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Vacuum-Assisted Venous Drainage: To Air or Not To Air, That Is the Question. Has the Bubble Burst?

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Abstract: Assisted venous drainage is a recent development in cardiopulmonary bypass (CPB) and was introduced to overcome limitations in achieving adequate blood flow through small diameter cannulas used in minimally invasive surgery. The more common application, vacuum assisted venous drainage (VAVD) is now widely used in both adult and pediatric CPB. During a clinical investigation into pharmacological cerebral protection at Green Lane Hospital, we repeatedly observed evidence of emboli in the right common carotid artery following both entrainment of air into the venous line, and also, reductions in the blood level of the hard-shell venous reservior. We subsequently embarked upon a series of in vitro experiments designed to identify sources of emboli from the CPB circuit, and to evaluate the ability of CPB circuit components to remove air entrained into the venous line under conditions of both gravity and vacuum assisted venous drainage. Initial experiments revealed design features of certain hard-shell venous reservoirs that generated gaseous emboli. In further studies using adult circuits, entrainment of air into the venous line under conditions of conventional gravity venous drainage resulted in emboli distal to the arterial filter. When these studies were repeated using VAVD, arterial line emboli increased eight to tenfold. Initial experiments with a pediatric circuit showed similar findings. Cerebral emboli during CPB have been positively correlated with increasing neurocognitive deficits. The application of VAVD has been employed clinically without any significant redesign of the components of the CPB circuit. While VAVD may be efficacious in certain scenarios, a thorough understanding of its influence on CPB is essential. Advantages must be balanced against potential hazards. The safe use of VAVD necessitates refinement of perfusion techniques, judicious choice of application, and further development of the CPB circuit. **Keywords:** cardiopulmonary bypass, vacuum-assisted venous drainage (VAVD), emboli. *JECT. 2002;34:24–28*

Debate on the ideals of venous drainage is not new, nor is the concept of assisted venous drainage. In the proceedings of a conference on extracorporeal circulation initiated by the National Institutes of Health (NIH) in the autumn of 1957, Henry Bahnson, speaking on the characteristics of an ideal pump, suggested that although gravity may be used for this purpose, a more readily regulated force seemed desirable (1). At the same symposium, DeWall suggested that gravity drainage was preferred and that a venous reservoir need not be more than 20 inches below the atrium. However, he went on to describe a cardiotomy system very similar to the current concept of vacuum-assisted venous drainage (VAVD) (2).

Clearly, numerous elements of the cardiopulmonary bypass (CPB) circuit in terms of the relationship between flow, pressure, and resistance that determine the venous return to the heart lung machine exist. These include the pressure gradient between the vena cava and the venous reservoir; the resistance of the cannulas, venous line, and connectors; and the required blood flow rate (3).

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WHY ASSIST VENOUS DRAINAGE?

The relatively recent development of VAVD has come about primarily as a simple option to provide adequate venous drainage through smaller diameter cannulas used in minimally invasive surgery (MIS), as compared to conventional CPB (4). Kinetic-assisted venous drainage (KAVD) has been shown to improve venous drainage when using peripheral venous cannulation for various procedures including port-access MIS (5) and reoperation (6). In addition, the use of VAVD has been advocated to miniaturize the perfusion circuit, resulting in a reduction of both priming volume and foreign surface area. (7,8). Vacuum-assisted venous drainage is also being used clinically for pediatric and neonatal CPB (9,10) and in some centers is commonly employed for routine CPB.

Of particular interest is the promulgation of advantages

of VAVD not only as a device for the elimination of air locks from the venous line but also as a method to avoid priming the venous line. This suggestion has been made by manufacturers of VAVD control devices (11) and by authors reporting potential applications of VAVD (12) despite early reports demonstrating that air entering the oxygenator can be detected in the arterial line (13) and more recent reports of the inability of hard-shell venous reservoirs to remove air entrained into the venous return line of the perfusion circuit (14).

IS VENOUS AIR A PROBLEM?

Over the past 6 years at Green Lane Hospital, Auckland, we have been involved in an investigative program into pharmacological and physical cerebral protective strategies, aspects of which were reported by Simon Mitchell (15) and Tim Willcox (16) at the 1999 Key West Outcomes. In these studies, sources of embolic load to the patient during aortic and mitral valve surgery were established using Doppler ultrasound monitoring of the right common carotid artery throughout the procedure. It was shown that, although the majority of right common carotid emboli counts occurred during the period of aortic cross-clamp removal through to 20 minutes after separation from bypass, and a comparatively small number of counts were obtained during cannulation and in the first 10 minutes of CPB, there were markedly variable emboli counts during the period of stable bypass. Two factors were observed to correlate with increased counts during this period. The first was the appearance of air in the venous line, and the second was when the level of the blood in the Medtronic Maxima hard-shell reservoir (Medtronic Inc., Anaheim, CA.) fell below 800 mL.

The subsequent development of a new de-airing technique resulted in a dramatic reduction in carotid emboli in the postcross-clamp period (17). Therefore, this leaves the period of stable bypass as potentially the highest emboli count phase of the procedure and analogous to a coronary artery bypass graft procedure where the left heart is not opened.

We then embarked on a series of in vitro experiments to establish the cause of the apparent generation of arterial emboli associated with reduced volumes in the Medtronic Maxima HSVR (Medtronic Inc., Anaheim CA) and were able to validate our hypothesis that two hard-shell reservoir designs caused gaseous microemboli generation by a fountain effect (15). Importantly, this study also demonstrated that 40-micron arterial line filtration failed to prevent significant numbers of microemboli from reaching the arterial line to the patient. A preliminary in vitro investigation into venous air entrainment revealed varying inability of a number of hard-shell venous reservoirs to remove entrained air with gravity venous drainage.

Simulating venous air entrainment in vitro posed a number of challenges, and we were keen to mimic as accurately as possible the clinical situation. In the experiments above, we allowed air to be entrained into the venous line through a fine-gauge needle for fixed periods of time. Although this method was repeatable, it did not allow us to quantify accurately the volumes of air entrained. In a more thorough investigation into the influence of venous air entrainment under conditions of both gravity and vacuum- assisted venous drainage (18), we devised a method to entrain air into the venous line in fixed volumes under conditions of both unrestricted-rated rate of entry and fixed rate entry. Obviously, venous air entrainment in the clinical scenario occurs at an unrestricted rate. We were able to show that air entrained at an unrestricted rate into the venous line under conditions of gravity venous drainage resulted in the appearance of emboli downstream from a 40-micron arterial filter. When the volumes of venous air were increased in fixed amounts there was a significant increase in arterial line emboli. The range of volumes of venous air (25–100 mL) used in these experiments is not excessive in terms of volumes that may be entrained clinically during CPB. Indeed, many cardiac surgeons consider venous air to be a benign event and may be reluctant to interrupt the procedure even briefly to eliminate the surgical sources of the entrained air.

The impact of the application of VAVD on unrestricted rate venous air entrainment using 60 mm Hg vacuum resulted in an almost tenfold increase in the number of arterial line emboli. When the volume of entrained venous air exceeded 50 mL, we were unable to make reliable recordings because of the magnitude of emboli appearing in the arterial line. If a fixed rate of entrainment was used, the resultant arterial line emboli were attenuated. It seems that the rate of entry of air into the venous line under VAVD influences the magnitude of arterial line emboli. This experiment did not attempt to simulate a minimally invasive circuit. Reducing the diameter of the venous line from one-half inch to three-eighths inch would result in a 78% increase in the velocity of blood in the venous line, which may further influence the behavior of emboli transiting the venous reservoir.

HOW DO PEDIATRIC PERFUSION CIRCUITS HANDLE ENTRAINED VENOUS AIR?

The effect of venous air entrainment in pediatric CPB circuits has not been investigated. A number of pediatric hard-shell reservoirs have a bottom entry upwardly directed venous blood portal, which is a design feature we have previously demonstrated to contribute to gaseous emboli generation (15). In addition, although the blood flow rate requirements of pediatric and neonatal perfusion

is low as compared to adult requirements, a minimum operating level of the hard-shell reservoir is often maintained to reduce the circuit prime volume and the need for allogenic blood transfusion. The use of VAVD to reduce the circuit size and prime further is appealing from the aspect of minimizing the circuit dimension and also from a practical point of overcoming intermittent interruption to perfusion attributable to venous line air lock. This is especially so, given that there have been relatively few advances in pediatric perfusion circuitry given the fact of increases in the complexity of CPB procedures now being performed in neonatal cardiac surgery.

We are currently investigating the effects of venous air entrainment in pediatric circuits and the impact of VAVD in that scenario. This preliminary in vitro investigation used salvaged clinical circuits consisting of; a 5/16 in inner diameter venous line connected to a Medtronic Minimax hard-shell venous reservoir (Medtronic, Inc., Anaheim CA) a roller pump (Stockert Instrumente, Munich, Germany), a Minimax Plus hollow fiber membrane oxygenator (Medtronic, Inc., Anaheim CA) a Capiox AF02 40 micron arterial line filter (Terumo Corp., Tokyo, Japan) a ¼ in inner diameter arterial line, and a 3.5 f Stockert arterial cannula (Stockert Instrumente, Munich, Germany). The in vitro circuit was set up as in our previously described adult circuit experiments with the Doppler sensor (Rimed 300) placed on the arterial line downstream from the filter. The arterial filter was purged to a filtered luer on the cardiotomy reservoir.

We initially needed to ascertain whether this bottom entry venous reservoir would influence arterial line emboli when the level of blood in the reservoir was reduced. The level of blood in the venous reservoir was maintained at 1000 mL at a flow rate of 1 L/min, and arterial line emboli counts were made over 3 min. The reservoir level was lowered successively to 500, 400, 200, 100, 50, and 25 mL, and repeated arterial line emboli counts were made downstream of the 40-micron filter over a 3-min count period. The 3-min counts were less than 10 at all levels.

We then set the reservoir level at 200 mL and counted emboli downstream from the arterial line over 3 min following the introduction of increasing volumes of air into the venous line at an unrestricted rate of entry under conditions of: gravity venous drainage; VAVD at a vacuum setting of 30 mm Hg; and VAVD at a vacuum setting of 60 mm Hg. Three runs were completed for each volume of entrained air under each drainage condition.

Although these data are preliminary, and the number of experiments is small, we were able to detect arterial line emboli as a result of venous air entrained into the venous line of a pediatric CPB circuit under conditions of gravity venous drainage at every volume of air entrained. The number of arterial emboli increased significantly with increasing volumes of venous air entrained in a manner similar to that which we have previously demonstrated in adult circuits.

DOES THE DEGREE OF VACUUM MAKE A DIFFERENCE?

The application of a moderate degree of VAVD (30 mm Hg) to the pediatric circuit resulted in a significant increase in arterial line emboli following entrainment of 50 mL of air into the venous line as compared to gravity venous drainage; however, we were unable to record arterial line emboli reliably following entrainment of volumes of air greater than 50 mL, because the Doppler counter was overwhelmed.

The degree of vacuum applied when using VAVD is empiric and is based on achieving adequate flow and avoiding venous line chatter and intermittent interruption to flow attributable to the collapse of cava of atrium around the venous cannula. There is a negative pressure in the venous line under conditions of gravity venous drainage related to the height of the fluid column from the level of the atrium to the level or blood or the entry portal of the venous reservoir. This will be in the order of −15 to −30 mm Hg. The effective additional amount of applied vacuum during VAVD is, therefore, greater than the observed setting on the regulator.

Venous air was then entrained at an unrestricted rate into the venous line of the in vitro pediatric circuit under an increased degree of vacuum assist (60 mm Hg). There was a significant increase in the resultant arterial line emboli as compared to 30 mm Hg vacuum, and again, volumes of entrained air greater than 50 mL produced arterial line emboli too numerous to count. In addition, the appearance of emboli in the arterial line occurred earlier in comparison to lesser-applied vacuum.

IS THE EXACERBATION OF ARTERIAL LINE EMBOLI FOLLOWING VENOUS AIR BY VAVD OF CLINICAL IMPORTANCE?

The perfusion circuit is a potential source of gaseous emboli (19), and we have shown that vacuum-assisted venous drainage will potentiate this embolic load in the presence of venous air. In hindsight, the explanation for emboli detected in the right common carotid artery in the first 10 minutes of CPB in the Mitchell studies may not have been related to an incompletely de-aired CPB circuit. A more plausible explanation is that, because the venous cannulas were not de-aired when connected to the venous return line, the bolus of venous air entrained at the commencement of CPB resulted in arterial line emboli. In light of our findings, this would suggest that the practice of using VAVD to commence CPB with an unprimed venous return line in both adult and pediatric circuits would result

in a significant number of arterial line emboli being delivered to the patient's circulation. The extent of perioperative cerebral emboli has been positively correlated with increasing neurocognitve deficits following cardiac surgery in adults (20,21). Neurocognitive assessment of neonatal and pediatric patients is obviously more demanding than in the adult population, and evaluation of the sequelae of exposure to emboli during CPB may not be possible until later in life. The perceived benefits associated with VAVD in both adult and pediatric populations need to be carefully weighed against possible hazards. The impact of assisted venous drainage on entrained venous air has been demonstrated in vitro elsewhere (22). Such perfusion interventions as drug administration to the CPB circuit notably under conditions of conventional gravity venous have been shown to result in the appearance of emboli in the middle cerebral artery during coronary artery bypass grafting (CABG) (23). The effects of VAVD may well exacerbate arterial emboli resulting from perfusionist interventions.

WHAT ARE THE SOLUTIONS?

Vacuum-assisted venous drainage offers a number of potential benefits to CPB. The potential disadvantage associated with venous air being transmitted to the patient's cerebral circulation is less likely where alternative arterial cannulation is employed. Cannulation of the distal aortic arch as compared to the ascending aorta has been shown to reduce the number of cerebral emboli during coronary bypass surgery (24). Although it might be thought that peripheral arterial cannulation of the femoral artery would lessen the likelihood of emboli reaching the brain because of remoteness of the cannula to the aortic arch vessels, there is a recent surgical preference away from femoral arterial cannulation. This is because of concerns of inferior cerebral perfusion as compared to antegrade aortic blood flow, increased solid embolic load from the thoracic and abdominal aorta, and vascular disruption in cases of aortic dissection. These concerns do not seem to be based on evidence.

The use of VAVD has, in part, been promoted by manufacturers of related devices and perfusion circuitry. The same industry produces the major components of such perfusion circuit as the venous reservoir, the oxygenator, and the arterial filter. These devices, especially the hard-shell venous reservoir, have not been redesigned to accommodate this substantial change in the use of this equipment. Indeed, we believe that the industry has been tardy to acknowledge and address the shortcomings of current hard-shell venous reservoir design. Promoting the use of VAVD as a tool to remove venous air is, at best, questionable.

The development of novel de-airing devices that can be incorporated safely into the perfusion circuit may offer a solution. An effective method of removing air from the venous line before it enters the reservoir would be one option. A means of more effectively removing micro air from the arterial line is also a possibility, and such devices are currently being developed.

Further research is clearly indicated. The measurement of microemboli using Doppler ultrasound is not an exact science, and in vitro investigators use different methods and equipment. We previously showed an identical trend in simultaneous emboli counts using the Rimed 300 and the Hatelland CDM 10 (Hatelland Intstrumentering, Royken, Norway) but with consistently lower counts recorded by the latter (15). The methods of simulating entrainment of venous air must be standardized to mimic the clinical scenario better. The behavior of bubbles will vary depending on the nature of the circuit prime. Blood is not a pure Newtonian fluid such as water, and as a thixotropic fluid, will alter its viscosity with velocity (25), which may affect the stability of bubbles. In the interim, it seems that, indeed, the bubble has not burst but can and does transit the CPB circuit intact and, similar to the "love letter" virus, has the potential to wreck havoc for the unwary.

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