PROCEEDINGS

An *In Vitro* Comparison of the Venous Return Dynamics of Eleven Bubbler Oxygenators and Four Venous Reservoirs for Extracorporeal Circulation

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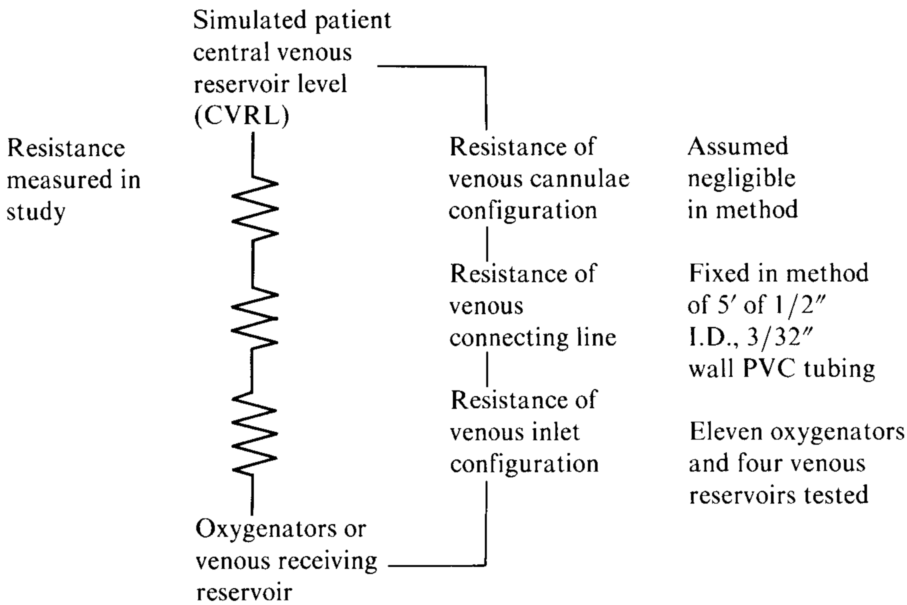
PURPOSE

Gravity venous drainage to an oxygenator or venous reservoir during Extracorporeal Circulation is affected by the central venous pressure (CVP), cm of gravity drainage, mechanical placement of cannula and cannula resistance to venous drainage. It is the purpose of this study to determine the value of the hydrostatic forcing function for gravity flow and the resistance at the venous inlet in disposable venous reservoirs and bubble oxygenators at various gas to blood flow ratios.

BACKGROUND



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The forcing function for gravity venous return flow through the series of resistances in the venous drainage system is the pressure difference between the CVP and the effective venous inlet pressure (Pvi).

There are two points on a venous return function curve for device comparison; the height below the CVRL where venous return begins and the height where 5 L/min of gravity venous return flow occurs. The effective Pvi may be observed by the height of the fluid column in the cardiotomy drain line in parallel to the venous drain line or by a water manometer placed in the venous line at the device inlet and has previously been cited by other authors and manufacturers as the "venous inlet resistance"[1,2].

The inverse of the slope of the gravity venous return flow versus the pressure curve (height of the simulated patient CVRL above the venous inlet on the CVRL-Vi) may be calculated to quantitate the sum of the venous line and device venous inlet resistance (Rvi), assuming negligible resistance in the cannulae and connectors. For example, if venous gravity return flow begins with an oxygenator at -30 cm below the reservoir level and 5 L/min of gravity return flow is achieved at -70 cm below the reservoir in a test device, the slope of the line is $(5000\ ml/min)/(-70) - (-30)\ cm = (5000\ ml/min)/40\ cm$. One cm pressure of 25% glycerol in water is equal to 1034 $dyne/cm^2$, hence, $(5000\ ml/min)/(1034 \times 40)\ dyne/cm^2$. Flow is changed to cm^3/sec and the equation inverted to give the proper units for resistance; $(40 \times 1034\ dyne/cm^2)/(5000/60)\ cm^3/sec = (60 \times 40 \times 1034\ dyne\ sec\ cm^{-5})/5000 = 470.40\ dyne\ sec\ cm^{-5}$. More simply, the resistance may be related: 40 cm/5000 ml/min or for every 8 cm of glycerol fluid column pressure, one L/min gravity venous return is allowed by the system. The gravity venous return versus height difference is linear to a point where the flow increase with increasing pressure difference decreases.

TABLE I
Adult Oxygenator Parameters @ 1:1 Gas to Blood Flow Ratio

Oxygenator	Rvi ($dyne\ sec\ cm^{-5}$) (2.5-6.2 L/min Blood Flow)	MOL-Vi (cm)	Pvi (cm) @ 5 L/min	Gravity Flow Begins (cm)	CVRL-Vi (cm) @ 5 L/min	CVRL-MOL (cm) @ 5 L/min
Travenol Bag* 5 M0314 @ 240 mmHg shim	357.9	−45.0	55	−39	−68	−23.0
Cobe Optiflo I**	426.4	−37.0	49	−45	−72	−35.0
Cobe Optiflo II**	436.6	−10.8	42	−20	−51	−40.2
Shiley S100***	441.6	+3.0	21	−24	−46	−49.0
Harvey H1000****	450.1	−10.5	37	−39	−59	−48.5
Bentley Q200A*****	503.6	−11.0	52	−39	−71	−60.0
Bentley BOS 10*****	519.2	+34.0	42	0	−26	−60.0

* Travenol Laboratories, Inc., Deerfield, Illinois 60015.
** Cobe Laboratories, Inc., Lakewood, Colorado 80215.
*** Shiley Corporation, Irvine, California 92714.
**** William Harvey Research Corporation, Santa Ana, California 92705.
***** Bentley Laboratories, Inc., Irvine, California 92705.

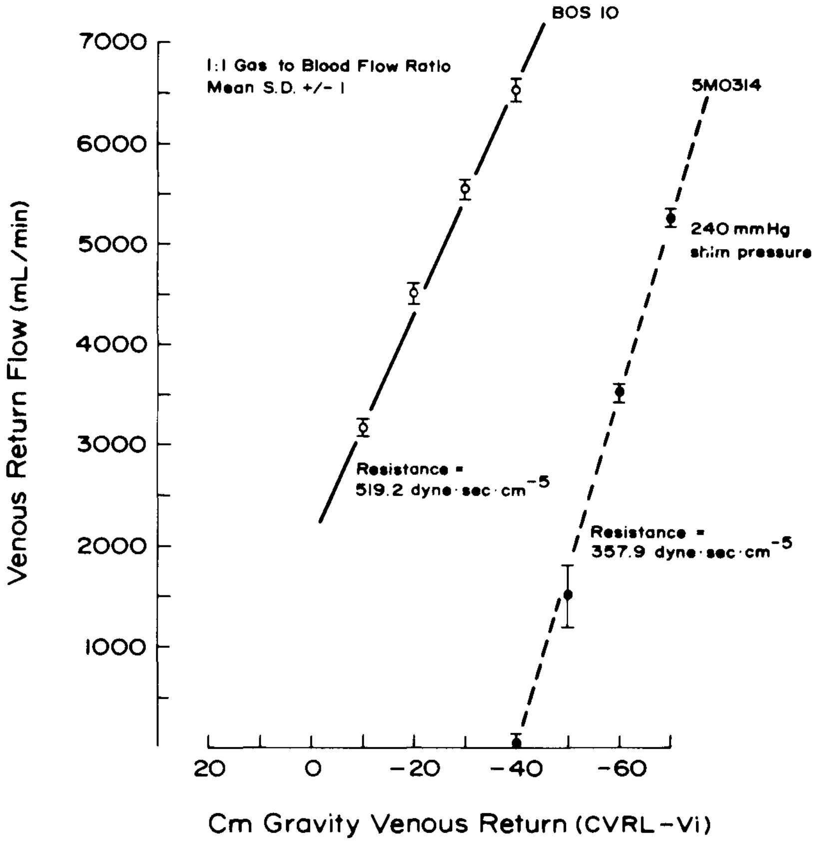

Figure 1. Flow versus pressure curve for the adult oxygenators with the greatest and least Rvi, the BOS 10 and Travenol 5 M0314, respectively.

METHOD

A circuit was constructed to measure venous return operating characteristics of several extracorporeal devices presently available on the market. A 60″ segment of PVC tubing (1/2″ I.D., 3/32″ wall) was connected to a large reservoir and the test device venous inlet. The venous inlet was placed 90 cm below the fluid level in the simulated patient CVR. Venous gravity return flow was matched and measured by a calibrated Travenol modular roller pump #2378, returning the 25% glycerol in water prime to the CVR. The pump flow meter was set to maintain a constant level at the test oxygenator minimal operating level (MOL) or a constant pressure of 4 cm in the test venous reservoir bag.

The effective Pvi, the flow from the calibrated pump and the CVRL-Vi were recorded as the test device was raised in 10 centimeter increments. The process was repeated three times at gas to blood flow ratios of .5:1, 1:1, and 2:1 for eleven test oxygenators and at various fluid volumes in four test venous reservoirs. The mean flows between 2.5 to 6.2 L/min and .25 to 3.0 L/min at various CVRL-Vi for each adult and pediatric device respectively, were entered into a linear regression model for each test condition. The slope

TABLE II
Membrane Venous Reservoir Parameters

Reservoir	Rvi (dyne sec cm^{-5}) (2.5–6.2 L/min Blood Flow)	MOL-Vi (cm)	Pvi (cm) @ 5 L/min	Gravity Flow Begins (cm)	CVRL-Vi (cm) @ 5 L/min	CVRL-MOL (cm) @ 5 L/min
Travenol* 5 M1460 +4 cm Pressure	295.1	−33	33.0	−33	−57	−24.0
Travenol* Expanded bag 5 M1461/Extra Portion Filled +4 cm Pressure	308.4	−50	50.0	−43.7	−69	−19.0
Travenol* Expanded bag 5 M1461/Extra Volume Clamped +4 cm Pressure	314.3	−28	28.0	−21	−47	−19.0
Sci Med RV** 1300-1 Level @ 860 ml	333.3	−46	46.0	−37	−64	−18.0
Sci Med RV** 1300-1 Level @ 700 ml	341.1	−42	42.0	−31	−59	−17.0
Sci Med RV** 500-1 + 4 cm Pressure	487.2	−46.5	46.5	−38	−77	−30.5

* Travenol Laboratories, Inc., Deerfield, Illinois 60015.
** Sci Med Life Systems, Inc., Minneapolis, Minnesota 55441.

from the linear regression was reported as the venous inlet resistance in dyne sec cm^{-5} and the zero flow intercept as the CVRL-Vi where gravity flow is initiated. The reported Rvi includes the fixed resistance of the 60″ venous line.

TABLE III
Pediatric Oxygenator Parameters @ 1:1 Gas to Blood Flow Ratio

Oxygenator	Rvi (dyne sec cm^{-5}) (.25–3.0 L/min Blood Flow)	MOL-Vi (cm)	Pvi (cm) @ 3 L/min	Gravity Flow Begins (cm)	CVRL-Vi (cm) @ 3 L/min	CVRL-MOL (cm) @ 3 L/min
H800*	397.2	−10.5	32	−34	−45	−34.5
S070**	734.6	+7.0	39	−16	−49	−56.0
BOS 5***	794.3	+27.5	5	−3	−35	−62.5
H400*	940.0	−10.5	53	−33	−65	−54.5

* William Harvey Research Corporation, Santa Ana, California 92705.
** Shiley Corporation, Irvine, California 92714.
*** Bentley Laboratories, Inc., Irvine, California 92705.

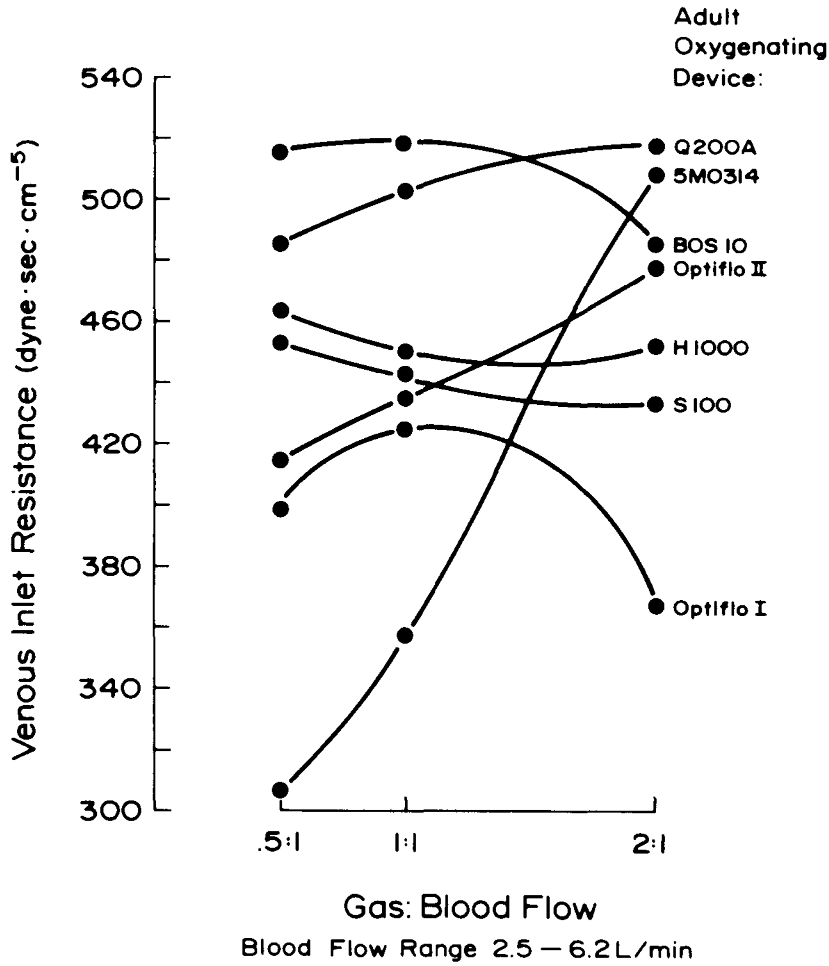

Figure 2. The effect of gas:blood flow ratio on the Rvi of seven adult oxygenating devices.

RESULTS

Table I ranks the seven adult oxygenators studied according to Rvi. The CVRL-Vi that venous return flow begins and achieves 5 L/min are listed along with the difference in centimeters between the devices' MOL and its Vi port (MOL-Vi). The CVRL-MOL at 5 L/min is listed also.

Figure 1 depicts the flow versus pressure curve for the adult oxygenators with the greatest and least Rvi. The BOS 10 exhibited the greatest Rvi at 519.2 dyne sec cm^{-5}, and −26 cm gravity drainage from the Vi was necessary for 5 L/min flow with a 1:1 gas to blood flow ratio, however, the CVRL-MOL at this flow is −60 cm. The Travenol bag 5 MO314 demonstrated the least Rvi at 357.9 dyne sec cm^{-5} with −68 cm gravity drainage at the Vi necessary for 5 L/min flow. The 5 M0314 MOL was −23.0 cm below the CVRL in this operating condition.

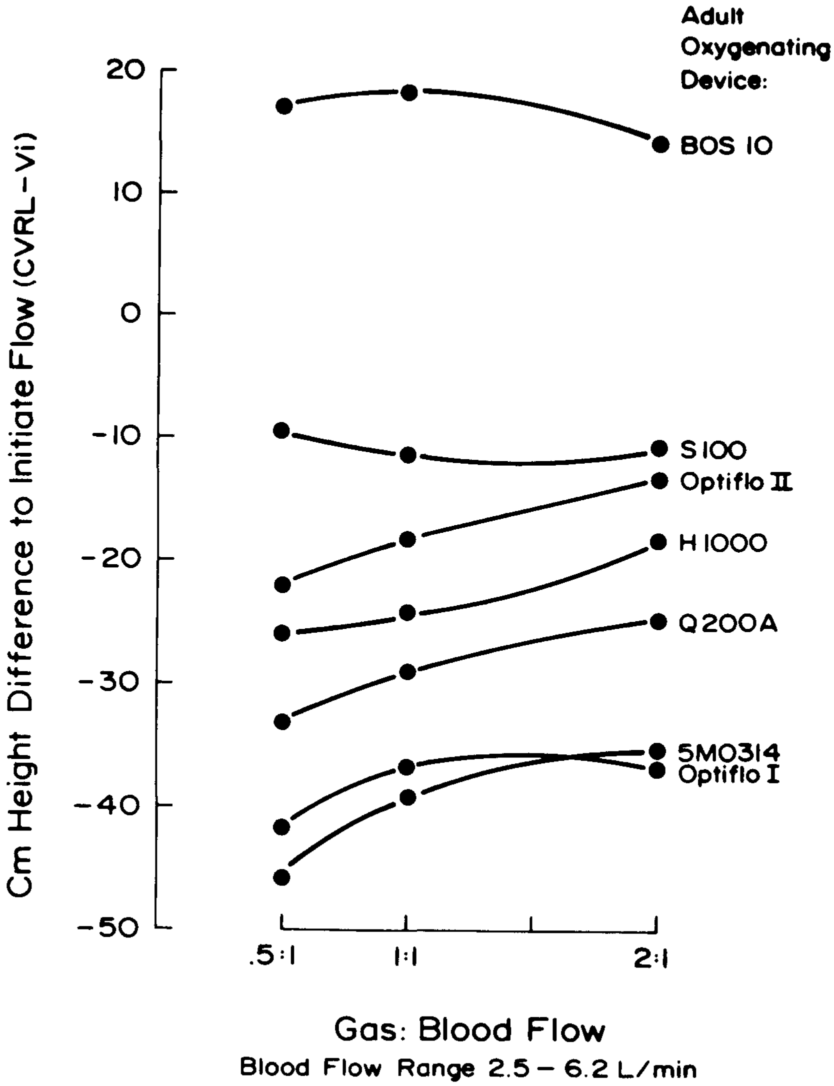

Figure 3. The effect of gas:blood flow ratio on the CVRL-Vi height difference where venous return flow is initiated in seven adult oxygenators.

As in Table I, Table II lists the four venous reservoirs studied in this method. The Sci Med RV 500-I with +4 cm glycerol bag pressure exhibited the greatest Rvi at 487.2 dyne sec cm^{-5} and needed a CVRL-Vi = −77 cm to attain venous drainage of 5 L/min. The bag CVRL-MOL at this point was −30.5 cm. Travenol Laboratories venous bag 5 M1460 filled +4 glycerol pressure demonstrated the least Rvi at 295.1 dyne sec cm^{-5} with CVRL-Vi = −57 cm for gravity drainage of 5 L/min flow. The bag CVRL-MOL was −24 cm at this point.

Table III also ranks the four pediatric and infant oxygenators studied according to Rvi. The CVRL-Vi that venous return flow begins and achieves 3 L/min are listed along with the MOL-Vi and CVRL-MOL at 3 L/min.

The H400 displayed the greatest Rvi at 940.0 dyne sec cm^{-5} and required −65 cm gravity drainage from the Vi at 3 L/min flow at a 1:1 gas to blood flow ratio. The CVRL-MOL at 3 L/min is −54.5 cm. The H800 exhibited the least Rvi for the pediatric and infant oxygenators at a 1:1 gas to blood flow ratio of 397.2 dyne sec cm^{-5} with −45 cm gravity drainage at the Vi needed for 3 L/min flow. The H800 CVRL-MOL at 3 L/min is −34.5 cm.

Rvi appeared to be related to gas to blood flow ratio (Figure 2). Rvi for the Q200A, 5 M03414, Optiflo 11, BOS 5 and the H800, the devices with tortuous oxygenating columns, increased with increasing gas to blood flow ratio. The Rvi decreased or did not vary as gas to blood flow ratio increased for the BOS 10, H1000, S100, Optiflo 1, S070 and the H400.

CVRL-Vi, where venous return initiates, appeared to be affected by the gas to blood flow ratio (Figure 3). This CVRL-Vi, where venous flow begins, decreased with increasing gas to blood flow ratio for all adult oxygenators tested except the S100 and the BOS 10.

DISCUSSION

Knowledge of a device's Rvi, Pvi, CVRL-Vi values where flow begins and reached 5 L/min and the value of MOL-Vi are useful parameters for device comparison and selection prior to clinical trial. If the CVRL-MOL for a device is known prior to bypass initiation, the user does not have to hang the device low to the floor, and the manufacturer may make a reproducible and intelligent recommendation to the user on purchase.

During cardiopulmonary bypass, the CVRL-Vi will be equal to the patient CVP plus the height difference between the right atrium and the Vi of the device, given no unusual obstruction to flow at the venous cannulation sites or in the venous line and connectors. Increasing CVRL-Vi increases venous gravity return flow linearly between 2.5 and 6.2 L/min and tends to be nonlinear at lesser and greater flow values of CVRL-Vi in adult oxygenating units. The prime solution in this method has the approximate specific gravity, density and vicosity of the human blood with a hematocrit of 25%. The results of this methodology should yield a similar clinical experience.

The use of Pvi to relate Rvi may be misleading. It is more accurate and clinically applicable to construct the venous return flow versus CVRL-Vi curve and take the inverse slope of the curve and report the value of the Rvi in units of dyne sec cm^{-5} or in cm/L/min.

Rvi and CVRL-Vi where venous return flow is initiated changes with gas to blood flow ratio (Figure 3), however, once venous return is established, alterations in the gas to blood flow ratio will not lead to clinically perceivable changes in venous return or CVP, except possibly in the 5 M0314 and Optiflo 1. In general, simple chimney design oxygenating columns allow a decrease in Rvi with increasing gas to blood flow ratio. Tortuous oxygenating columns present more Rvi when the gas flow is increased.

Should the MOL-Vi in a device design be a large positive value as in the BOS 10, S100, BOS 5, and S070, it necessitates that the device be operated such that visualization of the MOL may be a problem or even hazardous in the clinical setting. The BOS 10 oxygenator allows venous return flow to begin at a CVRL-Vi = 0 cm, the highest of the devices tested. Venous return reaches 5 L/min at 26 cm below the CVRL at a gas to blood flow ratio of 1:1 in the BOS 10. The BOS 10 has excellent results in these two parameters, however, the MOL is 34 cm below the Vi, hence, the MOL during operation is approximately 60 cm below the right atrium, the greatest CVRL-MOL of the adult devices tested in this method.

CONCLUSIONS

1. The BOS 10 exhibited the greatest Rvi of the adult oxygenators at 519.2 dyne sec cm^{-5} and the Travenol 5 M0314 measured the least Rvi at 357.9 dyne sec cm^{-5} at a gas to blood flow ratio of 1:1 between 2.5 – 6.2 L/min of gravity return flow.

2. H400 exhibited the greatest Rvi of the pediatric oxygenators studied at 940.0 dyne sec cm^{-5} and the H800 the least Rvi at 397.2 dyne sec cm^{-5} at a gas to blood flow ratio of 1:1 between .25 – 3.0 L/min of gravity return flow.

3. The Sci-Med RV500-1 filled to 4 cm pressure, exhibited the greatest Rvi of the venous reservoirs at 487.2 dyne sec cm^{-5} and the Travenol 5 M1460 filled to 4 cm pressure measured the least Rvi of 295.1 dyne sec cm^{-5}.

4. Rvi and the CVRL-Vi, where gravity flow begins, are a function of gas to blood flow ratio, however, altering the ratio would not result in clinically measurable changes during operation.

5. The BOS 10 and Q200A have the greatest CVRL-MOL of −60 cm at 5 L/min venous return flow. Operating levels of oxygenating devices should be reported in reference to the MOL especially if the MOL-Vi is a large difference by design in the device (e.g. BOS 10, S100, BOS 5, and S070).

6. The pressure at the venous inlet should not be reported as "venous inlet resistance." It is necessary to construct the venous return flow versus CVRL-Vi curve to calculate Rvi. The gas to blood flow ratio or pressure in the venous reservoir bag and test prime solution must be reported for the measured Rvi.

REFERENCES

1. Streczyn, M. V.: Oxygenator Profiles, William Harvey Research Corporation, 1978.
2. Shiley Laboratories, Personal Communication, 1978.