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Total extrathoracic cardiopulmonary support with kinetic assisted venous drainage: experience in 50 patients

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Extrathoracic cardiopulmonary bypass is used in special situations when normal access to the right atrium and aorta is difficult or not practicable. Femero-femoral bypass using gravity drainage is effective for partial cardiopulmonary support, but cannot usually provide adequate venous drainage for full circulatory support. Kinetic assisted venous drainage (KAVD) is the process of applying a controlled suction on the venous line with a kinetic pump to augment venous drainage.

KAVD has been used in 50 patients where femero-femoral bypass was selected as the mode of circulatory support. These cases included: redo-operations with significant sternal adhesions (15), minimally invasive port-access cardiac surgery (12), haemodynamic instability (10), left thoracotomy (10), and others (3). In 11 cases, a second venous catheter was added because of protocol. No appreciable increase in venous return occurred with the addition of a second drainage catheter. All patients were adequately supported and a 20–40% increase in venous return was observed once KAVD was implemented.

A wide variety of different venous catheters have been used with KAVD. Optimal use relates to having a thin-walled catheter with multiple side holes, not exerting an excessive negative pressure with the pump and positioning the catheter tip at the right atrio-superior vena cava junction. Optimal catheter tip placement is enhanced by using transoesophageal echocardiography. KAVD is best regulated by measuring the siphon generated by the kinetic pump. When the inlet pressure is properly monitored and controlled, KAVD can provide adequate venous drainage to completely support the circulation on a single femoral venous cannula.

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Introduction

Most cardiothoracic operations use extracorporeal circulation with catheters inserted directly into the right atrium and ascending aorta. A wide variety of catheters and cannulation techniques exist. This method has been used widely for decades in initial and repeat surgical procedures. Direct atrial cannulation has been shown to provide adequate venous flow rates for complete cardiopulmonary support.

There are special situations where direct cannulation of the heart is impractical, difficult or impossible. These situations usually relate to the patient's underlying pathology or to the surgical approach to be undertaken. Reoperative sternotomy has the risk of the heart being adherent to the sternum, as well as distorting several anatomical landmarks, creating a greater risk of inadvertent entry into the heart or great vessels upon reopening the sternum. A thoracotomy is used for some procedures such as single-lung transplantation or repair of the descending thoracic aorta, but provides a difficult or impossible task of accessing the heart directly if cardiopulmonary bypass is required. In these cases, peripheral vessels must be considered for extracorporeal access.

Extrathoracic cannulation can provide vascular access sites for extracorporeal support. The jugular vein and carotid/axillary artery have been used widely for extracorporeal life support, but are usually not used during cardiovascular surgery. Cerebral vascular injury would be possible in patients with increased cerebral vascular risk factors, especially if cerebral perfusion was not managed optimally. Neck vessel cannulation is often impractical in emergency situations and would potentially impair the anaesthesiologist's access to the neck vessels for anaesthetic or haemodynamic management.

The femoral vessels provide an easy site for planned or emergency bypass. Femoral cannulation has been widely used for a variety of different cardiovascular procedures and provides good access for direct or percutaneous cannulation. However, special care must be taken to prevent aortic dissection during cannulation and initiation of retrograde aortic perfusion.

Regardless of the venous extrathoracic cannulation site, a gravity siphon is often insufficient in providing adequate flow for complete cardiopulmonary support even when the patient's table height is maximized. In extrathoracic bypass, blood flow is limited by the diameter and length of the venous catheter. Femoral venous catheters are longer and have smaller drainage lumens compared to the large bore, sometimes bicaval venous drainage catheters used during direct cannulation. Blood flow rates can be suboptimal until an additional venous drainage catheter is inserted into the right atrium.

Kinetic assisted venous drainage (KAVD) is the process of mechanically increasing the venous drainage siphon. Increased venous blood flow can be achieved by inserting a kinetic pump into the venous line between the venous catheter and venous reservoir, then engaging the blood pump. A kinetic pump is capable of generating a significant negative pressure, so proper siphon monitoring is necessary to prevent the right atrium from collapsing around the venous cannula and impairing venous drainage. KAVD was used in 50 patients who presented a wide variety of surgical aetiologies that required extrathoracic bypass.

Methods

KAVD was used in 50 patients (35 male, 15 female) between December 1993 and October 1996. These patients were presented for surgical correction for a wide range of procedures and aetiologies including valve replacements, aortic dissections, myocardial revascularization, lung transplantation and congenital heart disease. The patients ranged in age from 10–90 years (mean 54.9 years) and weighed from 45–126 kg (mean 76.0 kg). Twenty-six patients (52%) were presented for their first operation and 24 patients (48%) were presented for reoperation. Of the reoperations, two patients had three prior cardiac operations. The patients were categorized into one of five subgroups: severe adhesions related to reoperation (15), port-access minimally invasive cardiac surgery (12), haemodynamic instability (10), left thoracotomy (10), and other (3). Of the last group, one patient each presented with an infected aorta, one with a renal–atrial tumour, and one with a false aortic aneurysm.

The cardiopulmonary bypass circuit was modified slightly to accommodate components for KAVD (Figure 1). Either 3/8″ or 1/2″ ID × 3/32″ venous tubing was used. A Biomedicus BP-80 pumphead

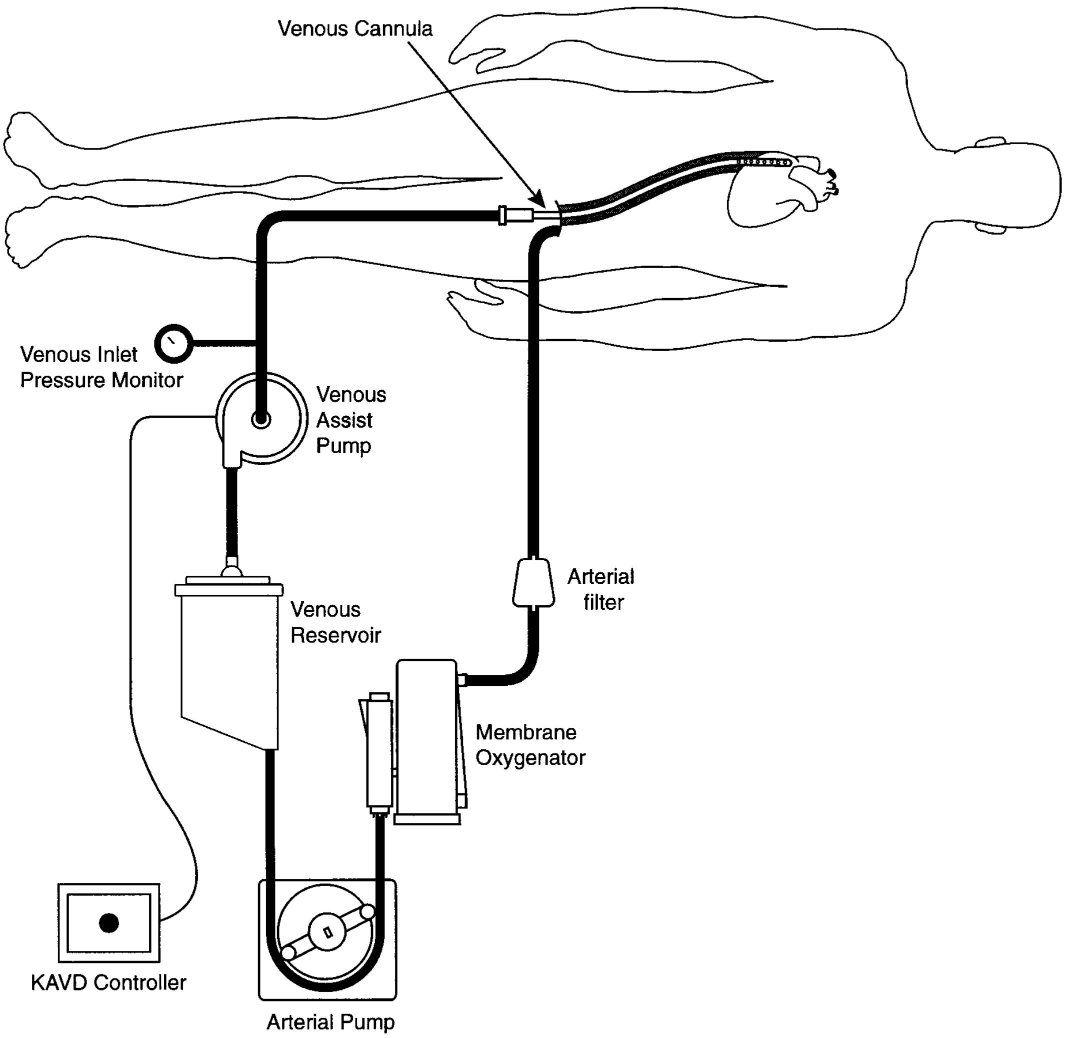

Figure 1 Schematic of KAVD circuit. Venous blood is aspirated from a peripherally placed venous catheter by a kinetic blood pump which is inserted into the venous drainage line prior to entry into the venous blood reservoir. The kinetic pump inertia is controlled to maintain a pressure between –50 and –80 mmHg proximal to the pump's blood inlet.

(Medtronic Biomedicus, Eden Prairie, MN, USA) was inserted into the venous line at the level of the console roller pump tubing. The pumphead was placed inside a Biomedicus remote drive unit attached to a pump mast. The remote drive unit was driven by a Biomedicus 540 pump (Medtronic Biomedicus). A luer-lock connector was positioned approximately 10 cm before the inlet to the kinetic pumphead. A pressure separation dome was connected to 1/8″ tubing and attached to a pressure monitoring site on the Biomedicus pump console to monitor the negative pressure generated by the kinetic pump. The pumphead outlet tubing was adapted to accommodate the venous inlet port of several different open-reservoir membrane oxygenators. In some cases a Biomedicus flow probe was inserted between the pumphead and venous reservoir inlet to measure venous flow rates. The remainder of the bypass circuit was assembled as usual and primed according to standard protocols.

A roller pump was used for arterial blood reinfusion. During priming and recirculation the kinetic pump was not engaged.

Each patient was anaesthetized, positioned, prepped and draped according to institutional protocols and guidelines. The femoral artery and vein were dissected and exposed. Following heparinization (300 U/kg), the femoral vein was cannulated with one of several commercially available femoral venous cannulae ranging from 18–28 F and 50–65 cm in length. The femoral artery was cannulated with an appropriately sized return cannula (16–23 F). Following connection to the perfusion drainage and reinfusion lines, bypass was instituted following instructions from the surgical field.

Bypass commenced with gravity drainage and the maximum reinfusion rate was noted. Once stable, KAVD was initiated by engaging the kinetic-pump motor and increasing the speed to approximately 1000–1200 rpm until the venous inlet pressure reached –50 to –80 mmHg. The venous reservoir volume subsequently increased as a result of the increased venous siphon. The arterial blood reinfusion rate was increased until a stable venous reservoir level resulted. The maximum flow rate was noted and compared to the initial gravity flow rate.

Systemic hypothermia was used in 48 patients (range 18–32°C). Eighteen patients required some period of circulatory arrest. In 11 patients, a second venous drainage catheter was inserted into the right atrium later in the operative course upon completion of dissection. Standard myocardial preservation and rewarming protocols were used when indicated. Upon weaning from cardiopulmonary bypass, the KAVD assist pump was first weaned off, reducing the drainage siphon and venous return to the heart–lung machine. Bypass was discontinued by further reducing the venous drainage volume and pump flow as well as reinfusing volume into the patient, as necessary, to stabilize haemodynamic parameters.

Results

In all 50 patients, KAVD improved the blood flow rate during cardiopulmonary bypass. KAVD increased the venous blood return to the heart–lung machine from baseline gravity rates of 2.3–3.8 l/min (mean 3.0 l/min) to 3.1–6.0 l/min (mean 4.4 l/min), regardless of the patient subgroup. This resulted in a 19–48% improvement in flow over baseline gravity flow values (mean 31.2%). In the 11 patients who had a second catheter placed in the right atrium, only a small improvement in flow resulted (5%). Total support could be achieved with one extrathoracic catheter when positioned properly in the right atrium. The use of transoesophageal echocardiography was helpful in guiding the catheter to a proper position within the right atrium. Flow rates were adjusted appropriately to meet the metabolic requirements of each patient as measured by arterial and venous blood gases.

In approximately 20% of cases, venous drainage was reduced when the heart was retracted or manipulated. In approximately 10% of cases, the venous catheter was repositioned during the case to improve flow. In two patients, air was intermittently aspirated into the venous line. One came from a hole in the vena cava and the second involved an undiagnosed patent foramen ovale which caused air to be aspirated into the venous system when the left atrium was incised. The siphon was lowered, as necessary, to reduce the air until the hole or shunt was closed. There was some variation, and no correlation, between venous and arterial pump flow rates. All patients were weaned from cardiopulmonary bypass by first terminating KAVD and then reducing venous drainage while reinfusing volume back into the patient.

Discussion

KAVD was effective in providing additional flow using a single femoral venous catheter. Flow was best when a catheter with multiple side holes was used. The increase in the arterial blood flow rate allowed the surgical procedure(s) to be conducted without the addition of a second venous catheter in most cases. Complete cardiopulmonary support was achieved and venous flow optimized when the venous catheter tip was positioned near the atrio-superior vena caval junction with the use of transoesophageal echocardiography (Figure 2).

A single venous catheter, when properly positioned, provided adequate flow rates for complete cardiopulmonary support. In the 11 cases in which a second catheter was added, the small increase in

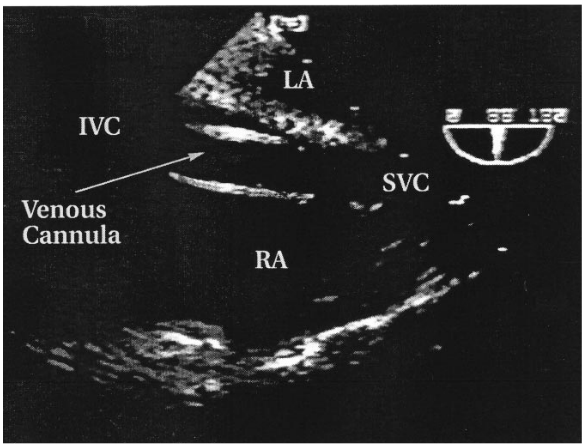

Figure 2 Echocardiographic venous cannula positioning within the right atrium. The tip of the venous catheter is positioned in the right atrium by use of transoesophageal echocardiography near the atrio-superior vena caval junction.

flow was not considered significant. The use of an additional right atrial catheter occurred relatively early in the series and has not been used with the availability of transoesophageal echocardiography.[1]

Venous air can be aspirated into the venous line and cause a significant airlock if the right atrium is opened or if an intravenous line is not property secured. In addition, a patent foramen ovale or ductus arteriosus can be a source of air when the heart is opened. Air management is often not as difficult when using an open venous reservoir, but care must be taken in removing the air without disrupting extracorporeal flow. Inadvertent venous air can be reduced or eliminated by reducing the venous assist pump siphon or resorting to gravity drainage. Air may persist until the hole or shunt is closed, thus partial bypass flow rates must be tolerated during that period.

A kinetic pump inserted in the venous line of a standard heart–lung machine constitutes a two-pump augmented venous assist system. One kinetic pump is used to aspirate blood and either a roller or kinetic pump is used in the arterial position to reinfuse blood back into the arterial circulation. A roller pump could be used as a venous assist pump, but special caution must be used, since without some form of pressure-feedback servo control to measure and regulate negative pressure, an unregulated roller pump can generate extremes in negative pressure which can cause cavitation, haemolysis and air to be entrained. Early studies determined that several mechanical and physiological factors contribute to blood element damage, including: excessive negative pressures, cavitation, turbulence and the prosthetic surface–blood surface interaction.[2,3]

The KAVD siphon was best regulated by measuring the kinetic pump inlet pressure. The siphon range (–50 to –80 mmHg) was adequate in most cases. Regulation of the pressure within this range prevents excessive pressure, line chatter and potential intermittent disruption of flow which would collapse the right atrium around the venous catheter. In this series, venous inlet pressures that exceeded –100 mmHg caused excessive line chatter and reduced flow.

Gravity drainage is limited by the internal diameter and length of the venous drainage catheter. A significant improvement in extrathoracic bypass occurred with the advent of thin-walled femoral drainage catheters, which effectively increase the internal diameter, lumen size and drainage capabilities. As described in a series of 35 patients, gravity flow rates of 3.5–4.0 l/min were obtained from transfemoral right atrial cannulation with these new cannulae.[4]

Assisted venous drainage has been used by others.[5–9] A two-pump assisted venous drainage system was described where femoral venous blood was routed through a silicone rubber drainage catheter to a Biomedicus pump and into a drainage reservoir. Arterialized blood was returned to the femoral artery. Flow rates of 1.8–3.0 l/min/m^2 were obtained in 11 patients undergoing redo mitral valve surgery from a right anteriolateral thoracotomy. Good right-side decompression was observed.[5]

Flow rates of 3.3–5.7 l/min (>2.4 l/min/m^2) were obtained with assisted venous drainage in a series of 18 patients with cannulae inserted by cutdown or percutaneous techniques. By comparison gravity flow rates were only 1.1–1.7 l/min (<1.5 l/min/m^2). All intravenous lines were closed or placed on an infusion pump to prevent air from entering the system when the kinetic pump was engaged.[6]

Augmented venous drainage was used in 54 patients to drain blood with a centrifugal pump into an open reservoir with percutaneous cannulation. Blood was reinfused at a cardiac index of 2.4–2.6 l/min/m^2. Proper venous catheter position was essential to maximize flow rates.

Hybrid or partial use of KAVD exist. Centrifugal pumps can be used for both arterial and venous positions. Once the right atrium is dissected out, direct right atrial cannulation can occur. KAVD can be discontinued when standard gravity drainage is established with direct atrial cannulation.[8]

A single-pump system to both aspirate and reinfuse blood from the femoral vessels has been described.[9] Flow rates of 1.0–5.0 l/min were maintained on six patients. A purge–recirculation line allowed for extra volume to be pumped into a storage reservoir while maintaining the central venous pressure between 2–4 mmHg. Storage reservoir blood was reinfused when venous line chatter became significant or when hypovolaemia resulted from purging or suctioning.

Potential problems of a two-pump system include inflow line chatter and mismatched flow between the venous and arterial pumps. Inflow line chatter results due to improper catheter positioning or when the siphon on the venous line is excessive. The venous siphon is best regulated by monitoring the kinetic pump inlet pressure. Once the venous siphon is set, it rarely fluctuates and the need to adjust the venous pump inertia is rare and usually relates to hypovolaemia.

Imbalanced flow rates do occur with a two-pump system, but that is to be expected. The arterial and venous pump flow rates differ and relate to transient changes in blood flow being diverted through the drainage catheter as well as manipulation of the heart. In addition, venous line chatter causes the venous flow rate to vary compared to the arterial rate. Once the drainage siphon is set and stabilizes, the flow rates equalize. An increase in the arterial flow rate reflects the amount of blood that the KAVD contributes to the venous reservoir. Therefore, measuring the venous flow is not essential, because the perfusion rate is still determined by the arterial pump. In a two-pump system, extra volume is stored in the venous reservoir and not held in a storage reservoir to be intermittently reinfused according to some haemodynamic parameter range. In that regard, a two-pump system may be easier and more simplistic.

KAVD has been used for interventions that require extracorporeal circulation where a sternotomy is not desired or practical. Closed portable bypass systems that utilize a kinetic pump have been used for emergency or rescue bypass,[10,11] rewarming from exposure hypothermia,[12] supportive angioplasty,[13–16] valvuloplasty,[17] extracorporeal life support,[18] neurosurgical clipping of giant cerebral aneurysms,[19] and port-access minimally invasive cardiac surgery.[20,21]

In summary, KAVD is a useful tool that can be utilized in extrathoracic cardiopulmonary support to increase venous drainage and arterial flow. Positioning of the venous catheter is critical and is enhanced by using transoesophageal echocardiography. The optimal venous siphon is best managed by measuring the assist pump's inlet pressure. With proper catheter insertion and placement, sufficient blood flow rates can be achieved on a single femoral venous cannula to support the circulation.

References

1 Toomasian JM, Conte JV, Reitz BA. Kinetic assisted venous drainage as an adjunct to multiple redo sternotomy. In: Toomasian JM, Kurusz M, Stafford TB eds. *Case reports: clinical studies in extracorporeal circulation*. Houston, TX: The PREF Press, 1996: 1–10.
2 Bernstein EF, Blackshear PL, Keller KH. Factors influencing erythrocyte destruction in artificial organs. *Am J Surg* 1967; **114**: 126–38.
3 Indeglia RA, Shea MA, Varco RE, Bernstein EF. Mechanical and biologic considerations in erythrocyte damage. *Surgery* 1967; **67**: 47–55.
4 Jones RE, Fitzgerald D, Cohn LH. Reoperative cardiac surgery using a new femoral venous right atrial cannula. *J Cardiac Surg* 1990; **5**: 170–73.
5 Praeger PI, Pooley RW, Moggio RA, Somberg ED, Sarabu MR, Reed GE. Simplified method for reoperation on the mitral valve. *Ann Thorac Surg* 1989; **48**: 835–37.
6 McCusker K, Hoffman D, Maldarelli W, Toplitz S, Sisto D. High flow femoral–femoral bypass utilizing small cannulae and a centrifugal pump on the venous side. *Perfusion* 1992; **7**: 295–300.
7 Soloman L, Sutter FP, Goldman SM, Mitchell JM, Casey K. Augmented femoral venous return. *Ann Thorac Surg* 1993; **55**: 1262–63.
8 Wallock M, Kuehn B, Hoff W. Letter regarding, Fried DW, Zombolas TL, Weiss SJ. Single pump mechanically aspirated venous drainage (SPMAVD) for cardiac reoperation. *Perfusion* 1996; **11**: 351–53.
9 Fried DW, Zombolas TL, Weiss SJ. Single pump mechanically aspirated venous drainage (SPMAVD) for cardiac reoperation. *Perfusion* 1995; **10**: 327–32.
10 Reiclirnan TR, Joyo CI, Dembitsky WP *et al*. Improved patient survival after cardiac arrest using a cardiopulmonary support system. *Ann Thorac Surg* 1990; **49**: 101–105.

11 Raithel SC, Swartz MT, Braun PR *et al*. Experience with an emergency resuscitation system. *Trans Am Soc Artif Intern Organs* 1989; **35**: 475–77.
12 Hill JG, Bruhn PS, Cohen SE *et al*. Emergent applications of cardiopulmonary support: a multiinstitutional experience. *Ann Thorac Surg* 1992; **54**: 699–704.
13 Abshier DA, Gallagher ML. Cardiopulmonary support device: three case studies. *Proc Am Acad Cardiovasc Perf* 1987; **8**: 265–68.
14 Harloff M. Supportive angioplasty utilizing the Bard cardiopulmonary support device. *Perfusion* 1990; **5**: 53–56.
15 Shawl FA, Domanski MJ, Wish MH, Davis M. Percutaneous cardiopulmonary bypass support in high risk patients undergoing percutaneous transluminal coronary angioplasty. *Am Heart J* 1990; **120**: 195–203.
16 Vogel RA, Shawl F, Tommaso C *et al*. Initial report of the national registry of elective cardiopulmonary bypass supported coronary angioplasty. *J Am Coll Cardiol* 1990; **15**: 23–29.
17 Gundry SR, Brinkley J, Wolk M *et al*. Percutaneous cardiopulmonary bypass to support angioplasty and valvuloplasty technical considerations. *Trans Am Soc Artif Intern Organs* 1989; **35**: 725–77.
18 Gruenwald C. Post-cardiotomy pediatric ECMO using a cannula-to-cannula Carmeda-coated circuit. In: Toomasian JM, Kurusz M, Stafford TB eds. *Case reports: clinical studies in extracorporeal circulation.* Houston, TX: The PREF Press, 1996: 83–92.
19 Mongero LB, Sistino JJ, Beck J, Smith CR. Current perfusion techniques for repair of giant cerebral aneurysms using deep hypothermia and circulatory arrest. *J Extracorp Technol* 1994; **26**: 13–17.
20 Toomasian JM, Peters WS, Siegel LC, Stevens JH. Extracorporeal circulation for port-access cardiac surgery. *Perfusion* 1997; **12**: 83–93.
21 Toomasian JM, Williams DL, Colvin SB, Reitz BA. Perfusion during coronary and mitral valve surgery utilizing minimally invasive port-access technology. *J Extracorp Technol* 1997; **29**: 66–72.