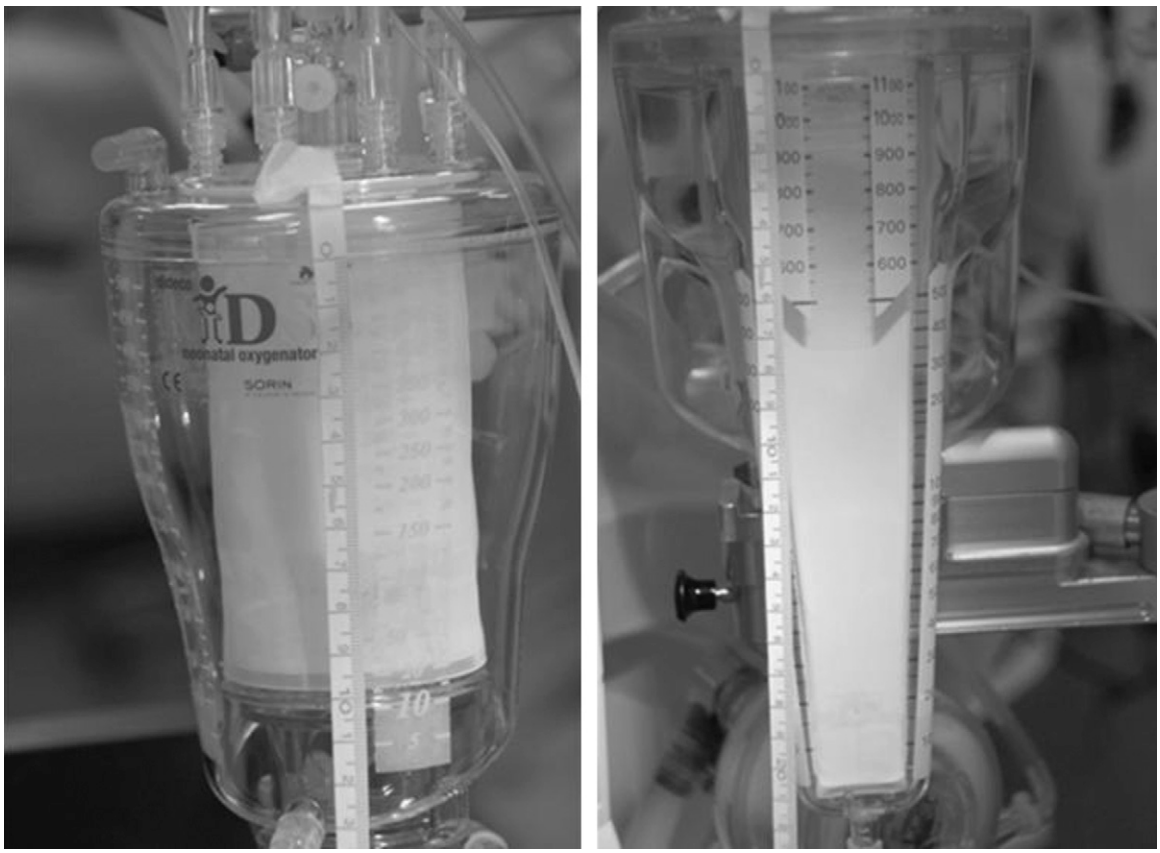

Figure 1. Cardiotomy reservoirs: on the right panel, a Kids D100 oxygenator with a cardiotomy 13 cm in height; on the left panel, a Baby FX oxygenator with a cardiotomy 21 cm in height.

(increased entrainment of air in bypass lines, increased blood trauma, and hemolysis).

To maximize the benefits of VAVD, we limited venous siphon drainage gravity by using a two-level heart–lung machine dedicated to pediatric perfusion (Figure 2). The top level of the venous reservoir was positioned at the patient atrial level, making it possible to downsize the length of venous and arterial lines to 1 m and the diameter of lines from 5/32 inches for smaller babies (maximal flow 600 mL/min^{-1}) to 1/4 inches for young children (maximal flow 1500 mL/min^{-1}).

Since 2008, VAVD has been used for all patients (gravity drainage being insufficient to achieve full flow bypass) with a negative pressure of approximately –30 mmHg but never below –40 mmHg.

Initiation of bypass is performed in a classical way with a venous reservoir open; vacuum is added when the maximal siphon gravity drainage is reached. During bypass, when blood level in the venous reservoir decreases to the safety limit level, a small increase in negative pressure is used to improve venous drainage. While on bypass, we frequently test the minimal effective negative pressure by limiting vacuum contribution as much as possible. During weaning from bypass, the negative pressure is gradually decreased to zero, then the venous reservoir is opened and the venous line progressively closed.

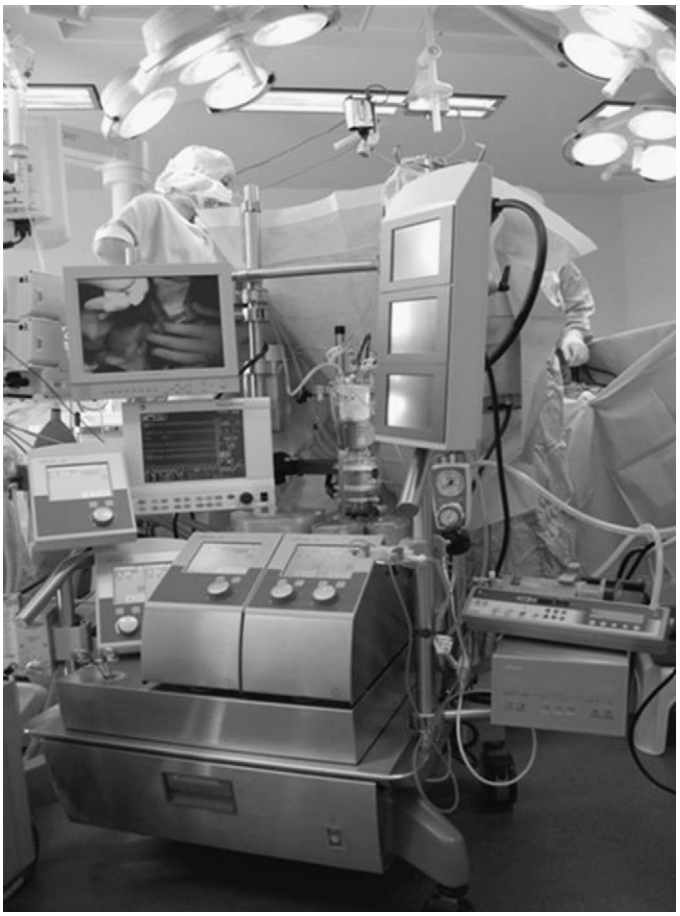

Figure 2. Two-level heart–lung machine: the top of the cardiotomy reservoir is at the level of the patient's right atrium.

Prime volumes have been significantly reduced to 100 mL for small neonates (up to bypass flow of 600 mL/min^{-1}), 125 mL for neonates and infants (up to bypass flow of 900 mL/min^{-1}), and 175 mL for bypass flow up to 1500 mL/min^{-1}.

Our first study, in 2009, aimed to test the influence of miniaturized bypass circuit and VAVD on blood conservation (4). It included 150 patients weighing 2.3–10 kg. Bypass components were a Kids D100 hollow-fiber membrane oxygenator (Sorin Group, Mirandola, Italy) with a built-in pressure relief valve and 3/16-inch silicon tubing arterial venous and sucker lines. We never used an arterial filter, the efficiency of this component being controversial since the introduction of membrane oxygenators (5), hemofiltration, or cell saver. The total prime volume was 120 mL, including priming of the cardioplegia circuit. All patients were operated on with normothermic perfusion and intermittent warm blood microplegia, and our goal was to maintain a hemoglobin level of at least 8 g/dL throughout the perioperative period. Before priming the circuit, we estimated the predicted hemoglobin level with a blood-free prime applying a previously validated, empirical formula.

Predicted hemoglobin was considered equivalent to the product of patient blood volume by preoperative hemoglobin divided by the sum of patient blood volume and prime volume. In this group of patients, blood volume valuation was 80 mL/kg. Whenever the predicted hemoglobin on initiation of bypass was 8 g/dL or more, a blood-free prime was used and when the predicted hemoglobin was below 8 g/dL, a blood prime composed of whole blood (50% packed red blood cells + 50% fresh–frozen plasma) was necessary.

After bypass, blood remaining in the bypass circuit was collected without any alteration and reinfused to the patient according to his or her needs.

The results are summarized in Table 1. The two groups of patients being different, no statistical analysis could be fairly done, but it is interesting to note that:

- More than 17% of patients weighing less than 10 kg had blood-free surgery, meaning that none of them received any blood products during their whole hospital stay.
- None of the transfused patients had platelet infusion and redo for bleeding was <1% (one patient out of 150).
- Ninety-eight percent of transfused patients had a donor exposure of 2 (one packed red blood cells and one fresh–frozen plasma) and the two units were seldom entirely infused.

Table 1. Comparison of patients with and without blood transfusion during their hospital stay.

Data	<6.4 kg, 102 Patients	6.4–10 kg, 48 Patients	Preoperative Hb	Intraoperative Hb	Postoperative Hb	Preoperative Lactate	Intraoperative Lactate	Postoperative Lactate	Ti-to-ex Lactate	Ti-to-ex
Transfused patients	100%	45% (22 patients)	10.2 6.7–15.9	11.5 7.8–15.8	15 11.2–16.8	1.3 .7–4.6	2.4 1.2–5.3	2.5 1.1–7.9	1.5 .9–3.5	12 2–290
Bloodless surgery	0%	55% (26 patients)	11.4 9.7–16.8	8.7 7.5–12.9	10.6 8.5–14.9	1.1 .7–1.7	1.8 1.0–3.2	1.5 .9–3.1	1.6 .9–2.5	3 1–12

Hb, hemoglobin; Ti-to-ex, Time to extubation.
Results of hemoglobin, lactate blood level, and time to extubation are expressed as median (range). Hemoglobin is in g/dL; lactate blood level is in ng/mL; time to extubation is in hours.

- Lactate blood levels were lower in the nontransfused group during and immediately after surgery.

DISCUSSION

VAVD was used to improve venous return through peripheral venous cannulation or to decrease the diameter of the venous cannula (6), but in pediatric cardiac surgery, the primary goal is rather to decrease prime volume and to allow a more effective control of heart decompression and volume expansion during bypass.

A low prime volume is expected to:

- Improve blood conservation, decrease blood-bank product use and thus donor exposure;
- Decrease drawbacks of transfusion (transfusion-related acute lung injury, immunomodulation, bacterial or viral transmission);
- Decrease dilution, allowing higher incidence of blood-free surgery in smaller babies;
- Decrease whole-body systemic inflammation by decreasing total surface of foreign material in contact with blood (7,8), but also by decreasing inflammation associated with blood transfusion;
- Minimize volume expansion by maintaining the effective negative pressure to a constant level or by increasing it within a safe range;
- Achieve an optimal venous drainage with heart decompression and bloodless operating field; and
- Reduce bypass cost (in France, the cost of one unit of packed red blood cells is approximately $200 U.S.).

Most of these benefits have been described in the literature. We, like others, have demonstrated the benefit of VAVD in terms of blood conservation (2–4,9,10). Blood requirement as small as the volume needed for blood samples during bypass was described in an experimental study on 10 1-week old piglets (11). To the best of my knowledge, the least frequent expected benefits have not been reported, but a decrease in frequency of immunologic and infectious complications can reasonably be assumed. Attenuation of the postbypass inflammatory response was demonstrated with miniaturized circuit in animals (7,8) and conversely, allogeneic blood transfusion was described as a factor increasing inflammatory response during cardiac surgery (12).

One benefit of VAVD has been experienced by many perfusionists but remains difficult to quantify in a scientific study. Whenever the blood level in the cardiotomy reservoir gets dangerously low during gravity drainage, there are two options: either to decrease blood flow or to add volume, neither being totally satisfactory. During VAVD, a small increase in negative pressure is often effective in reversing the situation. This possibility is an important factor contributing to a reduced need for volume expansion during CPB. The improvement of heart decompression is also uneasy to quantify but is attested by surgeons routinely asking to increase negative pressure whenever blood arises in the operating field.

The major drawback described in the literature is retrograde flow in the venous line with cerebral air embolus through an atrial septal defect (13). Such a complication was also described during a Fontan procedure (14). Surprisingly, the patient had no atrial septal defect and the origin of air embolism was very likely to be the result of VAVD, but the authors failed to clearly demonstrate the mechanism of air embolism. In this case report, the effective negative pressure was not assessed, but the venous drainage was excellent, "so good, in fact, that the free wall of the right atrium was closely approximated to the atrial septum and there was virtually no residual blood in the right atrium." In this case, we can imagine that the passage of air through the bypass circuit was the result of an undetected entrainment of air from a nontotally occlusive venous pursestring suture. As stated by the authors, the use of transesophageal echo may be of great help in assessing the origin of air embolism. Furthermore, transesophageal echo is a useful tool for differential diagnosis of poor venous return (15). An excessive effective negative pressure may induce vena cava collapse and impair venous return by partial or total occlusion of the venous cannula. The increased risk of detected or undetected air microembolism is also a major concern (16–21). It is well acknowledged that significant systemic

gaseous microemboli from a venous source may occur despite an arterial filter, and it is also well demonstrated that VAVD increases the risk of air embolism (22). However, in the literature, the effective negative pressure is either higher than the one we recommend or unspecified. We must keep in mind that despite a 32-μm arterial filter, air can be transported from the venous reservoir to the aorta (23). Furthermore, there are significant differences among membrane oxygenators, venous reservoirs, and blood pumps in terms of their capability to trap microbubbles (24–27).

Many refinements in perfusion during VAVD are of utmost importance in limiting the number of microbubbles in the arterial lines:

- Avoiding macrobubbles in the venous line during initiation of bypass (23);
- Pursestring sutures on the venous cannula tight;
- Careful deairing of the syringe before drug administration as well as discarding stagnant blood before sampling (28);
- Withdrawing of blood and injection of drugs on the manifold in a gentle manner;
- Monitoring of venous reservoir pressure;
- Using membrane oxygenators with built-in or added pressure relief valve;
- Opting for a membrane oxygenator and a venous reservoir with the ability to remove gaseous microemboli; and
- Using a new membrane oxygenator with a built-in arterial filter or added arterial filter (despite controversial debate on the efficiency of arterial filters).

There is no consensus on the hemolytic effects of VAVD. In an experiment on calves perfused for 6 hours, Mueller (29) failed to demonstrate any increased trauma to blood cells compared with standard gravity drainage. Hemolysis was assessed on plasma-free hemoglobin and lactate dehydrogenase blood levels. These results were obtained with negative pressures between –35 and –60 mmHg (without precision on gravity contribution), i.e., higher than the one recommended in clinical settings. These results are in line with the ones obtained by Randall (30). During an 8-hour in vitro perfusion with fresh heparinized bovine blood (hematocrit 30–32%), vacuum assist, kinetic assist, and gravity drainage were compared with control. Vacuum negative pressure was –75 to –78 mmHg and kinetic negative pressure –88 to –97 mmHg. Plasma hemoglobin level was higher in the kinetic circuit, but there was no statistically significant difference among the three types of drainage. Furthermore, the analysis of the red cell osmotic fragility data performed after 8 hours of perfusion did not reveal any significant difference among groups.

Overestimation of blood flow was also described as a potential drawback of VAVD (31). The phenomenon was described in an in vitro study using negative pressure with or without gravity drainage (with a height gradient of 70 cm) and water-filled circuits. When gravity drainage was associated with vacuum, overestimation of blood flow was observed for negative pressures of at least –60 mmHg, far above the level used in pediatric surgery. The adjunction of an ultrasonic flow probe on the venous line was proposed and is probably effective in reducing the adverse side effects of VAVD (32).

I believe that the drawbacks described are mainly the result of the lack of perfusionist training before the implementation of the technique. When the effective negative pressure is equivalent, there is no specific risk of vacuum compared with gravity. The confounding fact is that effective negative pressure is not correctly described in the vast majority of studies. In fact, it is this effective negative pressure that must be considered for a fair risk assessment of VAVD. There were also complications during the "learning period" that should no longer be observed. When negative pressure is "reasonable," complications are more theoretical than significant in clinical practice.

CONCLUSION

A technique with a benefit/drawback ratio of 1:0 is utopian but I do believe that the advantages of VAVD, namely reduction in prime volume and blood transfusion, improved heart decompression and constant optimization of effective negative pressure, far outweigh any potential drawbacks, when applied properly.

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