The Effect of Vacuum on Venous Drainage: an Experimental Evaluation on Pediatric Venous Cannulas and Tubing Systems

Vladimiro L Vida,[1] A Bhattarai,[1] Simone Speggiorin,[1,2] Fabio Zanella,[3] Giovanni Stellin[1]

[1]Pediatric and Congenital Cardiac Surgery Unit, Department of Cardiac, Thoracic and Vascular Surgery, University of Padua, Italy
[2]Cardiothoracic Surgery Department, The Great Ormond Street Hospital for Children NHS Trust, London, UK
[3]Cardiac Perfusion Unit, University of Padua, Italy.

ABSTRACT

Introduction: To observe how vacuum assisted venous drainage (VAVD) may influence the flow in a cardiopulmonary bypass circuit with different size of venous lines and cannulas.

Methods: The experimental circuit was assembled to represent the cardiopulmonary bypass circuit routinely used during cardiac surgery. Wall suction was applied directly, modulated and measured into the venous reservoir. The blood flow was measured with a flow-meter positioned on the venous line. The circuit prime volume was replaced with group O date expired re-suspended red cells and Plasmalyte 148 to a hematocrit of 28% to 30%.

Results: In an open circuit with gravity siphon venous drain, angled cannulae drain more than straight ones regardless the amount of suction applied to the venous line (16 Fr straight cannula (S) drains 90 ml/min less than a 16 Fr angled (A) with a siphon gravity). The same flow can be obtained with lower cannula size and higher suction (i.e. 12 A with and -30 mmHg). Tables have been created to list how the flow varies according to the size of the cannulas, the size of the venous tubes, and the amount of suction applied to the system.

Conclusions: Vacuum assisted venous drainage allows the use of smaller cannulae and venous lines to maintain a good venous return, which is very useful during minimally invasive approaches. The present study should be considered as a preliminary attempt to create a scientific-based starting point for a uniform the use of VAVD.

Keywords: *cardio-pulmonary bypass; experimental study; vacuum assisted drainage.*

INTRODUCTION

Vacuum assisted venous drainage (VAVD) is a well known technique widely used in both adult and pediatric cardiac surgery. During the last 10 years VAVD has been mainly used to reduce haemodilution during cardiopulmonary bypass (CPB)[1-3] as it allows for a "lower prime" circuit,[4] and smaller venous cannulae during minimally invasive cardiac surgery (MICS) procedures without compromising patient blood flow.[5-8] Combined with VAVD, the use of shorter circuits, smaller cannulae and eventually lower priming volume, is closely associated to the ability to reduce homologous blood transfusion.[3-9] Indications and the use of VAVD are not uniform and differ from centre

Correspondence: Dr. Vladimiro Vida, Pediatric and Congenital Cardiac Surgery Unit, Department of Cardiac, Thoracic and Vascular Surgery, University of Padua, Via Giustiniani, 2-35128, Padua, Italy, E-mail: vladimirovida@yahoo.it, Tel: +39-049 8212410, Fax: +39 049 8212409

to centre according to the Institutional experience. In order to standardize our clinical practice we attempted to determine the effects of suction on the venous drainage and consequently on the blood flow dynamic produced by the circuit. In order to do that we applied increasing vacuum suction to an experimental CPB circuit and measured the flow produced.

The aim of this study is to observe how VAVD and the size of the venous line and cannulas affect the flow in a cardiopulmonary bypass circuit.

METHODS

This is an experimental and observational study. The experimental circuit was assembled as shown in Figure 1 and it represents the normal CPB circuit routinely used during cardiac surgical procedure. The patient is mimicked by a "patient reservoir" (PR) (Midicard System, Dideco, Sorin Group, Mirandola, Italy). The venous cannula (C) is positioned at the bottom of the PR and drained the blood into the venous reservoir (VR) positioned 50 cm below through a 150 cm long venous line (VL), mimicking the distance between the PR and the VR which is usually maintained in our Institution. The difference of height between the PR and the VR, and the length of the venous line are kept constant in all the tests. The pressure transducers were calibrated to atmosphere. Negative pressures mentioned throughout the paper are relative to atmospheric pressure.

A flow-meter (Bio-probe, transducer, Medtronic Inc, Minneapolis, MN, US) was positioned on the venous line (Figure 1). A roller pump (HLM, Cobe-Stockert, Munich, Germany) was used to pump the blood from the VR back to the PR. Wall suction was applied directly, modulated and measured into the venous reservoir (Midicard System, Dideco, Sorin Group, Mirandola, Italy) by two different systems: the first is integrated into the vacuum regulator system (Vacuum Regulator, Baxter) and the second is connected directly to the venous reservoir (Monitor Pressure Regulator, Medtronic). For this study we have measured the degree of vacuum which was applied into the venous reservoir. The circuit prime volume consisted of with group O date expired re-suspended red cells and Plasmalyte 148 (Baxter, Healthcare Corp) to a hematocrit of 28% to 30% at a room temperature (24 C°).

The blood re-circulated until steady state flow was reached and the flow, measured by the flow-meter, recorded. Measurements of flow were taken at the baseline (considered at siphon gravity) and subsequently, an increasing VAVD negative pressure (-10, -20, -30, -40, -50 and -60 mmHg) was applied to the system and measured. Three different tests were performed changing the tubing diameter of the VL, which was respectively 1/4 ", 5/16 " and 3/8 ".

Each test was repeated three times with every combination of venous cannulae and venous line tubing. We tested all the cannulae available and in use at our hospital: 1) metal angled cannulas (A)(DLP, Medtronic Inc, Minneapolis, MN, US) size 12, 14, 16, 18, 20, 24 Fr, 2) bullet-tip straight cannulas (S) (DLP, Medtronic Inc, Minneapolis, MN, US) size 12, 14, 16, 18, 20, 26 Fr. The drainage of two venous cannulae, at the same time, was also tested to mimic the bi-caval cannulation.

The mean value of the three different tests was considered in our results.

RESULTS

Three tables were generated showing the blood flow produced by each circuit according to the use of a specific cannula or a combination of cannulae and the degree of vacuum applied to the system (Table 1-3).

Resulted showed that angled cannulae drained more than the straight cannulae, increasing with increased vacuum is applied to the system. With a ¼" venous line, a 14 Fr straight cannula drains 30 ml/min less than a 14 French (Fr) angled one with a siphon gravity. This difference becomes 50 ml/min when vacuum -10 mmHg is applied to the system, 120 with -20 mmHg and 180 with -30 (Table 1-3).

The same single cannula (both straight (S) or angled (A)) drains more when a bigger venous line is used. As an example, with siphon gravity a 18 Fr straight cannula drains 800 ml/min with a ¼" venous line, 1280 with a 5/16" and 1560 with ½"(Table1-3).

The desired flow can be obtained by several combination of cannula size, vacuum applied to the system and size of the venous line. As an example, the flow of 1200 ml/min can be obtained with siphon gravity and a combination of angled 18Fr and angle 20Fr cannulae. The same flow can be achieved with a combination 16Fr A-18Fr A and -10 mmHg of vacuum to the system, 14Fr A-14Fr A with -20 mmHg or 12A-12A with -30mmHg (Table 1-3).

These tables are routinely used at our Institution to choose the best venous cannula or the best combination of venous cannulae in order to achieve the desired flow, especially in cases where a minimally invasive approach has been selected.

Table 1. **Venous drainage in ml/min according to different venous cannulas and to the type of drainage (syphon gravity of vacuum assisted drainage) utilizing a 1/4" venous line.**

		Vacuum assisted drainage (mmHg)					
Cannulas	Syphon gravity (50 cm)	-10	-20	-30	-40	-50	-60
12 S	480	520	600	660	740	800	860
14 S	670	790	880	980	1070	1160	1240
16 S	720	830	1000	1150	1280	1400	1500
18 S	800	1000	1150	1300	1450	1600	1750
20 S	880	1100	1280	1460	1620	1770	1900
12 A	540	620	730	820	920	1020	1120
14 A	700	840	1000	1160	1290	1420	1530
16 A	810	920	1120	1280	1420	1560	1700
18 A	920	1080	1260	1440	1620	1770	1920
20 A	970	1200	1400	1580	1750	1920	2050
12 A-12 A	740	920	1080	1180	1330	1430	1520
12 A-14 A	820	1000	1160	1270	1430	1540	1630
14 A-14 A	880	1060	1230	1360	1520	1650	1750
14 A-16 A	950	1120	1300	1430	1600	1740	1850
16 A-16 A	1000	1160	1340	1500	1670	1820	1950
16 A-18 A	1100	1200	1390	1560	1730	1890	2030
18 A-18 A	1150	1230	1420	1610	1780	1950	2100
18 A-20 A	1200	1260	1480	1670	1850	2020	2190
20 A-20 A	1250	1300	1520	1730	1910	2080	2250
12 A-12 S	720	900	1060	1160	1310	1410	1500
12 A-14 S	780	960	1120	1230	1380	1490	1580
14 A-12 S	800	980	1140	1250	1400	1510	1600
14 A-14 S	850	1030	1200	1320	1480	1600	1700
14 A-16 S	900	1080	1260	1390	1560	1690	1800
16 A-14 S	920	1100	1280	1410	1580	1710	1820
16 A-16 S	940	1140	1320	1470	1640	1790	1910
16 A-18 S	1000	1170	1360	1520	1690	1850	1980
18 A-16 S	1050	1180	1370	1540	1710	1870	2000
18 A-18 S	1100	1220	1410	1590	1760	1930	2080
18 A-20 S	1150	1240	1440	1630	1810	1980	2140
20 A-18 S	1200	1250	1460	1650	1830	2000	2160
20 A-20 S	1250	1280	1500	1700	1880	2050	2220

Medtronic metal tipped angled cannulas (A), Medtronic straight cannulas (S) and the bicaval combinations of the two cannulas.

Table 2. Venous drainage in ml/min according to different venous cannulas and to the type of drainage (syphon gravity of vacuum assisted drainage) utilizing a 5/16" venous line.

		Vacuum assisted drainage (mmHg)					
Cannulas	Syphon gravity (50 cm)	-10	-20	-30	-40	-50	-60
12 S	620	800	880	950	1040	1130	1200
14 S	800	1140	1280	1360	1440	1500	1580
16 S	1000	1380	1560	1680	1800	1900	2020
18 S	1280	1690	1900	2050	2200	2330	2470
20 S	1570	2000	2230	2400	2580	2720	2880
12 A	750	1040	1210	1270	1310	1380	1460
14 A	980	1360	1540	1650	1740	1860	1990
16 A	1220	1640	1830	1970	2120	2270	2420
18 A	1530	1970	2180	2340	2510	2680	2850
20 A	1750	2210	2450	2640	2850	3050	3260
12 A-12 A	1400	1600	1790	1930	2060	2180	2300
12 A-14 A	1500	1900	2090	2240	2380	2520	2650
14 A-14 A	1600	2100	2290	2440	2590	2760	2900
14 A-16 A	1800	2300	2520	2700	2880	3080	3250
16 A-16 A	1900	2400	2640	2840	3040	3250	3450
16 A-18 A	2000	2550	2820	3050	3280	3530	3750
18 A-18 A	2200	2650	2910	3140	3350	3640	3850
18 A-20 A	2400	2800	3080	3330	3600	3870	4100
20 A-20 A	2600	3050	3300	3550	3800	4050	4250
12 A-12 S	1300	1500	1690	1840	1970	2090	2200
12 A-14 S	1400	1700	1900	2050	2190	2320	2450
14 A-12 S	1500	1800	1990	2140	2280	2420	2550
14 A-14 S	1600	2000	2200	2360	2510	2660	2800
14 A-16 S	1700	2200	2400	2560	2730	2900	3050
16 A-14 S	1800	2250	2460	2630	2800	2990	3150
16 A-16 S	1900	2350	2580	2770	2960	3170	3350
16 A-18 S	2000	2450	2700	2910	3120	3350	3550
18 A-16 S	2100	2500	2760	2980	3200	3440	3650
18 A-18 S	2200	2600	2860	3090	3330	3590	3800
18 A-20 S	2300	2700	2970	3210	3470	3730	3950
20 A-18 S	2400	2750	3020	3260	3520	3780	4000
20 A-20 S	2500	2900	3180	3430	3700	3970	4200

Medtronic metal tipped angled cannulas (A), Medtronic straight cannulas (S) and the bicaval combinations of the two cannulas.

Table 3. Venous drainage in ml/min according to different venous cannulas and to the type of drainage (siphon gravity of vacuum assisted drainage) utilizing a 3/8" venous line.

		Vacuum assisted drainage (mmHg)					
Cannulas	Syphon gravity (50 cm)	-10	-20	-30	-40	-50	-60
16 S	1200	1520	1700	1850	1950	2000	2050
18 S	1560	2080	2370	2600	2700	2800	2860
20 S	1820	2460	2800	3050	3250	3400	3500
26 S	2100	2750	3050	3300	3500	3650	3750
16 A	1400	1900	2200	2400	2500	2600	2650
18 A	1750	2400	2750	3000	3150	3300	3400
20 A	2050	2700	3050	3350	3550	3750	3900
24 A	2800	3500	4000	4450	4850	5200	5500
16 S-16 S	2200	2700	3000	3250	3500	3740	3900
16 S-18 S	2400	3000	3400	3700	3950	4200	4440
18 S-18 S	2600	3250	3700	4100	4450	4700	4920
18 S-20 S	2800	3500	3950	4370	4750	5030	5200
20 S-20 S	3000	3700	4140	4570	4930	5200	5460
20 S-26 S	3200	3850	4300	4700	5050	5400	5650
26 S-26 S	3400	4000	4460	4880	5270	5630	5900
16 A-16 A	2400	2900	3300	3580	3850	4100	4300
16 A-18 A	2600	3200	3600	4000	4300	4550	4800
18 A-18 A	2800	3450	3900	4310	4700	4980	5160
18 A-20 A	3000	3650	4100	4510	4900	5150	5380
20 A-20 A	3200	3800	4250	4650	5000	5350	5580
20 A-24 A	3500	4360	4890	5340	5750	6100	6450
24 A-24 A	3800	4660	5230	5730	6220	6640	7000
16 A-16 S	2300	2850	3220	3500	3750	4000	4160
16 A-18 S	2500	3100	3500	3850	4120	4350	4550
18 A-16 S	2600	3150	3550	3900	4200	4450	4690
18 A-18 S	2700	3350	3800	4200	4550	4800	5030
18 A-20 S	2800	3550	4000	4420	4800	5070	5270
20 A-18 S	3000	3600	4050	4470	4850	5130	5320
20 A-20 S	3100	3750	4190	4600	4950	5240	5500
24 A-18 S	3300	4100	4570	5000	5390	5750	6050
24 A-20 S	3400	4200	4680	5110	5520	5880	6200
24 A-26 S	3700	4250	4780	5230	5650	6000	6350

Medtronic metal tipped angled cannulas (A), Medtronic straight cannulas (S) and the bicaval combinations of the two cannulas.

DISCUSSION

Vacuum-assisted venous drainage is a widely used technique that cardiac surgeons and the perfusion team components use to reduce haemodilution[2-5,10] and to reduce the size of the cannulae during minimally invasive cardiac surgery (MICS).[5-7] Such assisted venous drainage allows to decrease the declivity of the reservoir, and thus, to significantly decrease the length of the venous, arterial and suction lines. The result is a shorter and smaller tubing system with a reduced priming volume.[3] Furthermore, VAVD has proven to increase the venous return through cannulae that demonstrate limited flow capacity under siphon drainage conditions.[11]

During MICS, surgeons perform surgical procedures through small incisions. To allow this approach, VAVD has become increasingly important in order to reduce the caliber of the venous cannulae while maintaining an adequate blood flow.[6-8,12]

Although the use of VAVD during MICS is used all over the world by adult and pediatric cardiac surgeons, its use is not uniform and varies according to the surgeon's or Institution experience.

Several reports in literature focused on studying the effect of the different negative pressures, applied to the system, on the flow produced by a CPB circuit.[11-16] Kurusz and coworkers[22] tested different femoral cannulae and assessed how their position (in inferior vena cava rather than in the right atrium) and the increasing negative pressure applied to the system affects the venous drainage flow. They concluded that the position of the cannula, rather than the design has effects on flow, that every cannula is capable of achieving higher flow when negative pressure is applied.[11-16] The pressure inside the reservoir is lower than the pressure at the tip of the venous cannula, in fact it is a combination of both siphon gravity and the applied vacuum pressure, thus increasing the drainage capabilities of each cannula.

We tested how the CPB flow changes when different negative pressures are applied to the system and different VL sizes. We produced three tables, one for each diameter of venous tubing, showing the maximum flow achieved with every venous cannula or combinations of cannulae at different negative pressures. In MICS, the use of small cannulae can drastically improve the approach to intra-thoracic structures. Our study shows that the same flow can be reached despite using cannulae (in some occasions even two sizes smaller) by adapting the amount of negative pressure applied to the venous system.[6-8] The angled cannulae have proven to drain more than a straight tip cannula of the same size. This allows both the surgeon and the perfusion team component to choose the right combination of cannula to achieve a desirable CPBP flow.

These tables are routinely used at the University of Padua in the Pediatric Cardiac Surgery Program to choose the best combination of venous cannulae and negative pressure according to the size of the surgical access and the size of the vena cavae, in order to achieve the desired theoretical flow. As an example, during MICS, with the aid of a maximum of 50 mmHg of vacuum, obtained either by a wall vacuum system or a centrifugal pump were are usually able to minimize the size of tubing and venous cannulas, which were usually 1-2 under the estimated size for patient's BSA).

We acknowledge this study presents some limitations. This is an experimental in-vitro study whose results may significantly differ from an in-vivo one. In fact, the maximum flow reported has been achieved in a "perfect position scenario", which might be due to the fact the cannulae have been positioned at the bottom of the patient-reservoir excluding any chattering or collapsing effect which is present in-vivo.

Another limitation we identified is that only cannulae available in our Institution (because routinely used in-vivo) were tested. We understand that different cannulae with different drainage capability could produce different flows when used in the same setting.

In conclusion, the vacuum assisted venous drainage allows the use smaller cannulae maintaining a good venous return, which proves very useful during minimally invasive approaches. The present study should be considered as a preliminary attempt to create a scientific-based starting point for a uniform the use of VAVD.

REFERENCES

1. Munster K, Andersen U, Mikkelsen J, Pettersson G. Vacuum-assisted venous drainage (VAVD). Perfusion 1999;14:419–23.
2. Taketani S, Sawa Y, Masai T, et al. A novel technique for cardiopulmonary bypass using vacuum system for venous drainage with pressure relief valve: an experimental study. Artif Organs 1998;22:337-341
3. Durandy Y. Perfusionist strategies for blood conservation in pediatric cardiac surgery World J Cardiol 2012;26;2(2):27-33
4. Sistino JJ, Michler RE, Mongero LB. Laboratory evaluation of a low prime closed-circuit cardiopulmonary bypass system. J Extra-Corpor Technol 1993;24:116–19.
5. Bevilacqua S, Matteucci S, Ferrarini M, et al. Biochemical evaluation of vacuum-assisted venous drainage: a randomized, prospective study. Perfusion 2002;17(1):57-61.
6. Vida VL, Padalino MA, Motta R, Stellin G. Minimally invasive surgical options in pediatric heart surgery. Expert Rev Cardiovasc Ther 2011;9(6):763-9.
7. Vida VL, Padalino MA, Bhattarai A, Stellin G. Right posterior-lateral mini-thoracotomy access for treating congenital heart disease. Ann Thorac Surg 2011;92(6):2278-80.
8. Vida VL, Padalino MA, Boccuzzo G, at al. Minimally invasive surgery for congenital heart disease: a gender differentiated approach. J Thorac Cardiovasc Surg 2009;138(4):933-6.
9. Nakanishi K, Shichijo T, Shinkawa Y, et al. Usefulness of vacuum-assisted cardiopulmonary bypass circuit for pediatric open-heart surgery in reducing homologous blood transfusion. Eur J Cardiothorac Surg 2001;20:233-238
10. Gregoretti S. Suction-induced hemolysis at various vacuum pressures: implications for intraoperative blood salvage. Transfusion 1996;36:57–60.
11. Fiorucci A, Gerometta PS, DeVecchi M, Guzman C, Costantino ML, Arena V. In vitro assessment of the vacuum-assisted venous drainage (VAVD) system: risks and benefits. Perfusion 2004;19(2):113-7.
12. Shin H, Yozu R, Maehara T, et al.Vacuum assisted cardiopulmonary bypass in minimally invasive cardiac surgery: its feasibility and effects on haemolysis. Artif Organs 2000;24:450–53.
13. Lau CL, Posther KE, Stephenson GR, et al. Mini-circuit cardiopulmonary bypass with vacuum assisted venous drainage. Feasibility of an asanguineous prime in the neonate. Perfusion 1999;14:389–96.
14. Kiyama H, Imazeki T, Katayama Y, Murai N, Mukouyama M, Yamauti N. Vacuum-assisted venous drainage in single-access minimally invasive cardiac surgery. J Artif Organs 2006;6(1):20-4.
15. Colangelo N, Torracca L, Lapenna E, Moriggia S, Crescenzi G, Alfieri O. Vacuum-assisted venous drainage in extrathoracic cardiopulmonary bypass management during minimally invasive cardiac surgery. Perfusion 2006;21(6):361-5.9
16. Kurusz M, Deyo DJ, Sholar AD, Tao W, Zwischenberger JB. Laboratory testing of femoral venous cannulae: effect of size, position and negative pressure on flow. Perfusion 1999;14:379-387.