

## Review Articles

# Vacuum-assisted Venous Drainage and Gaseous Microemboli in Cardiopulmonary Bypass

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**Abstract:** When conventional gravity siphon venous drainage cannot achieve satisfactory venous drainage during minimally invasive cardiac and neonatal surgeries, assisted venous drainage techniques are needed to ensure adequate flow. One assisted venous drainage technique, vacuum-assisted venous drainage (VAVD), the aid of a vacuum in the venous reservoir, is now widely used to augment venous drainage during cardiopulmonary bypass (CPB) procedures. VAVD permits the use of smaller venous cannulae, shorter circuit tubing, and lower priming and blood transfusion volumes, but increases risk of arterial gaseous microemboli and blood trauma. The vacuum should be set as low as possible to facilitate full venous return, and real-time monitoring of gaseous microemboli in the arterial and venous line should be used to achieve the safest conditions. With

current ultrasound technology, it is possible to simultaneously detect and classify gaseous microemboli in the CPB circuit. In this article, we summarize the components, setup, operation, advantages, and disadvantages of VAVD techniques and clinical applications and describe the basic principles of microemboli detectors, such as the Emboli Detection and Classification (EDAC) Quantifier (Luna Innovations, Roanoke, VA) and Bubble Counter Clinical 200 (GAMPT, Zappendorf, Germany). These novel gaseous microemboli detection devices could help perfusionists locate the sources of entrained air, eliminate hidden troubles, and minimize the postoperative neurologic impairments attributed to gaseous microemboli in clinical practice. **Keywords:** cardiopulmonary bypass, equipment, embolism, perfusion. *JECT. 2008;40:249–256*

Most cardiac operations require cardiopulmonary bypass (CPB) with cannulae directly inserted into the right atrium and ascending aorta. This conventional method relies on gravity and height differences between the venous cannula tip and the venous reservoir blood level to facilitate venous drainage. Thus, drainage is limited by the internal diameter and length of the drainage catheter, the central venous pressure, the tubing internal diameter and length, the venous reservoir air pressure, the height difference, etc. (1). As advances in cardiac surgery permit correction of congenital heart defects in small infants, smaller venous cannulae are required to prevent obstruction of the visual field and lower the priming volumes (2).

Additionally, the use of a sanguinous priming solution may further benefit neonates during CPB (3). In minimally invasive surgery, using peripheral cannulation and smaller diameter venous cannulae is also advantageous to the patient (4). These modifications, although beneficial to the patient and surgeon, are also limiting because they further restrict venous return. If resistance to venous return cannot be overcome, assisted venous return techniques are necessary to ensure adequate flow.

Vacuum-assisted venous drainage (VAVD), a vacuum in the venous reservoir, augments the venous drainage and is now widely used during CPB procedures. VAVD is not a simple perfusion technique and has both advantages and disadvantages, so correct, safe use of VAVD is essential.

## VACUUM-ASSISTED VENOUS DRAINAGE

Two types of assisted venous drainage are currently available: VAVD and kinetic-assisted venous drainage (KAKD). VAVD, also known as vacuum-assisted venous

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return (VAVR) or vacuum-augmented venous return (VAVR), uses a regulated vacuum source to generate negative pressure within a sealed hard-shell venous reservoir, augmenting venous drainage during CPB (Figure 1A). A soft-shell venous reservoir with a special rigid housing can also be used (5). KAVD uses a kinetic pump, inserted into the venous line between the venous cannulae and reservoir, to mechanically increase venous drainage. The kinetic pump (usually a centrifugal pump) is capable of generating significant negative pressures that augment venous drainage (Figure 1B) (6,7).

VAVD requires a closed venous system with a negative pressure region, usually a sealed hard-shell reservoir with an integrated hollow-fiber oxygenator and a vacuum regulator to adjust the negative pressure as needed. Several vacuum regulators are available for clinic use (Baxter, Polystan, etc.). The vacuum regulator should be limited to ranges of 0 to  $-100$  mmHg and must use negative and positive pressure relief valves. The vacuum regulator should be calibrated routinely. In total, a VAVD system consists of a hard-shell venous reservoir with a negative pressure relief valve, a vacuum regulator, a vacuum source, a pressure monitor (with an alarm at set to go off at the maximum positive and negative pressures), and a VAVD kit including suction tubing with a  $\frac{1}{4}$ " Y connector, a moisture trap, and a positive pressure relief valve.

When setting up VAVD, all ports on the hard-shell

venous reservoir should be sealed with caps sterile. One luer port on top of the venous reservoir should be connected to a pressure transducer for monitoring the internal venous reservoir pressure. A second luer port should be connected to a positive relief valve. The vacuum tubing, with a Y atmosphere vent line and a moisture trap, should be connected to the vent port of the venous reservoir. The second port on the moisture trap should be connected to the regulator, and the regulator itself should be attached to the standard vacuum wall source. After clamping the Y atmosphere vent line and turning the vacuum regulator to the desired level, the VAVD is ready for use.

When applying VAVD, CPB should be initiated according to standard procedure with the vacuum assist device turned off. The blood flow rate should be increased until equilibrium between the flow rate and the level of the venous reservoir is reached. Then the vacuum regulator can be turned on to a preset pressure of  $-20$  mmHg or less. Concurrently, the atmosphere arm should be clamped. The level of the venous reservoir should be monitored for increased return and the pump flow rate increased accordingly until adequate perfusion is obtained in terms of the blood flow rate, venous hemoglobin saturation, and mean arterial pressure. The negative pressure can be increased to achieve the appropriate blood flow rate with the minimum vacuum assistance necessary. To terminate VAVD and wean the patient from CPB, open the atmosphere arm, turn off the vacuum regulator, and wait until the

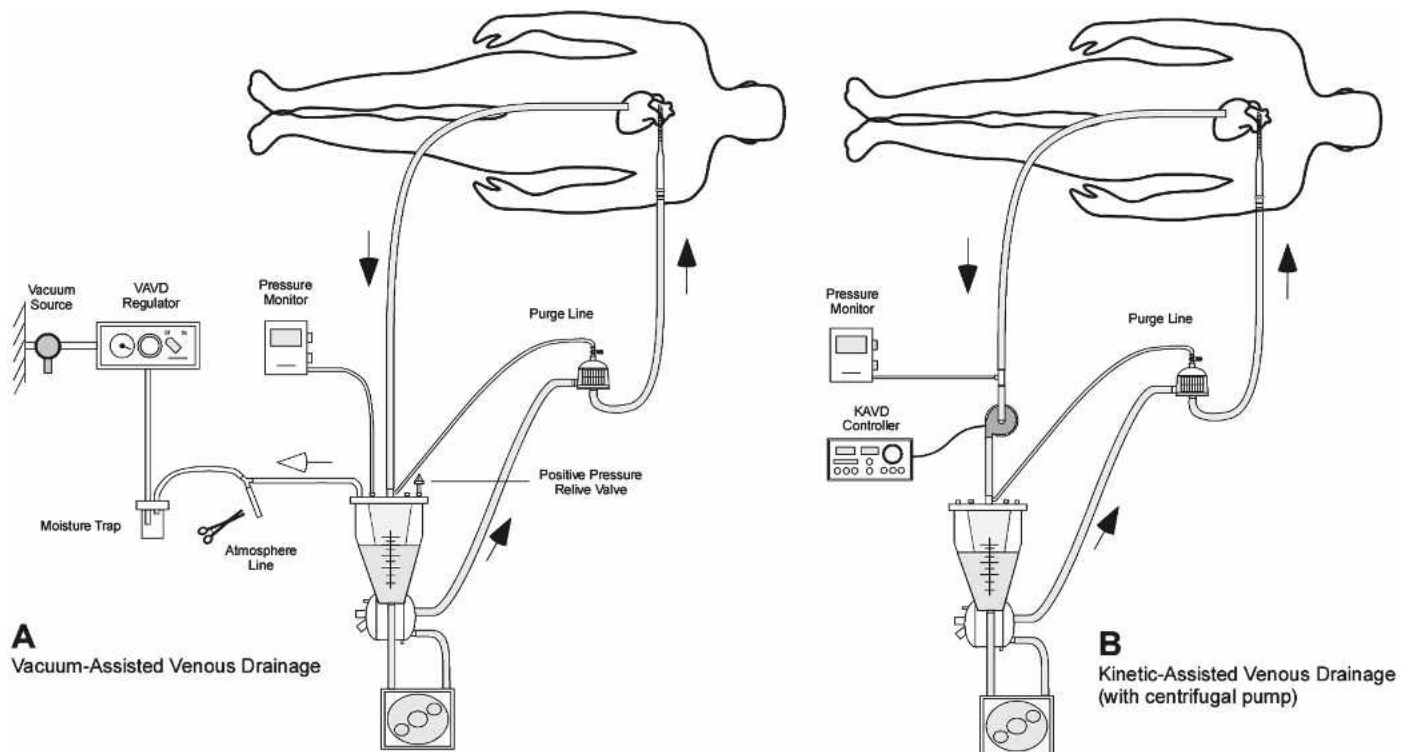


Figure 1. Schematic of VAVD and KAVD.

blood volume is transferred back to the patient. Weaning from CPB can proceed in the usual manner.

Generally, VAVD may be used whenever siphon venous drainage is insufficient to provide adequate flow for complete cardiopulmonary support. This is true regardless of the type of surgery being performed. Murai et al. (8) suggested that the indications for VAVD use include insufficient venous return by siphon drainage alone, persistent elevation of the central pressure, and insufficient venous drainage in the operative field. Ultimately, the decision to use VAVD rests with the surgical team.

### **VAVD Advantages**

**Permits the Use of Smaller Venous Cannulae:** Smaller venous cannulae facilitate venous cannulation, decrease the priming volume and maximizing the surgical visibility, particularly in pediatric cardiac surgery (2). With smaller venous cannulae, adjustable negative pressure in the venous line allows optimal venous return to the reservoir. Colangelo et al. (4) reported using a 14-Fr wire-bound arterial cannula inserted into the right jugular vein (positioned at the atrial/superior vena cava junction) and joined with a 21- or 28-Fr femoral venous cannula for venous drainage in extrathoracic CPB (age, 12–77 years; mean age, 39 years). Using VAVD at about  $-40$  mmHg, they successfully performed extrathoracic CPB in 37 patients with the Heartport technique (9) (Heartport, Redwood City, CA) and 156 patients with the trans-thoracic aortic clamp technique during minimally invasive cardiac surgery. Procedures included mitral valve surgery, atrial septal defect closure, cardiac mass removal, tricuspid repair, and repeated cardiac procedures. A pressure of  $-40$  mmHg sufficiently established appropriate venous drainage with small cannulae, without causing venous collapse. Excessive negative pressure should be avoided to minimize the risk of hemolysis and the chattering phenomenon (caused by right atrial collapse around the venous cannula), which may reduce venous return.

**Decreases the Priming Volume and the Volume of Blood Transfused:** Unlike conventional gravity siphon venous drainage, VAVD does not rely on the height differential between the patient's heart and the venous reservoir. Additionally with VAVD, it is possible to raise the height of the venous reservoir, shorten the venous and arterial lines, and decrease the tubing diameter. This further allows remodeling of the pump console and circuit. With smaller cannulae and shorter tubing, VAVD could dramatically reduce priming volumes, maximally decrease tubing dead space, and lower patient hemodilution (10). Furthermore, VAVD could reduce platelet consumption and postoperative chest tube drainage (10,11). Merkle et al. (3) reported that the significant reduction in priming volume with VAVD permitted the use of non-heme prime

in a modified neonatal CPB circuit in neonates and infants  $<6$  kg body weight.

In the clinical pediatric study of Nakanishi et al. (12), the lowest priming volume achieved was 350 mL in the VAVD group (49 cases; mean body weight,  $11.1 \pm 4.1$  kg) and 500 mL in the control group with gravity drainage (128 cases; mean body weight,  $11.7 \pm 4.4$  kg). The total priming volume was significantly lower in the VAVD group than in the control group ( $576.8 \pm 219.6$  mL in the VAVD group vs.  $639.4 \pm 88.3$  mL in the control group,  $p < .01$ ). Priming with non-blood solutions was significantly more common in the VAVD group than in the control group (37 cases, 75.5% vs. 56 cases, 43.8%;  $p < .01$ ). The patient with the lowest body weight without a blood transfusion was 6.1 kg in the VAVD group and 12 kg in the control group. Nakanishi et al. concluded that VAVD is beneficial for pediatric open heart surgery because asanguinous priming is feasible, priming and blood volumes are reduced, and venous return is improved.

Hayashi et al. (13) reported that a VAVD system with a pressure relief valve simplified the CPB circuit, resulting in a smaller CPB priming volume ( $1071 \pm 88$  mL with VAVD vs.  $1405 \pm 137$  mL with gravity siphon,  $p < .01$ ) and less hemodilution (minimum hemoglobin level:  $6.83 \pm 1.06$  vs.  $5.78 \pm .79$  g/dL,  $p < .01$ ) in comparison with the conventional siphon-dependent venous drainage system in adult CPB. They concluded that this system could be implemented in bloodless open heart operations and improve the safety of minimally invasive procedures.

**Increases Venous Drainage and Eliminates the Risk of Air Blocks in the Venous Line:** Compared with standard siphon gravity venous drainage, additional negative pressures in the venous line will undoubtedly augment venous blood return. An in vitro test showed positive relationships between vacuum pressure and venous drainage and between blood temperature and venous drainage (14). In the event that gross air entered the venous line, negative pressure easily handled the macrobubbles and eliminated the risk of air blocks in venous line (15).

**Maintains an Emptier Heart and Drier Operative Field:** VAVD can provide total cardiopulmonary support with adequate cardiac decompression and reduce blood exposure to the damaging effects of pump suction and basket suction salvage. At the same time, VAVD can maintain higher arterial perfusion flow and higher blood levels in the venous reservoir (11), resulting in a drier, "bloodless" surgical field while also minimizing blood cell trauma.

**Lower Cost than KAVD:** Compared with KAVD, which usually requires a centrifugal pump in the venous line, the cost of VAVD is substantially lower. However, in cases where KAVD can be performed with a roller pump, its costs are comparable to VAVD (7).

### VAVD Disadvantages

#### ***Induces Blood Trauma if the Vacuum Pressure Is Too High:***

Higher negative pressures result in higher shear stress and hemolysis. Negative pressure exhibits a threshold value of  $-120$  mmHg, beyond which the relationship between negative pressure and blood damage is linear (16). It should be noted that the negative pressure present in the venous cannulae is the sum of the venous reservoir negative pressure and the siphon gravity pressure. Judicious use of negative pressure to facilitate full venous return minimizes blood cell trauma.

***May Potentially Draw Air Into the Venous Line:*** Entry of air into the venous line during CPB is common, and it is assumed that the defoaming materials in the venous reservoir have the ability to remove such air from the venous line. Many researches have verified, however, that entrained venous air is the main source of gaseous microemboli in the arterial line during CPB, particularly when VAVD is used. LaPietra et al. (15) inserted an open-ended 25-gauge hypodermic needle into the venous tubing to mimic a small suture tear in the atrial cannulation site in a simulated adult CPB circuit primed with Ringer solution. Their results showed that using VAVD in an incompletely closed system permitted the entry of significant numbers of microbubbles into the patient despite filtration with a centrifugal arterial pump in combination with VAVD to clear air emboli. Their study showed that VAVD, while offering many benefits to the patient and surgical team, also has dangerous consequences when used in an open system. Willcox et al. (17) verified that entrained venous air is a potential hazard to the patient, particularly during CPB with VAVD. After the introduction of air into the venous line of a salvaged clinical adult circuit, there was almost a 10-fold increase in the arterial line emboli count with VAVD compared with gravity venous drainage. The study of Wang et al. (18) confirmed that, when a fixed volume air was introduced into the venous line of a simulated neonatal CPB circuit, VAVD with higher negative pressures, increased flow rates, and pulsatile flow delivered more gaseous microemboli at the post-pump site. Although the majority of gaseous microemboli were trapped by the oxygenator and arterial filter, at high flow rates, some gaseous microemboli still appeared in the arterial line, especially with pulsatile flow and high negative pressures. Furthermore, the negative pressure generated in the closed cardiotomy reservoir can be transmitted to the oxygenator if a non-occlusive or centrifugal arterial pump is used, possibly resulting in the transport of air emboli from the gas to blood compartment of the oxygenator (19). The use of VAVD may exacerbate the entrapment of air emboli into the arterial line, resulting in a critical error. On identifying air bubbles within the arterial line, the VAVD must be terminated, and the possible leak source should be investigated (20).

In addition, hardshell reservoirs were originally designed for gravity venous drainage. Negative pressure in the reservoir may influence clearance of gaseous microemboli in the flowing blood. Redesigning the venous reservoir may be necessary to enhance removal and minimize the delivery of gaseous microemboli with VAVD (21,22).

***Higher Cost than Siphon Gravity Drainage:*** VAVD requires a regulator device to adjust the negative pressure and a disposable VAVD kit to connect the vacuum source, regulator, and oxygenator. Compared with siphon gravity drainage, VAVD costs slightly more but is still less expensive than KAVD with a centrifugal pump.

***Reduces Pump Flow Rate When Using Higher Negative Pressures:*** An in vitro study showed that VAVD with a negative pressure  $>50$  mmHg could reduce the flow delivered by the roller pump. Increased negative pressure at the inlet of the raceway tubing reduces its re-expansion, resulting in a net reduction in the stroke volume. The investigators recommended using a flow probe on the arterial line to prevent reaching the vacuum threshold where a severe reduction in flow occurs (23).

***Complicates the Existing CPB Circuit:*** VAVD equipment attaches to the venous reservoir and changes an open system to a closed system. Using a closed system is quite different from using routine gravity venous drainage and requires additional perfusionists training to ensure functional understanding of the principles underlying VAVD. It is paramount that the pressure within the closed venous reservoir is closely monitored and that positive and negative relief valves are used. With VAVD, including an additional suction circuit reservoir to avoid excess negative or positive pressure in the venous reservoir is safe (8).

***May Lead to Serious Accidents:*** Davila et al. (24) reported a complication of VAVD in an adult patient with an atrial septal defect. In this case report, the ports on the venous reservoir were sealed with caps, the vacuum line with the needle valve assembly was connected to the vent port, and the Y line was open to the atmosphere. The suction line was activated 2–3 minutes before CPB. After removing the clamp on the venous line, air appeared in the venous cannula and transesophageal echocardiography showed air in the right atrium, left atrium, and left ventricle. The reasons were multifactorial—a sealed venous reservoir without a positive pressure release valve was used, the pressure alarm was set to trigger at a negative threshold pressure limit rather than at a small positive pressure, and a needle valve was inserted in an incorrect position. Fortunately, the patient was discharged with a normal clinical neurologic examination after a series of treatments. Jahangiri et al. (20) reported a cerebrovascular accident after VAVD in a Fontan patient. Lacking a bubble monitoring device, the origin of the observed air

during the CPB procedure was unclear. After the VAVD was disconnected, no further air bubbles were noted. The patient underwent severe left-sided hemiparesis after surgery. These are just two examples. Cautious use of VAVD and real-time monitoring of microemboli during CPB with VAVD are very important.

### CLINICAL APPLICATION OF VAVD

The benefits of VAVD include augmented venous drainage, the ability to use smaller venous cannulae, and decreased priming volumes. Therefore, increasing numbers of heart centers are using VAVD, particularly with minimally invasive cardiac surgery and pediatric open heart surgery. Although many studies have shown that VAVD is associated with increased gaseous microemboli in the arterial line, there are other animal experiments and clinical observations that do not show obvious complications. One animal experiment showed that VAVD (-40 to -60 mmHg) did not increase thrombocyte and white blood cell trauma in comparison with standard gravity drainage after 6 hours of CPB. The study also reported that drainage type had no significant influence on free plasma hemoglobin or free lactate dehydrogenase levels (25). Clinical application of VAVD showed that the plasma free hemoglobin and haptoglobin levels during CPB were within acceptable levels compared with the conventional siphon-dependent system (13,26). Research by Jones et al. (27) verified that VAVD at -40 mmHg does not statistically reduce the ability of CPB circuit components to remove gaseous microemboli at lower pump flow rates; however, higher vacuum levels, increased pump flow rates, and entrapment of venous air should be minimized and avoided. Infusion of CO<sub>2</sub> (1-2 L/min) into the operative field during and near the end of open heart surgery may help decrease the neurologic risks of CPB with VAVD (4). Carrier et al. (28) reported that VAVD did not increase the neurologic risk in adult valvular replacement surgery. They compared 822 consecutive adult patients undergoing valve replacement with VAVD to 723 consecutive patients without VAVD. Seven patients in the VAVD group (1%) and 11 patients without VAVD (1.5%) suffered temporary or permanent neurologic deficits. These results could be attributed to lower negative pressures (-5 to -15 mmHg), administration of all drugs through a central line, use of carbon dioxide to flood the surgical field, or the use of aprotinin. They emphasized that VAVD was a useful adjuvant to the modern CPB system when used carefully and applied with the proper equipment and techniques. A study of pediatric patients with VAVD (-10 to -40 mmHg) did not show any neurologic complications, even without an arterial line filter in circuit (12). There were, however, several accidents reported in clinic (20,24). Current theories maintain that

entrained venous air is the main source of arterial line gaseous microemboli, so every effort should be made to avoid this. Real-time monitoring of gaseous microemboli in arterial and venous lines is the best way to safely use VAVD, and its use could give clinicians the opportunity to implement VAVD during CPB while reducing the occurrence of major side effects associated with gaseous microemboli.

### GASEOUS MICROEMBOLI IN CPB

In general, a 200- $\mu$ m diameter is considered the upper limit separating micro- from macroemboli. The majority of microemboli occurring during cardiac surgery are gaseous (29). Air in the arterial line of CPB circuits is thought to be comprised of gaseous microemboli, which are not visible with the naked eye. If an arterial filter and hollow-fiber oxygenator are functioning normally, they should prevent gaseous macroemboli from reaching the arterial line; however, microemboli may penetrate the arterial line despite these devices. There are many possible sources of gaseous microemboli during CPB. Entrained gaseous microemboli may be introduced to the circuit through aortic and venous cannulation, CPB initiation (30), non-occlusive purse strings or caval snares, VAVD, perfusionist intervention (31,32), and excessive cardiomy suction (33). The microemboli can also be generated by circuit components including the venous reservoir, oxygenator, roller pump, and incomplete wrapping between the tubing and connectors (34,35). Temperature gradients during cooling or warming of CPB may be associated with gas emboli formation (36,37). Furthermore, hypothermic perfusates, higher flow rates, and the use of pulsatile flow may increase the delivery of entrained venous air into arterial line (38,39).

### GASEOUS MICROEMBOLI DETECTION

Regardless of the source, gaseous microemboli are responsible for neurocognitive impairment after CPB, and their entry into the patient should be avoided or minimized as much as possible (40,41). It is therefore worthwhile to monitor gaseous microemboli in real time during CPB procedures, particularly when VAVD is used. As early as 1965, Austen and Howry (42) first reported real-time detection of bubbles or particulate matter in the tubing of an animal CPB circuit, confirming that ultrasound techniques could measure the number and size of bubbles in the arterial line. Additionally, ultrasound did not seem to have any ill effects on the blood. The earliest bubble detector for use during CPB was the Technique Laboratories TM-8 detector, which used a continuous wave ultrasound at a frequency of 0.6 MHz, but it is no longer commercially available (43). The Hatteland BD-100 ultra-

sonic bubble detector (Hatteland Instrumentering, Royken, Norway) used a pulse wave ultrasound with a transducer frequency of 1.5 MHz, a repetition frequency of 11.3 kHz, and a pulse duration of 5  $\mu$ s and was widely used to detect bubbles in CPB circuits in the 1980s (43). Its updated model, the CMD-10, has proven insufficiently sensitive at detecting gaseous microemboli in the extracorporeal circuit (44). Transcranial Doppler (TCD) systems mostly use pulsed-wave ultrasound at a frequency of 2 MHz to monitor cerebral blood flow velocity and cerebral emboli in the middle cerebral artery (MCA) through the temporal window (45). The TCD detects emboli and records them as high-intensity transient signals (HITS), reflecting the number of microemboli in the particular artery being monitored, but it cannot classify different emboli sizes and cannot be used in CPB circuits. With current ultrasound technology, simultaneous detection and classification of gaseous microemboli in the CPB circuit is possible. The sensitivity and specificity of Doppler systems in classifying and detecting gaseous microemboli is influenced by many factors (46). As a result, several advanced Doppler emboli detection technologies have failed to gain widespread acceptance. This is largely because of their poor reliability in the operating room, with the potential for an inaccurate assessment of the clinical situation (35).

A novel EDAC QUANTIFIER system (developed by Luna Innovations, Roanoke, VA) uses a series of broadband ultrasound pulses with a central frequency of 4 MHz to detect and track microemboli in CPB circuits in real time. A unique feature is the elimination of Doppler processing in favor of motion tracking algorithms to detect echo signatures from individual emboli. The device is equipped with three transducers that are used in conjunction with  $\frac{1}{2}$ " (1.27 cm) diameter connectors inserted into the CPB circuit. The connectors consist of an unfocused piezo-element mounted on an angle wedge. The emboli flow in a straight path through the CPB circuit and move closer to the transducer with each successive pulse. The geometry of the transducer element allows the device to use a wall filter and other signal processing techniques to eliminate echoes from connector walls and stationary targets while enhancing the signal from the moving emboli. Successive signals obtained at a pulse repetition rate of 1 kHz from a moving embolus are associated with a track based on their estimated velocity, and the signals are accumulated and averaged to produce a characteristic echo for each detected embolus. Thus, improved sensitivity allows simultaneous detection and classification of gaseous microemboli as small as 10  $\mu$ m, at count rates exceeding 1000 emboli per second and flow rates between .2 and 6.0 L/min. Although large emboli may affect the accuracy of the sizing algorithm, the high-number and high-amplitude snowstorm-like signals are displayed on the monitoring screen, and the alarm system indicates to clinicians that a

large number of microemboli are present in the CPB circuit. The device may assist in localizing the source of gaseous microemboli and has the potential to minimize post-operative neurologic impairments attributed to gaseous microemboli in clinical practice (47). In our pilot experiments, the EDAC quantifier system worked well when simultaneously detecting and classifying gaseous microemboli in the arterial and venous lines at different flow rates and perfusion modes in a simulated neonatal CPB circuit (18,38,39). This system will be implemented in our institution's pediatric CPB procedures.

In May 2007, the EDAC quantifier was given market clearance by the U.S. Food and Drug Administration. This innovative bubble detector device uses quantitative ultrasound technology to non-invasively detect gaseous emboli in the CPB circuit. It not only provides real-time emboli counts and volume estimates, but also classifies the microemboli by size. The unique features of the device marks an important milestone for real-time microemboli detection technology for the optimization of CPB circuits and operative procedures, the minimization of neurocognitive problems secondary to gaseous microemboli, and improvement in the care of cardiac surgery patients. Recently, Riley (48) successfully used the EDAC system to measure the ability of arterial line filters to remove microemboli with hopes of identifying the most efficient gaseous microemboli separating filter.

The other real-time microemboli monitoring device used in clinical CPB is the Bubble Counter Clinical BCC 200 (GAMPT, Zappendorf, Germany). This device uses a pulsed ultrasonic Doppler system with a transmission frequency of 2 MHz and two independent non-invasive probes applied to the outside of the circuit tubing. It detects and quantifies microbubbles with diameters of 5–500  $\mu$ m, displays data in histograms, and has a detection limit of 1000 bubbles per second with flow rates ranging from .5 to 8.0 L/min. Continuous self-calibrating specificity provides clinicians precise results while a characteristic sound generated by each microbubble alerts clinicians who may be outside the monitor's line of sight. This allows the surgical team and other operating room personnel to react immediately and locate the source of the entrained air. The automatic calibration, lack of additional cost, and easy use make the BCC 200 a suitable option for supervising CPB circuits in clinical practice, as well as for laboratory investigation of filter systems and oxygenators (49,50).

The new Hatteland DMD25 (dual channels) and CMD20 (single channel) microbubble detectors (Hatteland Instrumentering) are update models of the CMD-10 and use an ultrasonic frequency of 1.5 MHz at a bubble velocity range from 5 to 2.5 m/s (51). The theoretical bubble size range of the DMD25 is 5  $\mu$ m to 2 mL in six selected ranges; the bubble size range of the CMD20 is

~10–300  $\mu\text{m}$  with standard probes (51), and the CMD20 has been used in experimental research (52,53).

## SUMMARY

VAVD is a useful technique for augmenting venous return when small venous cannula must be used. Direct benefits include shortened arterial and venous tubing (with decreased tubing dead space) and decreased priming and blood transfusion volumes. The use of minimal negative pressures to achieve optimal venous return in combination with real-time gaseous microemboli monitoring of the arterial and venous lines should minimize the risk of hemolysis and exposure to entrained air. Correct, safe use of VAVD should be emphasized for every perfusionist. The ease, efficiency, and affordability of VAVD ensure its widespread use in the future.

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