J Extra Corpor Technol. 2020;52:22–6
The Journal of ExtraCorporeal Technology

To Purge or Not to Purge

Juan D. V. Hugo, BTech;* Alexander Yeung, BSc;† Patrick W. Weerwind, PhD, CCP†

**Department of Cardiothoracic Surgery, Leiden University Medical Center, Leiden, The Netherlands; and †Department of Cardiothoracic Surgery, Maastricht University Medical Center and Cardiovascular Research Institute Maastricht–CARIM, Maastricht, The Netherlands*

Presented at the 55th International Conference of the American Society of Extracorporeal Technology, Boston, Massachusetts, April 29, 2017–May 2, 2017.

Abstract: To remove gaseous microemboli (GME) using an oxygenator with an integrated arterial filter, it is recommended by some manufacturers to purge the oxygenator as an additional safety feature while on bypass. In this in vitro study, we evaluated whether purging of oxygenators with an integrated arterial filter is efficient in reducing GME. Five different types of commercially available contemporary oxygenators with an integrated arterial filter based on progressive filter filtration (1), cascade filtration (1), screen filtration (2), or self-venting (1) were tested for their efficiency in removing GME while keeping the purge line open or closed. A bubble counter was used for pre- and post-oxygenator GME signaling, from which the filter efficiency was computed. Freshly drawn heparinized porcine blood was used at blood flow rates of 3 and 5 L/min. Three units of each oxygenator were tested with its specific reservoir at a fixed volume level of 1,500 mL. GME load was introduced into the venous line at 1,000 mL air/min. Measurements started as soon as GME were detected by the pre-oxygenator probe and then continued for 1 minute. There was no statistically significant difference in filter efficiency between the purged and non-purged groups for specific oxygenators. At a blood flow of 3 L/min, the average filter efficiency stayed approximately invariable when comparing the non-purged and purged groups, where 89.1–88.2% indicated the largest difference between the groups. At a blood flow rate of 5 L/min, the filter efficiency changed in one screen filter group from an average of 55.7% in the non-purged group to 42.4% in the purged group. Other filter efficiencies at the blood flow rate of 5 L/min for non-purged compared with purged groups were, respectively, 98.0 vs. 98.0% (screen filtration), 88.6 vs. 85.8% (self-venting filtration), 82.8 vs. 75.5% (progressive filter filtration), and 65.4 vs. 65.1% (cascade filtration). Based on these results, purging while confronted with continuous GME challenge did not result in an increased filter efficiency. **Keywords:** oxygenator, integrated arterial filter, purging, gaseous microemboli. *J Extra Corpor Technol. 2020;52:22–6*

The risk of gaseous microemboli (GME) during cardiothoracic surgery is irrefutable, and exposure to microemboli during cardiopulmonary bypass (CPB) may contribute to postoperative cognitive dysfunction following surgery as described by Stump (1). Roach and colleagues (2) found the incidence of adverse cerebral events following cardiac surgery to range from 1 to 3%, but more frequent is the occurrence of cognitive disturbances as shown by Newman et al. (3) with their data reporting a wide incidence rate of 20–60%. It is also important to note that methods previously used to detect GME (transcranial Doppler) can only detect microemboli greater than 40 μm, whereas the majority of microemboli that form during CPB are actually less than 40 μm (4,5).

Nowadays, all manufacturers provide availability of oxygenators with an integrated filter because of the desirable reduction in blood contact with a foreign surface area that accompanies these smaller systems and reduced priming volume. During CPB, a safety feature to remove emboli from the system is to purge the oxygenator. Indicated in most manufacturers' brochures, it is advised to purge during the entire CPB procedure to reduce the risk of GME and possibly neurological complications. One of the main concerns is whether GME can be adequately removed from the system with the purge line under a relatively high

Received for publication July 11, 2019; accepted February 24, 2020.
Address correspondence to: Juan D. V. Hugo, Leiden University Medical Center, P.O. Box 9600, 2300 RC Leiden, The Netherlands. E-mail: J.D.V.Hugo@lumc.nl
The senior author has stated that the authors have reported no material, financial, or other relationship with any healthcare-related business or other entity whose products or services are discussed in this article.

blood flow rate. GME removal is influenced not only by the blood flow rate but also by multitudinous factors, which include laminar flow versus turbulent flow, viscosity, velocity, pressure differential, and filter design (6). It should also be stressed that this is an evaluation of the specific oxygenator with regard to purge and no purge in that oxygenator and not different oxygenators with one another.

To optimize testing of GME, handling an in vitro setting is needed where emboli can be controllably created and introduced. This in vitro study compares five contemporary oxygenators with their respective hard-shell reservoirs in their efficiency to remove GME from the system with regard to purging and non-purging of the integrated arterial filter.

MATERIALS AND METHODS

Five different types of commercially available contemporary oxygenators (Table 1) with an integrated arterial filter based on progressive filter filtration (Affinity Fusion, Medtronic, Minneapolis, MN), cascade filtration (Admiral, Eurosets, Medolla, Italy), screen filtration (Inspire 8F, LivaNova, Mirandola, Italy, and Quadrox-i-Adult, Maquet Cardiopulmonary, Rastatt, Germany), or self-venting (Capiox FX25, Terumo Corporation, Tokyo, Japan) were tested for their efficiency in removing GME while keeping the purge line either open or closed.

To measure the GME, a BCC200 (GAMPT, Merseburg, Germany) bubble counter was used. The BCC200 is able to measure the volume and size of microbubbles between 5 and 500 μm; outside this range, it gives a reading "over-range." Ultrasonic Doppler is used as a calculating technique, with a transmission frequency of 2 MHz. It can count up to 1000 GME per second, with blood flows between .5 and 8 L/min. It consists of an arterial and a venous probe, where the first is connected after the component tested (channel 2) and latter before the component (channel 1). By measuring before and after the oxygenator, the efficiency of that unit in removing GME is determined. The efficiency of the oxygenator was computed using the formula for the filter index:

$$\text{Filter index FI} = \left(1 - \frac{\sum N_i \langle \text{output} \rangle}{\sum N_i \langle \text{input} \rangle} \times \frac{\sum N_i \times V_i \langle \text{output} \rangle}{\sum N_i \times V_i \langle \text{input} \rangle}\right) \times 100$$

The BCC200 was placed 15 cm before and after the component being tested. An additional oxygenator (Quadrox-i-Adult) in the mock circulation was connected to a vacuum device (Medi-Vac, Cardinal Health, Dublin, OH) and served as the pseudo patient in the circuit. This technique removes all the air from the system as described elsewhere (7). The circulating blood temperature was maintained at 37°C by a Bio-Cal® 370 heater cooler (Medtronic, Rastatt, Germany) that was connected to the additional oxygenator. A flow probe–calibrated roller pump (LivaNova, Mirandola, Italy) created blood flows of either 3 or 5 L/min to measure whether velocity affects oxygenator efficiency in GME removal.

The mock circuit (as seen in Figure 1) was primed with saline and then replaced with freshly drawn heparinized porcine blood with a hematocrit of 35 ± 2%. The BCC200 probes were calibrated for the circuit tubing to warrant a 99% accuracy for all measurements. A Hoffman clamp ensured a stable line pressure of 200 mmHg (Truwave pressure transducer, Edwards Lifesciences, Irvine, CA) that was connected to a custom-built data acquisition system (M-PAQ, Instrument Development Engineering & Evaluation, Maastricht University Medical Centre, Maastricht, The Netherlands). The circulating blood volume in the reservoirs was maintained at 1,500 mL to ensure conformity and maximal efficiency of each reservoir.

A calibrated air flow meter continuously introduced medical air in the venous line at 1,000 mL/min for a minute. Once the hard-shell reservoir was unable to handle the introduced air, GME subsequently will pass through to the oxygenator.

All the oxygenators were tested with their selective hard-shell reservoirs to conform to the setting in practice. A 1-minute measurement was started as soon as the venous probe (channel 1) detected microbubbles. Three units of each brand-specific oxygenator were tested providing three sets of data per system. Each circuit was tested at 3 L and then 5 L with the circuit being de-aired via the pseudo patient between tests and confirmed with the BCC200. After each system was tested, a completely new circuit with a new pseudo patient was constructed. A test started when a system was confirmed de-aired with the BCC200.

In addition to the specific oxygenator being evaluated for its GME removal efficiency, per the study design, the hard-shell reservoir could also be evaluated when using data from channel 1 immediately distal to the reservoir.

STATISTICAL ANALYSIS

For statistical analysis, IBM SPSS Statistics version 21 (SPSS, Chicago, IL) was used. A Wilcoxon signed-rank test for paired groups was used to evaluate the oxygenators, by comparing the filter efficiency of the specific oxygenator with the purge line open (with purge) and purge line closed (no purge) at blood flow rates of 3 and 5 L/min, respectively. A p-value $< .05$ was considered significant.

RESULTS

All hard-shell reservoirs performed relatively similarly with regard to the amount and volume of GME

Table 1. Different oxygenator and hard-shell reservoir specifications.

	Quadrox-i-Adult	Capiox FX25	Inspire 8F	Admiral AF	Affinity Fusion
Oxygenator					
Maximum blood flow (L/min)	7	7	8	7	7
Priming volume (mL)	335	260	351	190	260
Pore size (μm)	40	32	38	38	25
Arterial filter surface area	430 cm^2	600 cm^2	97 cm^2	135 cm^2	Progressive 2.5 m^2
Hollow fiber material	Polypropylene	Polypropylene	Polyester net	Polypropylene	Polypropylene
Surface coating	Softline	X-coating	Phisio	PC coated	Balance
Purging recommendation	Open	Closed	Open	N/A	Open
Reservoir					
Capacity (L)	4.2	4	4.5	3.2	4.5
Minimum volume (mL)	200	200	150	200	200
Cardiotomy filter pore size (μm)	40	40	41	40	26 and 25
Venous filter pore size (μm)	68	47	41 and 120	80	105

N/A, not available.

delivered to the oxygenator as shown in Table 2, except for the Medtronic reservoir, which caused a decreased amount but increased volume of GME delivered to the oxygenator.

The Inspire 8F and Capiox FX25 proved to be most efficient of the tested oxygenators at a blood flow rate of 3 L/min flow, with both having an efficiency of above 99%. At a flow rate of 5 L/min, the Inspire 8F performed best in this in vitro setup, with 98% efficiency.

An increase in the blood flow rate from 3 to 5 L/min resulted in a reduced computed filtering efficiency in all tested oxygenator–reservoir systems.

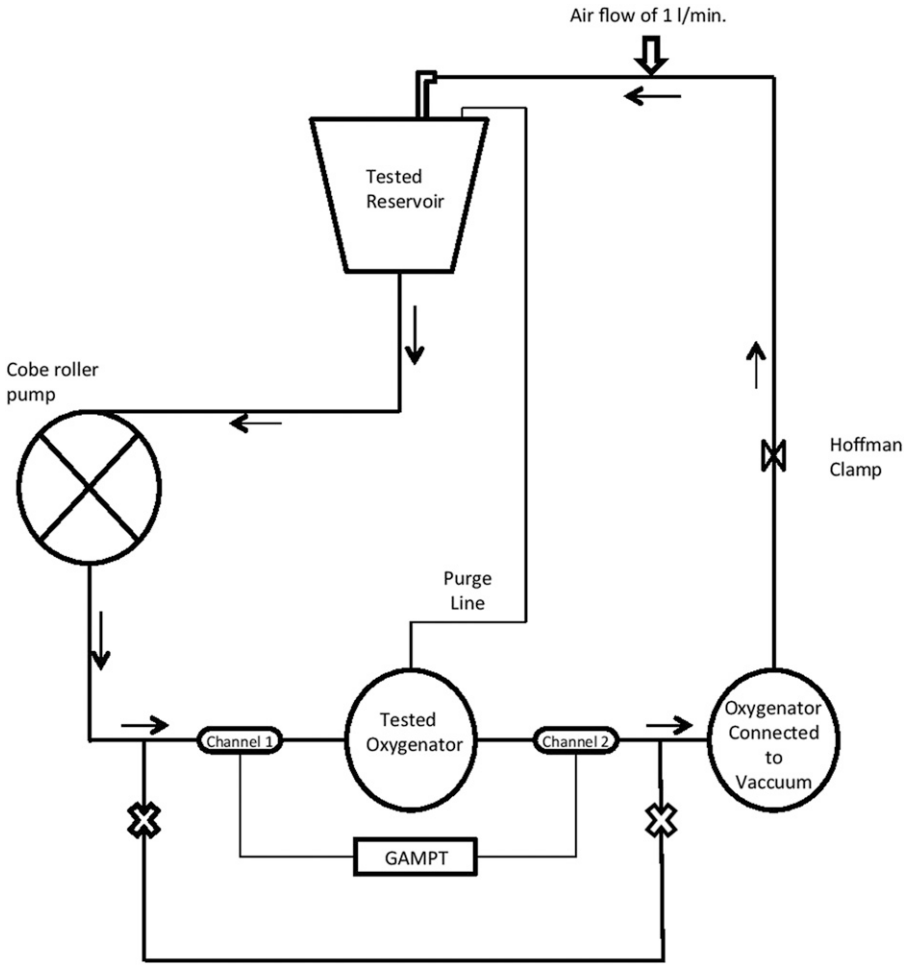

Figure 1. Schematic diagram of the mock circulation used to compare purged and non-purged oxygenators.

Table 2. Amount and volume of GME captured by the venous probe at 3 and 5 L/min with the purge line open (WP) and purge line closed (NP).

Flow (L/min)	Type of Oxygenator	Purge Status	Amount	Volume (μm)
3	Quadrox-i-Adult	NP	7,255	149
		WP	6,856	155
	Inspire 8F	NP	7,825	57
		WP	7,726	66
	Capiox FX25	NP	7,731	45
		WP	7,590	31
	Affinity Fusion	NP	406	494
		WP	211	496
	Admiral	NP	5,917	15
		WP	5,794	12
5 L/min	Quadrox-i-Adult	NP	4,057	434
		WP	3,738	378
	Inspire 8F	NP	5,982	309
		WP	6,253	300
	Capiox FX25	NP	6,462	293
		WP	6,138	331
	Affinity fusion	NP	1,412	475
		WP	1,184	455
	Admiral	NP	5,632	301
		WP	6,508	257

There were no statistically significant differences in filter efficiencies between the purged and non-purged groups for specific oxygenators at either velocity. Rather, all tested systems showed similar filter efficiencies regardless of whether the oxygenator purge line was kept closed. The largest recorded change in average filter efficiency at 3 L/min (Quadrox-i-Adult, $p = .258$) was only .9%, demonstrating how comparably well the oxygenators removed GME at both purge settings. At 5 L/min, the largest observed difference, 13.3%, was also not significant (Quadrox-i-Adult, $p = .109$). The other filter efficiencies are shown in Table 3.

DISCUSSION

We conducted this in vitro study with the intention of investigating whether purging during CPB is beneficial according to the manufacturers' instructions for use. Based on our results, purging while confronted with a continuous GME challenge results in similar filter removal efficiency.

GME removal by an oxygenator with integrated filter capability was influenced by the blood flow rate. As the blood flow rate increases, the oxygenator's efficiency in removing GME decreases. This is also well described in previous studies and is mainly because of the limited amount of time the fiber bundles have for diffusion across the microporous hollow fiber (8). Purging the oxygenator while confronted with continuous GME challenge did not lead to an increased filter efficiency (not statistically significant) when compared with keeping the purge line closed. By contrast, Mathis et al. (9) found purging of pediatric oxygenators to be beneficial for GME handling during CPB. This could indicate that during relatively lower blood flow rates in pediatric CPB, there might be a sense to purging because contact time is a crucial determining factor for GME removal by a filter (9). However, in a study by Lin and colleagues (10)also performed on pediatric oxygenators, the efficiency of purging

Table 3. Statistical data for the efficiency of purged and non-purged oxygenators at blood flow rates of 3 and 5 L/min in removing GME.

		Mean		Median		Wilcoxon
Oxygenator	Blood Flow (L/min)	No Purge	With Purge	No Purge	With Purge	*p*-Value
Admiral AF	3	89.33	88.49	88.33	88.13	1.0
	5	65.42	65.14	65.47	64.32	1.0
Quadrox-i-Adult	3	89.14	88.16	89.67	87.9	.285
	5	55.78	42.47	54.03	42.51	.109
Affinity Fusion	3	94.06	93.18	95.6	92.22	1.0
	5	82.75	75.49	82.4	81.72	.109
Inspire 8F	3	99.89	99.33	99.89	99.58	.109
	5	97.72	97.76	97.53	97.84	.715
Capiox FX	3	99.72	99.82	99.73	99.8	.180
	5	88.58	85.82	87.8	85.93	.109

could be questioned, as there was an increase in GME in some of their purged groups during simulated CPB.

The significance of the interconnection between two forces, namely, buoyancy and drag, when GME are present in a fluid is pivotal in a filter's removal capability. Buoyancy causes microemboli to rise in the fluid and drag the opposing force. Drag results from pressure differences arising from fluid motion; hence, when a fluid has no momentum, drag forces are not present and only buoyancy applies. When fluid is in motion, velocity and viscosity of the fluid greatly affect the drag force. In low flow velocities, as seen, for example, during pediatric CPB, buoyancy can trump drag and cause emboli to rise (11,12). An increase in the size of GME requires higher drag forces to account for buoyancy to keep microemboli in the fluid stream. In a study evaluating the efficiency of purging by a stand-alone arterial filter, it is seen that when the purge flow increases, drag force by the purge flow is also increased and the area it affects (6).

Importantly, most oxygenators are developed to aid buoyancy in the removal of GME, where in theory purging works on the principle that GME that counter drag would be expelled by the transition flow caused by the rapidly accelerating side stream exiting the filter's purge port and entering the cardiotomy reservoir. The remaining GME, mostly smaller because they cannot counter drag force, transition against a filter screen and are either held in place, diffused into the gas interface, and pass through intact screen, or are broken down into smaller GME by the micropore interface (11).

In addition, it could also be argued that the recirculating of microemboli from the purge line causes a breakdown to even smaller microemboli or leads to effervescence due to turbulent flow and possibly makes it even more difficult to remove these newly created smaller GME when they pass through the venous reservoir (13,14). Moreover, because of an extra shunt that might not have the desired effect in improving filter efficiency in GME removal, one could question if stolen blood flow during purging, in the case of an absent flow probe on arterial line and a roller pump as arterial pump, would not have a deleterious influence on the ability to measure or actual DO2.

A possible limitation of the present study refers to the quantification of the embolic load. The pulsed Doppler technique used by the Gampt apparatus assumes sphere-shaped GME, whereas the actual shape may have been nonspherical because of the influence that changes in velocity and shear forces have on GME. This theoretical reasoning may have been inferred with an accurate calculation of the embolic load. Moreover, Stanzel and Henderson (14) recently compared the Gampt BC200® with the EDAC® (Luna Technologies, Blacksburg, VA) device that uses fixed-beam ultrasonic imaging. The Gampt system was found to both under- and overestimate the bubble size depending on the actual flow setting, whereas the EDAC system consistently underestimated the bubble size diameter. Another limitation could arguably be the sample size of each tested oxygenator with regard to the reduced power of statistical testing when smaller sample sizes are analyzed. This could easily be rectified with an increase in the specific group size, but seeing that a new system was used in each testing condition, this had some economical constrains.

To the best of our knowledge, this study has the largest selection of integrated filter capability oxygenators evaluated in a single study when comparing the effect of purging on GME removal efficiency.

In conclusion, this study indicates that there is no beneficial reason for continuous purging of the oxygenator during simulated CPB. This being said when faced with a macro air challenge, the benefits of buoyancy might trump drag force and give purging preference in a clinical setting.

REFERENCES

1. Stump DA. Embolic factors associated with cardiac surgery. Semin CardioThorac Vasc Anesth. 2005;9:151–2.
2. Roach GW, Kanchuger M, Mangano CM, et al. Adverse cerebral outcomes after coronary bypass surgery. Multicenter study of perioperative Ischemia Research and Education Foundation investigators. N Engl J Med. 1996;335:1857–63.
3. Newman MF, Kirchner JL, Phillips-Bute B, et al. Longitudinal assessment of neurocognitive function after coronary-artery bypass surgery. N Engl J Med. 2001;344:395–402.
4. Su XW, Undar A. Brain protection during pediatric cardiopulmonary bypass. Artif Organs. 2010;34:91–102.
5. Win KN, Wang S, Undar A. Microemboli generation, detection and characterization during CPB procedures in neonates, infants, and small children. Am Soc Artif Intern Organs J. 2008;54:486–90.
6. Herbst DP. Effects of purge-flow rate on microbubble capture in radial arterial-line filters. J Extra Corpor Technol. 2016;48:105–12.
7. Rudolph JL, Tilahun D, Treanor PR, et al. Use of a large bore syringe creates significantly fewer high intensity transient signals (HITS) into a cardiopulmonary bypass system than a small bore syringe. Perfusion. 2006;21:67–71.
8. Johagen D, Appelblad M, Svenmarker S. Can the oxygenator screen filter reduce gaseous microemboli? J Extra Corpor Technol. 2014;46: 60–6.
9. Mathis RK, Lin J, Dogal NM, et al. Evaluation of four pediatric cardiopulmonary bypass circuits in terms of perfusion quality and capturing gaseous microemboli. Perfusion. 2012;27:470–9.
10. Lin J, Dogal NM, Mathis RK, et al. Evaluation of Quadrox-i and Capiox FX neonatal oxygenators with integrated arterial filters in eliminating gaseous microemboli and retaining hemodynamic properties during simulated cardiopulmonary bypass. Perfusion. 2012;1: 1–9.
11. Herbst DP. The effects of pressure on gases in solution: Possible insights to improve microbubble filtration for extracorporeal circulation. J Extra Corpor Technol. 2013;45:94–106.
12. De Somer F. Evidence-based used, yet still controversial: The arterial filter. J Extra Corpor Technol. 2012;44:27–30.
13. Myers GJ, Voorhees C, Haynes R, et al. Post-arterial filter gaseous microemboli activity of five integral cardiotomy reservoirs during venting: An in vitro study. J Extra Corpor Technol. 2009;41:20–7.
14. Stanzel RDP, Henderson M. An in vitro evaluation of gaseous microemboli handling by contemporary venous reservoirs and oxygenator systems using EDAC. Perfusion. 2016;31:38–44.