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Review

Systemic venous drainage: can we help Newton?☆

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Summary

In recent years substantial progress occurred in the techniques of cardiopulmonary bypass, but the factor potentially limiting the flexibility of cardiopulmonary bypass remains the drainage of the systemic venous return. In the daily clinical practice of cardiac surgery, the amount of systemic venous return on cardiopulmonary bypass is directly correlated with the amount of the pump flow. As a consequence, the pump flow is limited by the amount of venous return that the pump is receiving. On cardiopulmonary bypass the amount of venous drainage depends upon the central venous pressure, the height differential between patient and inlet of the venous line into the venous reservoir, and the resistance in the venous cannula(s) and circuit. The factors determining the venous return to be taken into consideration in cardiac surgery are the following: (a) characteristics of the individual patient; (b) type of planned surgical procedure; (c) type of venous cannula(s); (d) type of circuit for cardiopulmonary bypass; (e) strategy of cardiopulmonary bypass; (f) use of accessory mechanical systems to increased the systemic venous return. The careful pre-operative evaluation of all the elements affecting the systemic venous drainage, including the characteristics of the individual patient and the type of required surgical procedure, the choice of the best strategy of cardiopulmonary bypass, and the use of the most advanced materials and tools, can provide a systemic venous drainage substantially better than what it would be allowed by the simple 'Law of universal gravitation' by Isaac Newton.

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Keywords: Anomalous venous connection; Assist venous return; Cardiopulmonary bypass; Pump flow; Venous cannulas; Venous drainage

1. Introduction

. . . all matter attracts all other matter with a force proportional to the product of their masses and inversely proportional to the square of the distance between them.
'Law of universal gravitation'. Isaac Newton (1643—1727)

In recent years substantial progress occurred in the techniques of cardiopulmonary bypass, particularly for adult patients undergoing mini invasive procedures and for pediatric patients undergoing early repair of congenital heart defects. In infants and children significant reductions of the negative effects of cardiopulmonary bypass [1—15] have been achieved with the use of miniaturized circuits to decrease the priming volume, the use of normothermic high-flow cardiopulmonary bypass, the adoption of an increased hematocrit, the use of controlled re-oxygenation in cyanotic patients, a more effective prevention of the inflammatory reaction, the improvement of techniques of myocardial protection, the extended use of modified ultra-filtration, the improved management of the coagulation, and a better intra-operative monitoring of the physiological parameters [16—74].

Despite all the above improvements, the factor potentially limiting the flexibility of the techniques of cardiopulmonary bypass remains the drainage of the systemic venous return.

The parameters involved in the relationship between venous return and cardiac output in normal physiological conditions were established a long time ago with the original experimental and clinical studies by Guyton [75—78].

Recently, the principles of the Guyton model on venous return have been re-examined through review of the original experiments, presentation of a hypothetical alternative way for obtaining the same data, and analysis of an alternative simple model [79]. This review has been followed by strong criticism, originating an ongoing debate on the evaluation of the factors responsible for the relationship between venous return and cardiac output [80—84].

In the daily clinical practice of cardiac surgery, the amount of systemic venous return on cardiopulmonary bypass is directly correlated with the amount of the pump flow. As a consequence, the pump flow is limited by the amount of venous return that the pump is receiving.

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On cardiopulmonary bypass the amount of venous drainage depends upon the central venous pressure, the height differential between patient and inlet of the venous line into the venous reservoir, and the resistance in the venous cannula(s) and circuit, accordingly with the formula:

$$F = -2.6093 + 0.0512D - 1.2231L + 8.5016C$$

where F = flow (l/min), D = drainage load (cm H_2O), L = length of tubing (m), and C = cross-sectional area (cm^2) of the tubing system.

The practical consequences of the Poiseuille's law, establishing the relationships between flow and pressure in a tube, are the following:

(a) flow to length: doubling the length halves the flow
(b) flow to radius: halving the radius quarters the flow
(c) flow to viscosity: inverse relationship

Because of the above fixed limits, all the details of the surgical procedures have to be carefully planned in order to facilitate the unrestricted return of the largest possible amount of venous blood to the pump.

The *factors determining the venous return* to be taken into consideration in cardiac surgery are the following:

- characteristics of the individual patient
- type of planned surgical procedure
- type of venous cannula(s)
- type of circuit for cardiopulmonary bypass
- strategy of cardiopulmonary bypass
- use of accessory mechanical systems to increased the systemic venous return

2. Characteristics of the patient

The amount of the systemic venous return is directly correlated with the *morphological* and *functional* characteristics of the patient.

The most important *morphological elements* to be considered are the body weight and the body surface area. The size of the right atrium and, therefore, the blood volume ready available for the venous drainage is important, particularly in valve disease.

The unique individual morphology of the patient must then be taken into consideration in relationship with number, position, and size of the venae cavae. An anomalous systemic venous connection is associated with the main intra-cardiac malformation in 8–10% of patients with congenital heart defects [85–92]. The presence of an anomalous systemic venous connection may dictate not only the number and position of the venous cannulas but also the strategy of cardiopulmonary bypass: continuous perfusion versus circulatory arrest.

The most frequent congenital anomaly of systemic venous return is the presence of a persistent left superior vena cava [85–90], in most of the cases draining into the coronary sinus (Fig. 1). In theses cases the strategy of cardiopulmonary bypass is dependent upon the presence or the absence of the innominate vein joining the persistent left superior vena cava with the right superior vena cava. In the presence of innominate vein, the standard direct cannulation of the superior and inferior vena cava is enough to provide adequate venous return; if required by the intra-cardiac exposure, the persistent left superior vena cava can be temporarily occluded proximally to the connection with the coronary sinus, because the drainage will be accomplished by the superior vena cava cannula via the innominate vein. In the absence of innominate vein, three different strategies can be utilized: direct cannulation of the persistent left superior vena cava (in this case there will be a three venous cannulas drainage system), drainage of the persistent left superior vena cava with a cannula inserted through the coronary sinus after opening the right atrium, or a single venous cannula in the right atrium (in this case a deep hypothermia with circulatory arrest will be required to perform the intra-cardiac repair). The choice among these three techniques will depend upon the size of the patient (direct cannulation of the persistent left superior vena cava is generally avoided in neonates and small infants) and the preferred technique of cardiopulmonary bypass, with continuous perfusion or with circulatory arrest.

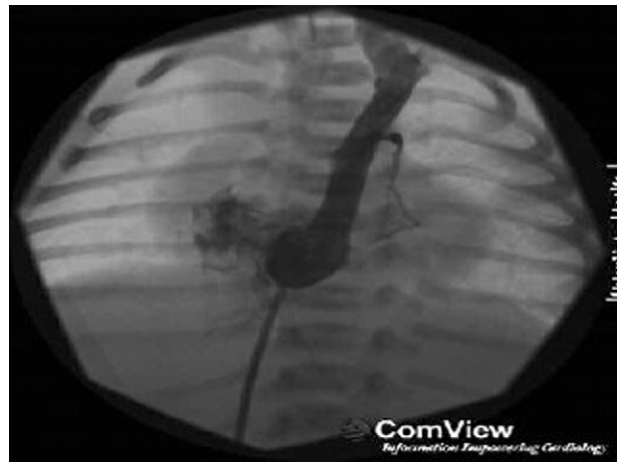

Fig. 1. Angiography with an antero-posterior view showing a persistent left superior vena cava draining into the coronary sinus, with absence of the innominate artery.

Sometimes, particularly in complex congenital heart defects, the persistent left superior vena cava is draining into the left atrium (Fig. 2), with associated cyanosis due to the right-to-left intra-cardiac shunt. In these cases, in the absence of the innominate vein, the anomalous connection of the persistent left superior vena cava with the left heart is interrupted, and the anomalous vein is re-connected to the right side of the heart by an anastomosis, either to the right superior vena cava or to the right auricular appendage.

In patients with complex congenital heart defects, a frequent anomalous systemic venous connection is the interruption of the inferior vena cava [85–90], with the drainage of the inferior part of the body occurring into the superior vena cava through an 'azygos continuation' (Fig. 3). Since these patients are frequently candidates to a uni-ventricular type of surgical repair [85–90], once the absence of the inferior vena cava had been confirmed, in order to plan the venous cannulation as well as the surgical procedure, it is important to identify number, size, and position of the superior vena(e) cava(e). Position, number, and site of

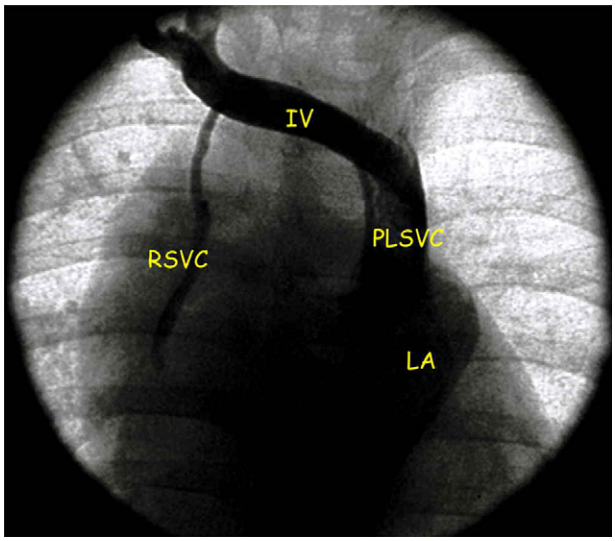

Fig. 2. Angiography with an antero-posterior view with contrast injection showing the persistent left superior vena cava draining into the left atrium, with presence of the innominate vein and hypoplastic right superior vena cava. IV = innominate vein; LA = left atrium; PLSVC = persistent left superior vena cava; RSVC = right superior vena cava.

connection of the hepatic veins need also to be identified. Particularly in patients with atrial isomerism, it is not infrequent to find additional features, further complicating the morphological aspect, like the presence of situs viscerum inversus (Fig. 4). Of course, peculiar anomalous systemic venous connections require individualized type of venous cannulation, correlated with the specific needs of the planned surgical procedure (Fig. 5).

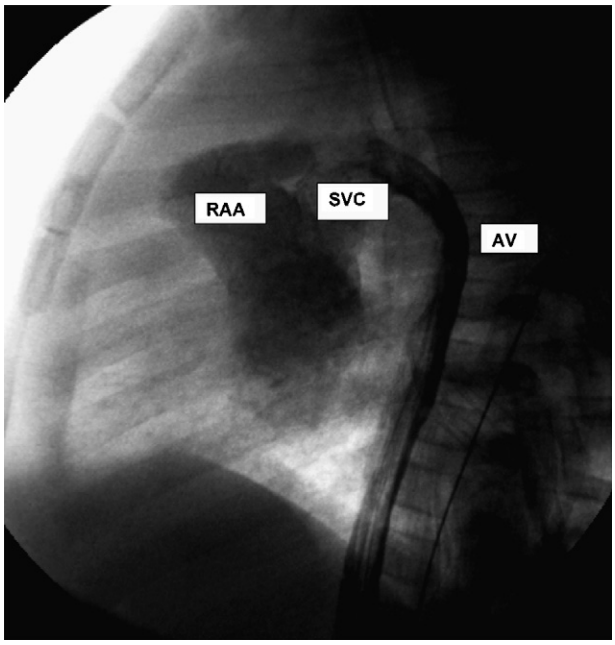

Fig. 3. Angiography in a patient with left isomerism with interruption of the inferior vena cava: lateral view showing the injection in the azygos continuation, with opacification of the superior vena cava and of the right auricular appendage, with evident morphology of left type. AV = azygos vein; RAA = right auricular appendage; SVC = superior vena cava.

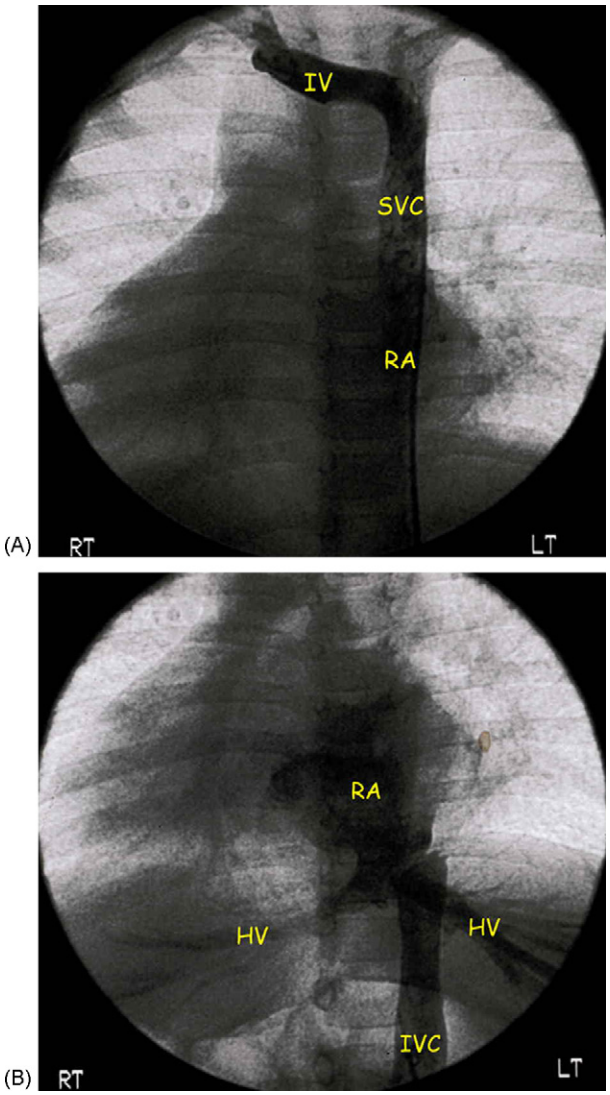

Fig. 4. Angiography in a patient with left isomerism and situs viscerum inversus. (A) Antero-posterior view with contrast injection in the innominate vein showing a persistent left superior vena cava draining into a left-sided morphologically right atrium. IV = innominate vein; PLSVC = persistent left superior vena cava; RA = right atrium. (B) Antero-posterior view with contrast injection in the inferior vena cava located on the left side of the spine, with opacification of the hepatic veins and the right atrium, located on the left side. HV = hepatic veins; IVC = inferior vena cava; RA = right atrium.

Among the *functional characteristics* to be considered are the degree of filling volume of the patient and the status of vein dilatation, frequently induced by the medications used for induction and maintenance of the general anesthesia.

3. Type of planned surgical procedure

The management of the venous return, particularly regarding the type and positioning of venous cannulation, depends upon the need of opening the right heart (very frequent in pediatric cardiac surgery for the intra-cardiac repair) and the need for a direct caval cannulation (like for a uni-ventricular type of repair requiring a direct cavo-pulmonary connection).

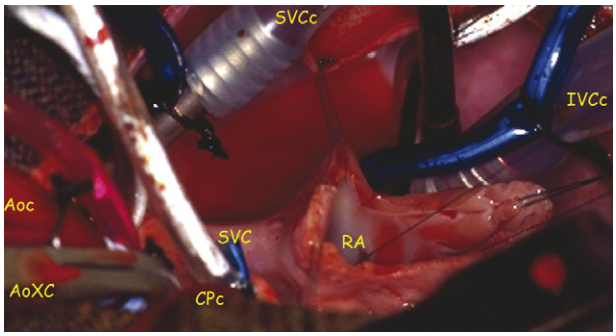

Fig. 5. Intra-operative photograph of the peculiar cannulation required for the intra-cardiac repair, performed through a right atriotomy, of the patient reported in Fig. 4. The venous cannulas are both placed on the left side of the chest; the photograph has been taken from the right side of the chest (position of the surgeon). Aoc = aortic cannula; AoXC = aortic cross-clamp; CPc = cardioplegia cannula; RA = right atrium; IVCc = inferior vena cava cannula; SVC = superior vena cava; SVCc = superior vena cava cannula.

When the surgical procedure includes the superior vena cava to right pulmonary artery connection (= bidirectional Glenn anastomosis) or the repair of a partial anomalous pulmonary venous connection in superior vena cava, the venous cannula for the drainage of the upper part of the body may well be directly positioned into the innominate vein, in order to allow complete access and mobilization of the superior vena cava [85–90].

Adequate exposure of the surgical field for intra-cardiac repair conventionally requires separate cannulation and snaring of the venae cavae, if circulatory arrest is not the method of choice.

The peripheral cannulation of a femoral vein to drain the venous return of the inferior half of the body can be used in two situations: (a) re-operations, where cardiopulmonary bypass need to be established before re-opening the sternum, because of cardiac adhesions due to the previous surgery through median sternotomy; (b) situations when the presence of a cannula in the inferior vena cava can complicate the surgical procedure, like in the total extra-cardiac cavo-pulmonary connection [85–90].

Recently it has been proven that right heart surgery can be accomplished without direct cannulation and snaring of the inferior vena cava, with adequate systemic venous drainage, provided that adequate peripheral venous cannulation is performed [93].

Adequate positioning of the venous cannula(s) is very important, and trans-esophageal echocardiography is useful to guide and verify the correct positioning [94,95]. In left heart surgery (mitral and/or aortic valve procedures) the total systemic venous return can be drained with a single venous cannula inserted from the femoral vein, provided that it is correctly positioned into the right atrium (Fig. 6A). In right heart surgical procedures (like Ebstein's anomaly or total cavo-pulmonary connection), the venous cannula inserted from the femoral vein has to be positioned in the inferior vena cava, without reaching the right atrium (Fig. 6B).

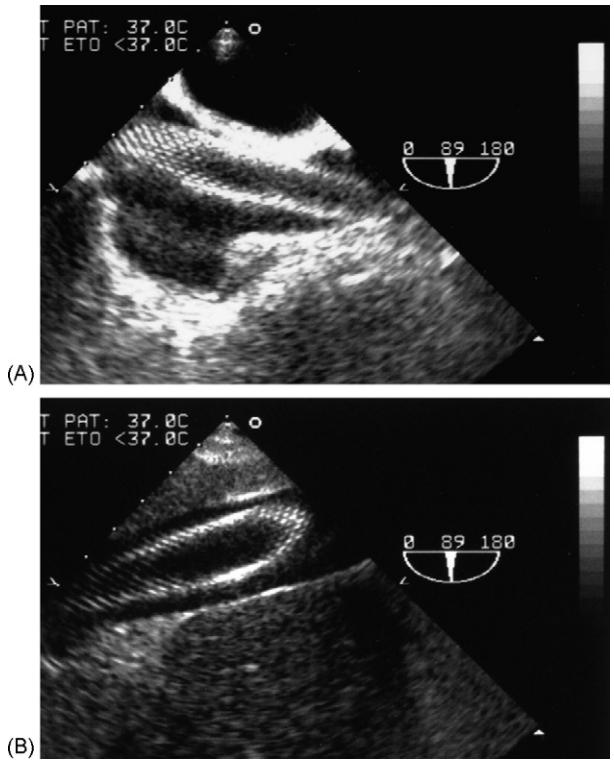

Fig. 6. Intra-operative esophageal echocardiography showing the adequate positioning of the venous cannula. (A) Venous cannula inserted from the right femoral vein and positioned into the right atrium. (B) Venous cannula inserted from the right femoral vein and positioned in the inferior vena cava.

4. Type of venous cannula(s)

The function of the venous cannula(s) is to provide an unobstructed passage from the wide, low-resistance, collapsible, systemic veins, to the downstream narrower, stiff, artificial system of the tubing of the cardiopulmonary bypass circuit.

In order to provide the optimal venous drainage the cannula(s) must be thin-walled, to offer the widest possible internal diameter, and with drainage holes, to avoid occlusion by collapse of the venous wall during suction. Other parameters affecting the performance of the venous cannula(s) are size, internal/external diameter ratio, pre-load, and whole surface area [86,90,96].

In neonates and small infants the length of the tip of the venous cannula is very important, particularly with regard the cannulation of the inferior vena cava: a cannula too long can easily obstruct the venous drainage from the liver, especially if the tip of the cannula is positioned beyond the connection of the hepatic veins to the inferior vena cava [86]. Evidently, the same is true for the size of the venous cannula: a size too large can prevent side hole drainage, particularly form hepatic veins [86]. An experimental study demonstrated that as the size of the venous cannula approaches the size of the vein, there is a marked decrease in the maximal flow rate [97].

A recently designed venous cannula (Smart-cannula®, Smartcanula LLC, Lausanne, Switzerland), obtained with self-expandable minimal (0.2 mm) wall thickness material, has proven to provide significantly superior results to the other commercially available venous cannulas with computational fluid dynamics [96], in vitro evaluation [98], as well

as in both adult [99] and pediatric [100] patients, thanks to its favorable internal/external diameter ratio and to its expandability up to the lumen of the patient's vena cava [96—100].

5. Type of circuit for cardiopulmonary bypass

As for the venous cannula(s) the size of the tubing in the venous circuit plays a pivotal role in determining the amount of the venous drainage. The adequate balance has to be considered between the largest possible size of the venous circuit and the smallest possible amount of priming of the circuit, for the adult [101] and the pediatric size [20,34,41,42,58,86,87,90].

As a consequence of the Poiseuille's law, not only the size of the venous tubing but also the length of the circuit is as important, particularly for small patients where the size of the tubing has to remain small [34,42,102—104]. Because of the relationship between flow and length, doubling the length halves the flow. With this regard, reducing the distance between the oxygenator and the patient — thanks to a custom-designed arm with remote double-headed roller pump — allows minimizing the circuit length. A clinical study using this type of circuit showed a 29% decrease in priming volume and 58% reduction in blood utilization in infants undergoing cardiopulmonary bypass for intra-cardiac repair [42].

6. Strategy of cardiopulmonary bypass

The same surgical procedure can be performed with a variety of techniques of cardiopulmonary bypass, all derived from the mismatch between the characteristics of the individual patient, the planned surgical operation, and the preference of surgical team.

The variables to be taken into consideration are the number of venous cannulas, the site(s) of cannulation, the number and position of the required incisions, particularly on the right heart, the use of total or partial cardiopulmonary bypass, the wanted flow, temperature, and hematocrit during cardiopulmonary bypass [34,36,39—42,46,53,55,56, 58,69,86—90,105].

Adequate left heart venting, essential in providing adequate return to the heart—lung machine, is particularly important in patients with cyanotic congenital heart defects and restricted pulmonary blood flow. Frequently, a massive amount of venous return to the left atrium is sustained by the presence of bronchial and chest wall collateral circulation to the lungs. In these cases the amount of venous return to the left atrium is directly correlated with duration and severity of the pre-operative cyanosis, and with the level of systemic pressure and flow maintained during the cardiopulmonary bypass [86—90].

To improve the venous drainage, and in the same time to avoid left ventricular distension and improve the surgical exposure for the intra-cardiac repair, a left heart vent is generally inserted into the left atrium, either through the junction of the right upper pulmonary vein with the left atrium or through the atrial septum after opening the right atrium, using an existing patent foramen ovale or atrial septal defect, or surgically creating an inter-atrial communication in the presence of intact atrial septum. Occasionally, the pulmonary venous return can be drained with a vent introduced from the left auricular appendage, from the apex of the left ventricle, or directly into the main pulmonary artery.

7. Use of accessory mechanical systems to increased the systemic venous return

Generally the venous drainage is obtained by gravity, placing the venous reservoir of the circuit of cardiopulmonary bypass about 30 cm lower than the heart level; in this way a negative pressure equivalent to about −20 to −25 mmHg is obtained.

This standard system is adequate for the vast majority of adult patients undergoing conventional procedures. In adult patients requiring mini invasive type of surgery, and in pediatric patients where relatively small-size cannulas and tubing of the venous circuit are used to reduce the pump priming, additional systems need to be used to artificially increase the venous drainage provided by the gravity only.

To further increase the negative pressure, and therefore to increase the systemic venous drainage, the two mechanical systems most used are the kinetic assist and the vacuum assist venous return.

7.1. Kinetic assist venous return

This is accomplished by placing a centrifugal pump on the venous line prior to the cardiotomy reservoir, generating a more negative pressure (between −40 and −60 mmHg) and, therefore, obtaining a pump-assisted venous drainage. Because of the proven efficiency in providing additional flow to the heart—lung machine — thanks to this kinetic assisted venous drainage — it has been particularly used for cardiac surgery procedures performed through a mini invasive surgical approach with peripheral venous cannulation [106—108].

7.2. Vacuum assist venous return

In this system a constant vacuum pressure (up to −80 mmHg) is created in an airtight venous reservoir, allowing more blood to be drained from the patient via the venous line. This system allows the performance of surgical procedure on cardiopulmonary bypass even in small infants, without the need of large-size venous tubing and, therefore, without increasing the volume of the pump priming [102].

The major potential limit in the clinical application of this system is the high risk of generating gaseous micro-emboli in the venous circuit. If the arterial pump is stopped for various reasons and the vacuum source is left on the venous reservoir, micro-bubble transgression can occur from the gas compartment to the liquid compartment of the oxygenator, creating another source of gaseous micro-emboli as soon as the arterial pump is turned on again [109—111]. The sudden need to stop the arterial pump, of course, may lead to a poor systemic perfusion.

8. Conclusions

The careful pre-operative evaluation of all the elements affecting the systemic venous drainage, including the characteristics of the individual patient and the type of required surgical procedure, the choice of the best strategy of cardiopulmonary bypass, and the use of the most advanced materials and tools, can provide a systemic venous drainage substantially better than what it would be allowed by the simple 'Law of universal gravitation' by Isaac Newton.

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