Gaseous Emboli Removal Efficiency in Arterial Screen Filters: A Comparative Study

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Abstract

Seven commercially available arterial filters were evaluated for their effectiveness in removing gaseous emboli produced by various sources. All filters were of the screen type and ranged from 20–40 micron pore size.

The first phase of the study consisted of an appraisal of carbon dioxide flushing to facilitate priming. Two filters of each type were used. The first filter was primed without a carbon dioxide flush. The second filter was flushed with carbon dioxide.

Immediately after priming, microemboli were monitored distal to the filters for 10 minutes at 6 L/Min.

In the second phase each filter’s capability of removing gaseous emboli when used in conjunction with a bubble oxygenator was evaluated. Microemboli were alternately monitored pre and post filter at fluid flow rates ranging from 1 to 6 L/Min. At each liter of fluid flow rate the gas:fluid ratio was varied from 1:1 to 3:1.

In the third phase of the study, the efficacy of each filter in removing varying amounts of room air was evaluated. Boluses of room air ranging from 1 to 50 cc. were injected proximal to the filter with microembolism monitoring distally. Injections were made at flow rates ranging from 1 to 6 L/Min.

Although carbon dioxide flushing does facilitate priming the filters, it does not reduce microemboli counts distally. Gaseous emboli removal rates ranged from 69.6 to 100% when used in conjunction with a bubble oxygenator. Air emboli activity distal to the filter after air injections ranged from 0 to 91,000 counts/L of fluid flow.

Introduction

It has been documented by ultrasonic technique that the simplest extracorporeal circuits contain microemboli.\(^1\) The effect of microbubbles in the circulation is not clearly understood. However, there has been a substantial body of evidence accumulated incriminating microemboli as a cause of tissue damage following cardio-pulmonary bypass.\(^3\)\(^,\)\(^4\) Clinically recognizable effects are seen principally in the form of visual field defects, central nervous system dysfunction and respiratory distress.\(^6\)\(^,\)\(^7\)\(^,\)\(^8\) It has also been noted that patients 65 years of age and older have a higher incidence of cerebrovascular accidents associated with cardio-pulmonary bypass.\(^5\) This may be due to their decreased tolerance to the effects of microemboli.

Methods and Materials

The circuit consisted of a Harvey H-1500 oxygenator\(^a\), a Bentley Q-220 cardiotomy reservoir\(^b\), a Stockert modular pump\(^c\), and polyvinyl chloride tubing with compliment connectors and other ancillary hardware (Figure 1). The system was primed with 0.9% sodium chloride solution. The oxygenator which was utilized for microemboli produc-
The cardiotomy was used as a supplementary volume reservoir to compensate for fluid dynamic changes within the oxygenator. Filtered 100% Oxygen was provided via a calibrated flowmeter. A 0-300 mmHg calibrated aneroid manometer was used to monitor line pressure and was maintained at 200 mmHg using a Hoffman clamp distal to the arterial filter.

Ultrasonic transducers with 7.5 MHz lithium niobate crystals were placed proximal and distal to each test filter. Both transducers were calibrated and verified to be of equal sensitivity prior to data collection. A Micropure Model 1100 ultrasonic microcontaminant monitoring system was utilized. The pulser component of the system generates an electrical pulse which stimulates the transducer causing it to emit a pressure wave at a resonant frequency of 7.5 MHz. Any contaminant, solid or gas, in the fluid will result in a reflection of the ultrasonic beam which will in turn re-excite the transducer. This results in an electrical signal being returned through the tuned pre-amplifier to the receiver of the microcontaminant monitor. Signals above a certain size (for this study 40 Mv = 25 microns in diameter) will then be counted by the monitor. The sample rate of the microemboli monitoring system is adjusted to the flow rate, so that each segment of fluid passing the transducer is sampled once. The sample rate is determined by dividing the flow rate by the volume of a cylinder 1.5 cm in length (the length of the active portion of the crystal) and a radius of 0.635 cm (the radius of the lumen of the chamber). This volume is approximately 1.9 ml. For example, at a flowrate of 6L/Min. the sample rate would be 6000 ml/Min./1.9 ml = 3,158 samples/Min. = 53 samples/Sec. Actual counts recorded by the system are then converted to counts /L. using the following formula:

$$\frac{1,000 \times \text{Counts}}{\text{Sample rate} \times \text{seconds} \times .01 \text{ ml}} = \text{Counts/L.}$$

Seven commercially available arterial screen filters were evaluated. Physical characteristics of each filter are listed in Table 1, and filters are illustrated in Figures 2–7.

### Phase I—Priming Evaluation

Two clinical filters of each type were used. The first filter was primed without carbon dioxide and the second filter was flushed with medical grade carbon dioxide via the purge port prior to priming for a 5 minute interval at 2 L/Min. Each filter was primed retrograde via a bypass line at 1 L/Min. Room air/carbon dioxide was displaced with the purge line. To ensure continuity of priming technique, filters were tilted 45° left and right from the upright position allowing any entrapped room air/carbon dioxide to escape. No filter was inverted completely or tapped during the priming procedure. Each filter was then isolated from the circuit by clamping the inlet and outlet ports. A flow rate of 6 L/Min. was instituted via a bypass line. At this time a zero baseline was established and recorded to preclude the possibility of counting emboli generated by the oxygenator. Flow was then redirected through the filter and the line resistance was adjusted to 200 mmHg. with an open purge.

<table>
<thead>
<tr>
<th>FILTER</th>
<th>SURFACE AREA (cm²)</th>
<th>PRIME VOLUME (cc)</th>
<th>HOUSING MATERIAL</th>
<th>FILTER MEDIA</th>
<th>PORE SIZE (microns)</th>
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<tbody>
<tr>
<td>BENTLEY AF-10</td>
<td>700</td>
<td>220</td>
<td>Polycarbonate</td>
<td>Nylon</td>
<td>25</td>
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<tr>
<td>HARVEY H-625</td>
<td>645</td>
<td>195</td>
<td>Polycarbonate</td>
<td>Polyester</td>
<td>33</td>
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<tr>
<td>PALL (Filter)</td>
<td>645</td>
<td>190</td>
<td>Polypropylene</td>
<td>Polyester</td>
<td>40</td>
</tr>
<tr>
<td>DELTA (BTF-377)</td>
<td>645</td>
<td>230</td>
<td>Polycarbonate</td>
<td>Nylon</td>
<td>37</td>
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<tr>
<td>EXTRACORPOREAL (Intercept)</td>
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<td>245</td>
<td>Polycarbonate</td>
<td>Nylon</td>
<td>20</td>
</tr>
<tr>
<td>SHILEY SAF 20</td>
<td>630</td>
<td>215</td>
<td>Polycarbonate</td>
<td>Nylon</td>
<td>20</td>
</tr>
<tr>
<td>SHILEY SAF 40</td>
<td>630</td>
<td>215</td>
<td>Polycarbonate</td>
<td>Nylon</td>
<td>40</td>
</tr>
</tbody>
</table>

FIGURE 1. Circuit diagram used for Phase I, II, and III of the study. T1 and T2 illustrate proximal and distal transducer placement.
FIGURE 2. Bentley (AF-10)—Note that blood enters through a horizontal port located near the base of the unit, then circulates through the pleated filtering medium.

FIGURE 3. Delta (BTF-37)—Blood enters at the bottom and flows up through a divergent cone which reduces blood velocity while curved vanes create a circular flow pattern.

FIGURE 4. Extracorporeal (Intersept)—Blood enters the top of the unit and is oriented down the sides of the filter medium by the top housing cap flow deflector. Since the space between the filter medium and the case is wider at the top than bottom, the blood flows uniformly across the filter medium.

Microemboli counts were monitored distal to the filter for 10 minutes.

Phase II—Filter Efficiency with Oxygenator Produced Microemboli

Each filter was sampled at gas:fluid ratios of 1:1, 2:1, and 3:1. The fluid flow rate for these ratios ranged from 1 to 6 L/Min. For example: 1 L/Min. fluid flow rate was sampled at ratios of 1:1, 2:1, and 3:1. Emboli counts were alternately sampled proximal and distal to the filter for 30 second intervals. Total sample time on each side of the filter was 1 minute.

Phase III—Bolus Injection Study

Each filter was challenged with the injection of varying amounts of room air into the tubing up-
FIGURE 5. Harvey (H-625)—Blood enters tangentially into an "air separator" chamber at the top, flows around the cone and down through the filter medium.

FIGURE 6. Pall (Ultipor)—After blood enters the top of the filter it is diverted to the outside of the support structure. Blood passes through the filtration medium at reduced velocity.

FIGURE 7. Shiley (SAF 20 and SAF 40)—The inlet is positioned on a tangent above the element so that circular flow is established before the perfusate crosses the filter element which is supported by a perforated polypropylene core.

stream of the filter ("injection site" in Figure 1). Three injections were made proximal to the filter in amounts of 1, 3, 5, 10, 20, 30, and 50cc. of air at flow rates ranging from 1 to 6 L/Min. in 1 liter increments. Data collection commenced with initiation of air injection and continued until no microemboli were counted distal to the filter. Each filter was then tapped vigorously to remove any extraneous air trapped in the filter. A stable baseline was established prior to subsequent injections. Data from each group of three injections was averaged to yield one point on the graphs.

Results

Phase I—Carbon dioxide flushing prior to priming generally showed no reduction in microemboli counts as compared with no Carbon dioxide flush, during the 10 minute sampling period immediately after priming (Graphs I-VII).

Phase II—Filter efficiency, expressed as % re-
GRAPH I. Effectiveness of carbon dioxide flushing with the Extracorporeal (Intercept).

GRAPH II. Effectiveness of carbon dioxide flushing with the Shiley (SAF-20).

GRAPH III. Effectiveness of carbon dioxide flushing with the Bentley (AF-10).

GRAPH IV. Effectiveness of carbon dioxide flushing with the Delta (BTF-37).

GRAPH V. Effectiveness of carbon dioxide flushing with the Pall (Ultipor).

GRAPH VI. Effectiveness of carbon dioxide flushing with the Shiley (SAF-40).

GRAPH VII. Effectiveness of carbon dioxide flushing with the Harvey (H-625).
duction of upstream counts recorded with oxygenator produced microemboli ranged from 100% to 85.5% at a gas:fluid ratio of 1:1 (Graph A), 100% to 78.5% at a gas:fluid ratio of 2:1 (Graph B), and 100% to 69.5% at a ratio of 3:1 (Graph C).

Phase III—Generally, there was a commensurate rise in emboli counts downstream of the filter with increasing flow rate after upstream bolus injections. No embolic counts were recorded at a fluid flow rate of 1 L/Min. (Graphs 1–5).

Discussion  
It should be noted that optimum sensitivity with our microemboli detection system is achieved with
GAS : FLUID RATIO = 3 : 1

GRAPH C. Percent removal of previous counts at a gas:fluid ratio of 3:1.

GRAPH 1. Counts released at 2 L/Min. after room air injections of 1 to 50 cc.
GRAPH 2. Counts released at 3 L/Min. after room air injections of 1 to 50 cc.

GRAPH 3. Counts released at 4 L/Min. after room air injections of 1 to 50 cc.
Graph 4. Counts released at 5 L/Min. after room air injections of 1 to 50 cc.

Graph 5. Counts released to 6 L/Min. after room air injections of 1 to 50 cc.
saline rather than with blood due to the differences in their physical characteristics. Reliable detection of emboli as small as 25 microns is possible in saline, whereas blood primes will only allow detection at 50 microns. It seems logical that if one were to compare relative efficiencies between filters with pore sizes ranging from 20 to 40 microns, detection of microemboli should obviously not be limited to 50 microns and greater. Counting gaseous emboli 25 microns and above gave us the opportunity to record the subtle differences among filters. For these reasons, all phases of this study incorporated saline primes. Results on blood may vary from those obtained in this study.

Our findings indicate no decrease in emboli counts using a carbon dioxide flush before priming, although CO₂ flushing does facilitate priming. To maintain priming continuity, filters were not vigorously debubbled as in a clinical situation. Microemboli recorded in this portion of the study were not indicative of presumed activity after clinical debubbling methods, such as tapping, inversion, etc., to clear visual air. The relative difference between priming with or without a carbon dioxide flush were recorded in this study without introducing these variables.

Generally, filter efficiency decreased with increasing pore size when used in conjunction with a Harvey H-1500 bubble oxygenator. However, there were two exceptions: The Delta BTF-37² (37 microns) approached the efficiency range of the 20 micron filters, whereas the Harvey H-625 (33 microns) fell below the efficiency range exhibited by 40 micron filters. This appears to indicate that factors other than pore size such as design and flow dynamics may be substantial contributors to filter efficiency. These observations were reinforced with the bolus injection study, in that efficiency, once again, was not totally dependent on filter pore size.

Conclusions

Overall, our results indicated the Extracorporeal Intersept to be the most efficient. We feel that this performance is the result of an effective combination of pore size and flow dynamics.

The Harvey H-625 was found to be the least effective. If pore size were the only determinant in filter efficacy, one would expect better performance from the Harvey H-625 (33 microns), than the Delta BTF-37 (37 microns), Pall Ultipor (40 microns), or the Shiley SAF-40 (40 microns). However, this is not the case.

Acknowledgment

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References


REFERENCE SOURCES:
- Micropure Inc., Greenville, RI 02909
- Delta Medical, Costa Mesa, CA 92626
- Extracorporeal Medical Specialties, Inc., King of Prussia, PA 19406
- Pall Biomedical Corp., Glen Cove, NY 11542
- Shiley, Inc., Irvine, CA 92714