

The Effectiveness of Low-Prime Cardiopulmonary Bypass Circuits at Removing Gaseous Emboli

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Abstract: During extracorporeal circulation, the patient's blood is siphoned into the extracorporeal circuit (ECC) by gravity or may be assisted kinetically or by vacuum. In all instances, negative pressure is generated in the venous line, which can cause entrainment of air into the ECC at the cannulation site. The typical ECC uses a venous reservoir, membrane oxygenator, and arterial line filter, which together aid in removal of air that has entered the venous line and minimize the transmission of gaseous microemboli to the patient. Recently, several manufacturers have introduced low prime ECCs with component configurations that differ from conventional ECCs, including the omission of a venous reservoir. These configuration changes may change the ability of the circuit to handle air and therefore their ability to minimize gaseous microemboli. The purpose of this study was to test the ability of new low prime ECCs to remove air introduced into the venous line and minimize gaseous micro-

emboli from entering the patient's circulation. Using a model of CPB, air was introduced into the venous line of a low prime ECC and a conventional CPB circuit. The detection of the gaseous microemboli produced was monitored distal to the oxygenator by an ultrasonic emboli detector to determine if venous air was able to traverse the ECC at varying rates of air introduction and blood flow. Data was collected using data acquisition software loaded on a personal computer. Gaseous microemboli levels detected in the arterial line of the low prime ECC were 8 to 10 times higher than the microemboli levels detected in the conventional ECC at all blood flow rates. Every effort should be made to minimize and prevent air from being entrained in the venous line of a low prime CPB circuit to minimize the risk of arterial gaseous microemboli generation. **Keywords:** cardiopulmonary bypass, venous air, air removal, low-prime. *JECT. 2004; 36:336-342*

Cerebral injury is a recognized complication of cardiopulmonary bypass (CPB) during cardiac surgery (1). Etiologies of cerebral injury include hypoperfusion, vascular inflammatory response, and emboli (1). It has been previously demonstrated that there is a relationship that exists between the number of intravascular microemboli detected during CPB and the incidence of postoperative cerebral injury (2).

Gaseous microemboli during CPB have many different etiologies. The occurrence of gaseous microemboli increases with the use of bubble oxygenators (3), excessive heating gradients (4), unfiltered arterial lines (5), low volume in venous reservoirs (6), and entrained venous air (7) while on CPB. It has also been reported that pump flow rate, type of perfusate, and the use of vacuum-assisted venous drainage affects the ability of the CPB circuit components to remove a quantity of entrained venous air (8),

a known cause of arterial gaseous microemboli. Because the behavior of gaseous microemboli within the CPB circuit results from a complex interaction between flow effects, gaseous partial pressures, volume, solubility, buoyancy, perfusate, temperature, and fluid velocity, the components comprising the CPB circuit can effect the ability of the circuit to filter or eliminate such emboli from the perfusate.

A low-prime closed circuit CPB system for cardiac surgery may be an advancement in priming volume reduction compared with priming volumes used in current conventional CPB circuits (9). This allows better preservation of red blood cells, plasma proteins, and platelets and less patient hemodilution. As a result, the patient's blood maintains a more adequate oxygen carrying capacity, oncotic pressure, and coagulation. These circuits also have a reduced foreign surface area, which may or may not be advantageous to the patient. The aim of the present study was to determine the ability of low-prime CPB circuits to reduce or eliminate a quantity of entrained venous air during CPB as compared to conventional extracorporeal circuits.

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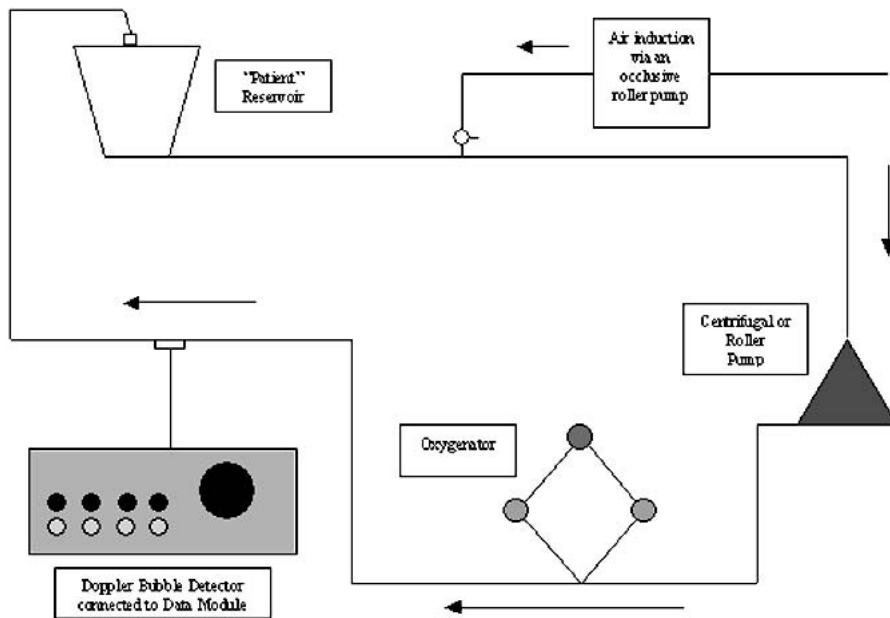


Figure 1. Diagram of CPB circuit used in testing of removal of entrained venous air.

MATERIALS AND METHODS

Two CPB circuits were assembled to compare the air-handling capabilities of each. The first circuit was constructed using a low-prime circuit design. The circuit was designed to mimic the Jostra MECC (Jostra, Hirrlingen, Germany), a miniature CPB circuit containing a Rotaflow centrifugal pump, a Quadrox oxygenator, and a Quart arterial filter. Because a Rotaflow pump could not be obtained within the time constraints of this experiment, a Biomedicus (Medtronic-Biomedicus, Minneapolis, MN) centrifugal pump was used in its place. Because the Rotaflow centrifugal pump has a priming volume of 60 mL, the Biomedicus pump-head was configured on the pump with the outlet at the highest point of the holder so that the centrifugal pump-head would be less likely to collect entrained venous air. The second circuit was constructed identical to the CPB circuit used at our institution. The circuit consisted of an open venous reservoir (BMR 4500SG, Baxter Healthcare, Deerfield, IL), and a Spiral Gold hollow fiber oxygenator (Baxter Healthcare Deerfield, IL). A slightly nonocclusive Sarns (Sarns 3 M Health Care, Ann Arbor, MI) roller pump provided blood flow through this circuit. Arterial filters were not placed in either circuit because our equipment did not allow us to detect gaseous microemboli within a time period in multiple locations of the circuit.

Each circuit was connected to an open hard-shell reservoir (HVR 4000, Cobe Cardiovascular, Arvada, CO; Figure 1), which served as the pseudo patient in this study and was maintained at a fixed level above the circuits. All circuits were flushed with CO_2 , de-aired, and primed using

anticoagulated porcine blood. The heat exchanger in each circuit was connected to a Bio-Cal 370 external heater-cooler unit (Medtronic-Biomedicus, Minneapolis, MN) with all circuits maintained at 37°C . Tubing clamps were adjusted on the venous line to maintain a blood level above 800 ± 50 mL in the patient reservoir and the venous reservoir in the third circuit was operated at 200 ± 50 mL, which is the minimum safe reservoir level as suggested by the manufacturer. Oxygenators were ventilated to achieve a perfusate pO_2 of 150 ± 50 mmHg and a pCO_2 of 40 ± 5 mmHg. A tubing clamp was placed proximal to the patient reservoir inlet to maintain a mean arterial line pressure of 200 ± 30 mmHg. A DLP (Medtronic-Biomedicus, Minneapolis, MN) pressure box connected to the venous line of each circuit allowed monitoring of the negative pressure within the venous line.

Venous air was introduced to each circuit using an occlusive roller pump (Sarns 3 M Health Care, Ann Arbor, MI) loaded with quarter-inch tubing. A perfusion adapter connected to a three-way stopcock was placed at the end of the quarter-inch tubing, and a 23-gauge needle was attached to the stopcock. The needle was inserted into the venous line and air was infused at a constant rate for 30 seconds. Arterial bubble counts were taken for 2 minutes after the opening of the air introduction stopcock.

Between trials, the air injection was stopped and the blood was circulated until the Doppler probe detected no bubbles for 5 consecutive minutes. Air that had collected within the cone of the centrifugal pump was removed by manipulating the cone. Care was taken to re-prime the centrifugal head.

Bubble counts were repeated in both the standard and

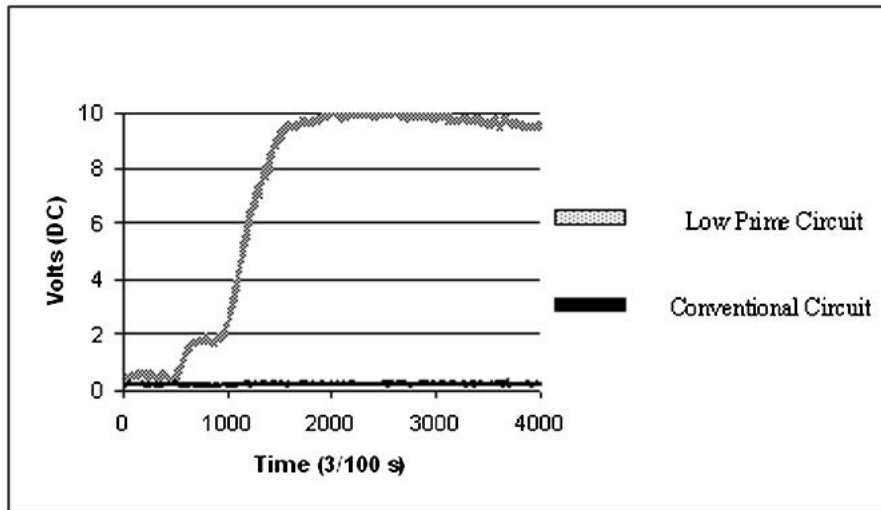


Figure 2. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 2 L/min and venous air introduction rate of 100 mL/min.

low prime circuits at blood flow rates of 2, 4, and 6 L/min. Because the conventional circuit was not capable of maintaining a blood flow rate of 6 L/min using gravity drainage, suction was applied to the venous reservoir by sealing the reservoir and applying negative pressure via an occlusive roller pump (Sarns 3 M Health Care, Ann Arbor, MI). The negative pressure generated in the venous line allowed us to achieve the 6 L/min target blood flow rate. Air was introduced into each circuit, at each blood flow rate, at 100, 200, and 300 mL/min.

The Hatteland CMD 10 gas microemboli detector (Hatteland Ind., Røyken, Norway) was used to monitor the amount of venous entrained air able to traverse the circuit components. The Hatteland CMD 10 uses Doppler SONAR technology to detect and quantify gaseous microemboli. A detector was mounted on the CPB circuit tubing on the arterial line just distal to the arterial filter. Care was taken and ultrasound gel was applied to make sure that no air was in between the Doppler probe and the tubing. The

system was configured so that a one-volt output from the bubble detector correlates to a 40-micron bubble passing through the detector. Data from the bubble detector was collected for 2 minutes after each air introduction into the venous line, with a computer loaded with data collection software (BioBench, National Instruments) and recorded as embolic activity.

RESULTS

With the conditions of a 2 L/min blood flow rate and venous air introduction rates of 100, 200, and 300 mL/min, no gaseous microemboli greater than 40-microns were detected distal to oxygenator of the conventional CPB circuit (Figures 2–4). However, the low-prime CPB circuit was not able to remove all of the venous air and gaseous microemboli distal to the oxygenator produced up to a 10-volt signal in the detector. This suggests an arterial gaseous microemboli load that is 8 to 10 times that observed

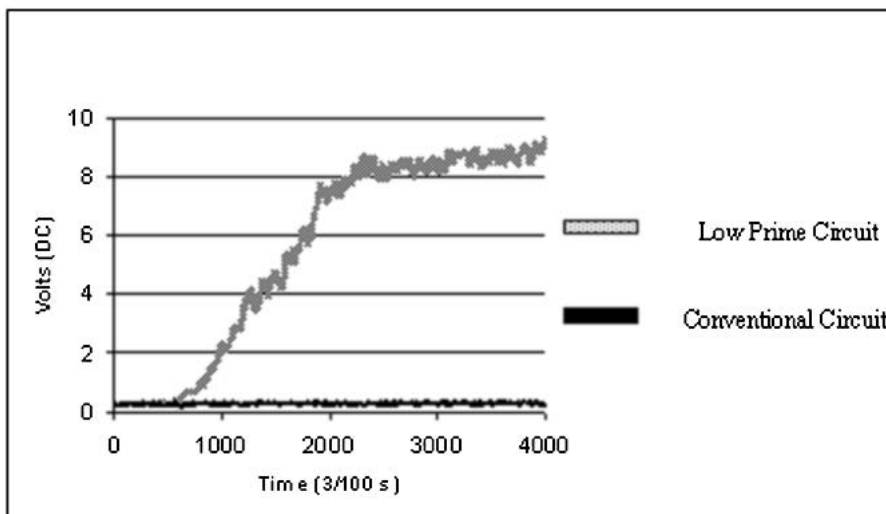
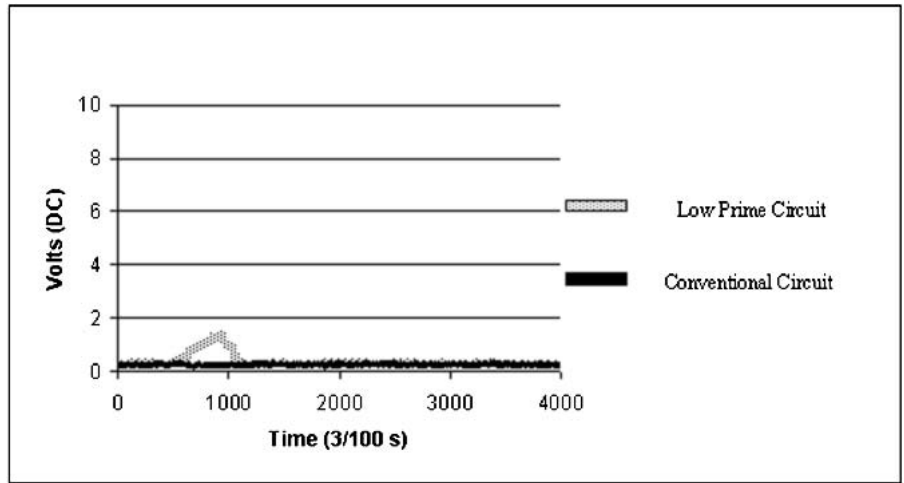


Figure 3. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 2 L/min and venous air introduction rate of 200 mL/min.

Figure 4. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 2 L/min and venous air introduction rate of 300 mL/min.



in the conventional circuit at the same blood flow rate, well above the 1 volt/40-micron level. Gaseous microemboli activity within the low prime circuit at 2 L/min of blood flow and an air introduction rate of 300 mL/min produced a sudden drop in detected microemboli levels at 4 volts. This was caused by the rapid accumulation of air in the centrifugal pump head causing it to de-prime, and halt blood flow through the circuit.

Similar microemboli detection levels were seen at a blood flow rate of 4 L/min through each circuit (Figures 5–7). The conventional circuit consistently had no gaseous microemboli detected greater than 40 μm in size. The low prime circuit transmitted microemboli levels that were up to 10 times those seen in the conventional circuit throughout the majority of the 2-minute interval after venous air introduction at all three air introduction rates. The only time that activity in the low prime circuit fell below 8 volts occurred during acute loss of flow through the circuit caused by the centrifugal pump de-priming.

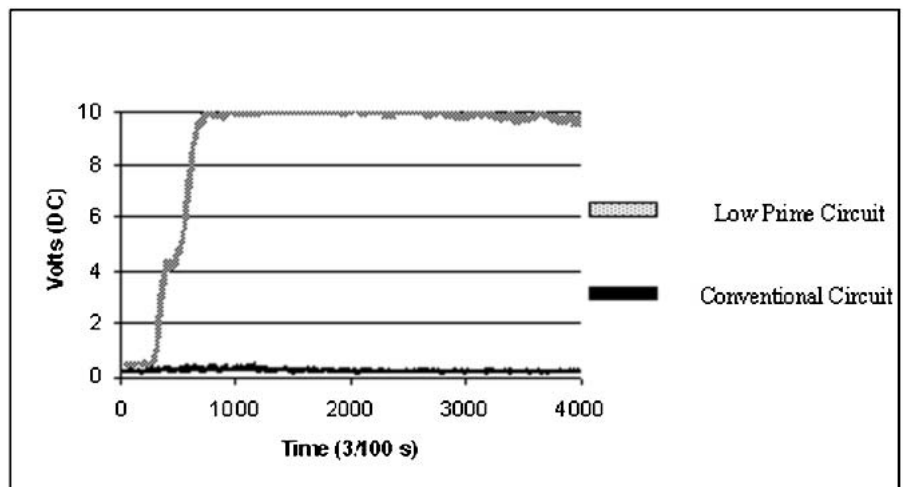
Results seen in the conventional circuit at 6 L/min did detect bubbles larger than 40 μm (Figures 8–10); however,

detected gaseous microemboli activity did not surpass 2 volts and was markedly lower than the 7 + volt levels detected in the low prime circuit at the same blood flow rate. It should also be noted that this trial required the application of greater levels of negative pressure in the venous line of the conventional circuit than at the other two blood flow rates tested. Previous research suggests that it is unclear as to whether this would increase gaseous microemboli levels detected in the arterial line in the conventional circuit (10–12).

DISCUSSION

The results of this study support the hypothesis that a low prime CPB circuit may be less efficient at removing air entrained within the venous line, and may allow gaseous microemboli to traverse the extracorporeal circuit (ECC), thus entering the systemic circulation of the patient. Previous research has shown that a circuit’s ability to remove air from circulation is dependent on the design and components of the circuit (10). Furthermore, the number of

Figure 5. Comparison of arterial gaseous microemboli detected in the 2 minutes following the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 4 L/min and venous air introduction rate of 100 mL/min.



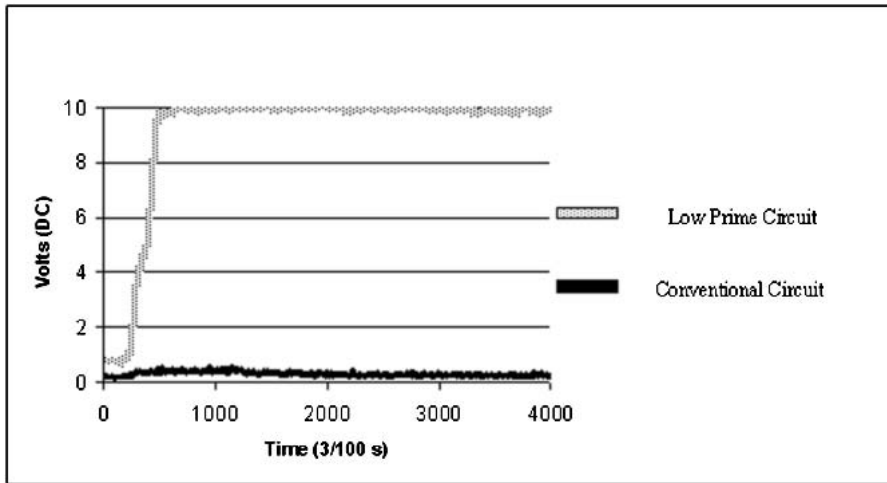


Figure 6. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 4 L/min and venous air introduction rate of 200 mL/min.

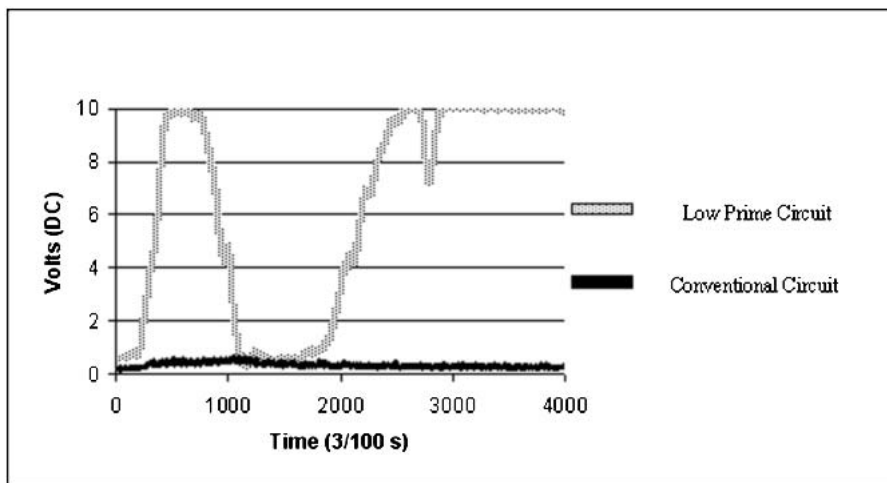


Figure 7. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 4 L/min and venous air introduction rate of 300 mL/min.

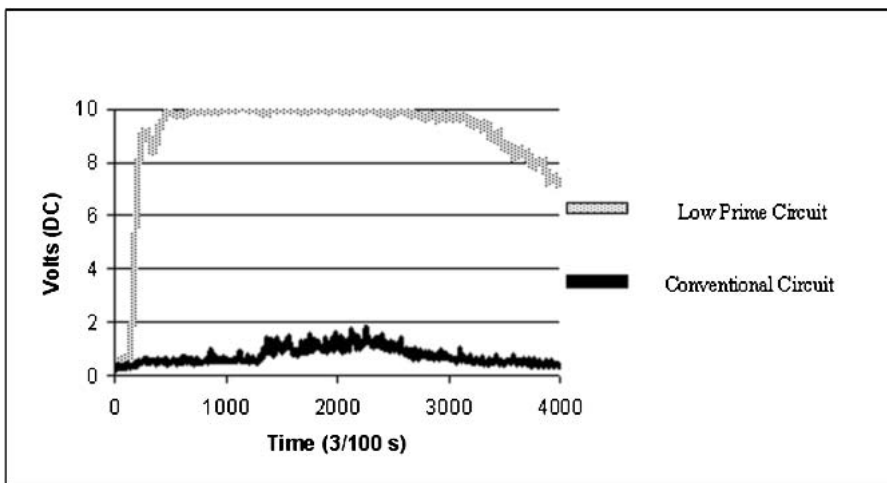


Figure 8. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 6 L/min and venous air introduction rate of 100 mL/min.

gaseous microemboli delivered to the patient was dependent on the circuit components and not the method of venous drainage used in the circuit (10). These are two considerations that should be weighed heavily when de-

bating the advantages and disadvantages of low prime ECCs of various designs.

The morbidity caused by microemboli entering the patient has been well documented. As the ECC has evolved,

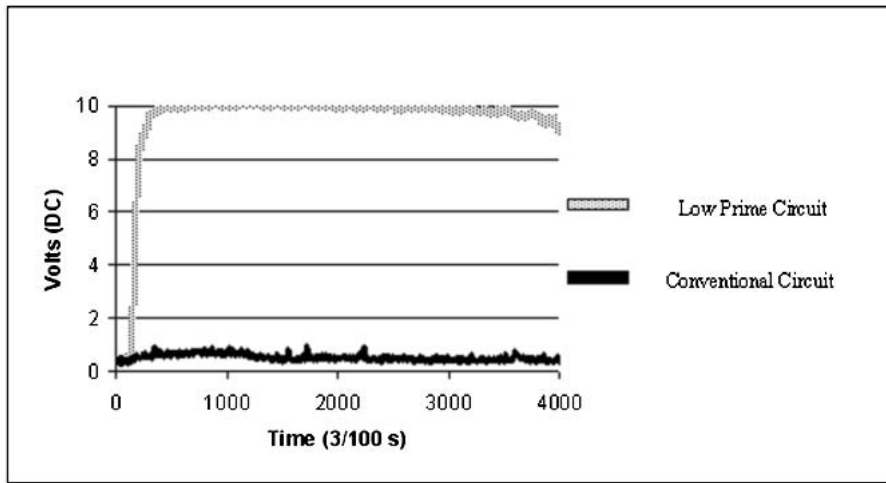


Figure 9. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 6 L/min and venous air introduction rate of 200 mL/min.

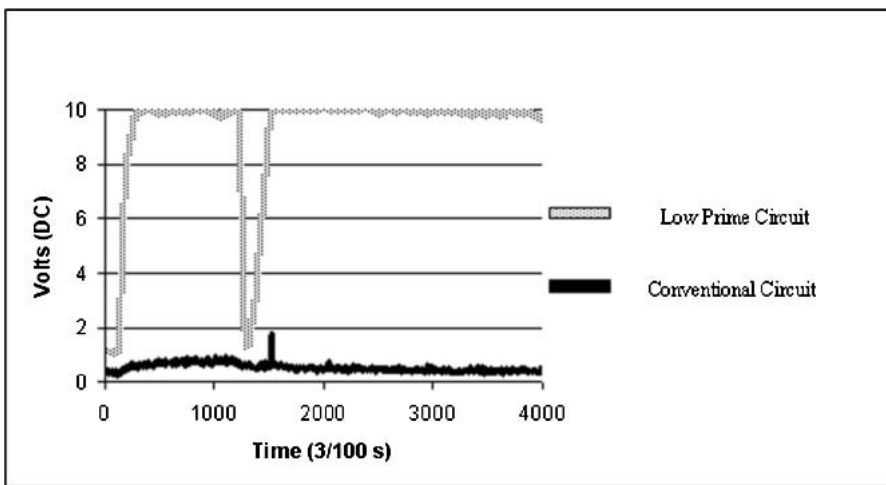


Figure 10. Comparison of arterial gaseous microemboli detected in the 2 minutes after the introduction of venous air in the low-prime and conventional ECC at a blood flow rate of 6 L/min and venous air introduction rate of 300 mL/min.

circuit component design has progressed to newer, safer designs as technology and expense allow. Bubble oxygenators used to be the standard for oxygenating the patient's blood; however, an increased awareness of the gaseous microemboli they produce (13) has aided in the progression of the use of membrane oxygenators in clinical practice. Arterial filters have also been shown to reduce the number of gaseous microemboli in the circuit (5) and have become standard in many CPB circuits. Various studies have shown the ability of components within the circuit to remove gaseous microemboli, but what have eluded researchers are the reasons why a given component is so competent at removing air versus another. Is one membrane oxygenator composed of fibers that are superior at gaseous microemboli removal, or perhaps the blood flow pattern within an arterial filter enables a greater amount of gaseous microemboli to be removed, preventing microemboli sent to the patient. These are questions that require published answers to improve upon the elimination of air within a conventional or a low prime ECC.

The results of this study appear most applicable within

the clinical realm of perfusion. In clinical perfusion, entrained venous air may enter the ECC from improper priming of the venous line at the surgical field or loose purse strings around the venous cannula. Whatever the etiology, venous air is a source of gaseous microemboli that current circuit components are unable to completely remove.

During this study it was observed that the use of an arterial centrifugal pump may make it more difficult for other circuit components distal to the pump to remove air entrained within the blood. It was observed that air visibly seen entering the inlet of the centrifugal pump head was subjected not only to the negative pressure created in the venous line, but also the kinetic activity within the pump head. This appeared to create much smaller individual gaseous emboli in greater quantity, which then become suspended in solution. This "breaking up" of venous air has been confirmed in previous research (12), and may have influenced the greatly increased levels of gaseous microemboli detected within the low prime circuit. To verify this hypothesis, further research should investigate

the differing designs of centrifugal pump heads and determine if the design of the centrifugal pump contributes to the number of gaseous microemboli able to traverse the components of a CPB circuit.

CONCLUSION

Air entrained within the venous line of both circuits resulted in an increased number of gaseous microemboli detected in the arterial line of the low prime CPB circuit as compared to those detected in a conventional circuit. This statement holds true at various blood flow and venous air introduction rates. It should be noted that the conclusion drawn from this study could not be applied to all low prime and conventional ECCs because of the differences in design of circuit components from various manufacturers. Although this is an initial study of the ability of a low prime ECC to remove air entrained in the venous line, the results warrant serious consideration of the design variances of low prime CPB circuits with that of conventional circuits, and the potential for a greater risk of gaseous microemboli seen when using a low prime circuit.

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