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Water Condensation and Gas Exchange Correlation in Different Models and Fibers of Blood Oxygenators: "How Can We Improve Performance?"

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Abstract: Creation of water condensation in blood oxygenators is a phenomenon that is constantly present during cardiopulmonary bypass and in medium- to long-term extracorporeal life support. Clinical observation of condensation at the oxygenator exit is still a common event normally associated with sudden cooling of the gas flow proximal to the outlet cover (after exiting the fiber bundle), where the warming effect of blood is no longer present. Condensation could progressively obstruct a certain number of fibers, reducing the efficiency of gaseous exchange in the membrane of the oxygenator surface. The study included 48 patients divided into four oxygenator groups of 12 each: group 1 used an Inspire 6 F oxygenator from Livanova; group 2, an Affinity Fusion from Medtronic; group 3, an Alone from Eurosets, and group 4, an ECMO Alone from Eurosets; while the last group used an ECMO Alone oxygenator from Eurosets with polymethylpentene fiber. Each group of oxygenators comprising 12 patients were divided into two groups, namely, A and B, with six patients in each group. Group A used mild hypothermia during the procedure, and group B of six patients used normothermia; Groups A and B were further subdivided into four subgroups: A1, A2, B1, and B2, each consists of three patients; subgroups A1 and B1 used negative aspiration (−8 mmHg) measuring humidity (%) and temperature (°C) in the gas oxygenator output; consequently, a measurement system was necessary to be created; Subgroups A2 and B2 did not use negative aspiration in the oxygenator outlet. No statistically significant difference for PaO_2 and humidity values was found in polypropylene and polymethylpentene oxygenators with mild hypothermia management with vacuum and without vacuum in the gas outlet in the first 60 minutes and 60 minutes later during cardiopulmonary bypass. In normothermia, a statistically significant difference in the PaO_2–humidity relationship was observed with polypropylene and polymethylpentene fiber models. Results of this study show an inversely proportional correlation between gas exchange and condensation in statistically significant values during the use of normothermia and a reduction in oxygenation performance, in polypropylene and polymethylpentene fiber oxygenators. *J Extra Corpor Technol. 2020;52:43–51*

Cardiopulmonary bypass (CPB) is performed during open-heart surgeries when patients' heart and lungs need to stop functioning, as well as during extracorporeal life support for patients with severe respiratory and/or heart diseases. The blood is collected from the venous circulation and diverted to an extracorporeal circuit, where it is oxygenated and pressurized before being redirected to the arterial systemic circulation. A blood pump replaces the heart function, while a blood oxygenator provides the gaseous exchange. Blood oxygenators have experienced several changes in the past 50 years (1), and currently, the oxygenating module consists of a bundle of polymeric hollow fibers that carry the gaseous mixture (usually, nitrogen and oxygen), with the blood flowing externally around them. The microporous semipermeable membrane of the fibers allows for oxygen (O_2) and carbon dioxide (CO_2) exchange between the extraluminal (blood) and intraluminal (gas) flows. Because of the microporous nature of the membrane, blood plasma can evaporate at the liquid–membrane interface and diffuse as water vaporizes through the pores into the intraluminal gas phase. Despite the fact that the supplied gaseous mixture is dry, because of the large water vapor mass

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Table 1. Sample characteristics.

	Groups A and B (n = 48)
Age (year), mean	68 (68.7)
Body surface area (m^2)	1.85
Pre-CPB hematocrit (%), mean ± SEM	35
Pre-CPB Hb (g/dL)	11.5
CPB Time (min)	120
Cardiac index (L/min/m^2)	2.4
Activated clotting time in CPB (sec), mean ± SEM	525 ± 35

Values presented in table are mean values.

transfer coefficients of the microporous membranes, the gas is expected to become highly saturated with a short fiber length. The current study focuses on the analysis of different models of oxygenators and different types of fibers, in terms of production of water condensation to the oxygenator exhaust outlet, and oxygenation performance, in terms of PaO_2/FiO_2 and $PaCO_2$/LPM air/blood, and (P (E) CO_2) oxygenator exhaust PCO_2, during rewarming in CPB. Condensation could progressively obstruct a certain number of fibers, reducing the effective membrane surface area for gaseous exchange. Therefore, a number of studies investigated possible strategies for preventing or limiting water condensation: by warming the gas at the inflow, or outflow section, creating a warm environment around the whole oxygenator, or blowing off the condensed droplets from the clogged fibers by gas flushing. In this study, two different temperature managements were compared and analyzed in the four models of oxygenators, which are widely used in clinical practice during cardiopulmonary bypass: for mild hypothermia, without a heat exchanger managing temperatures leaving the oxygenator at 33.9°C and nasopharyngeal temperature at 33.8°C, whereas for normothermia, with a heat exchanger managing temperatures leaving the oxygenator at 36.4°C and nasopharyngeal temperature at 36.2°C and the two respective heating phase nasopharyngeal temperature at 36.7°C. There are two types of management of condensation at the oxygenator output: with negative pressure (−8 mmHg) and without negative pressure. Each oxygenator ensures a constant 50% of FiO_2 maintained as a result of the benchmark of nadir since the beginning of CPB for values in the arterial blood between 150 and −220 mmHg of PaO_2; liter per minute of air (mean value 2.6 L/min) was compared with the technical characteristics of the oxygenator and with the blood flow for the maintenance of values of (40 mmHg) $PaCO_2$. The increase in FiO_2 required to maintain PaO_2 ranges during the extracorporeal circulation was recorded within the groups, and the percentage (%) of humidity and water loss in the oxygenator outlet (mL) was measured together with (P (E) CO_2) oxygenator exhaust PCO_2.

METHODS

Forty-eight patients similar in characteristics were recruited (Table 1), undergoing elective cardiac surgery using mild hypothermic and normothermic CPB. Surgery included both cardiac bypass grafts and aortic valve replacement.

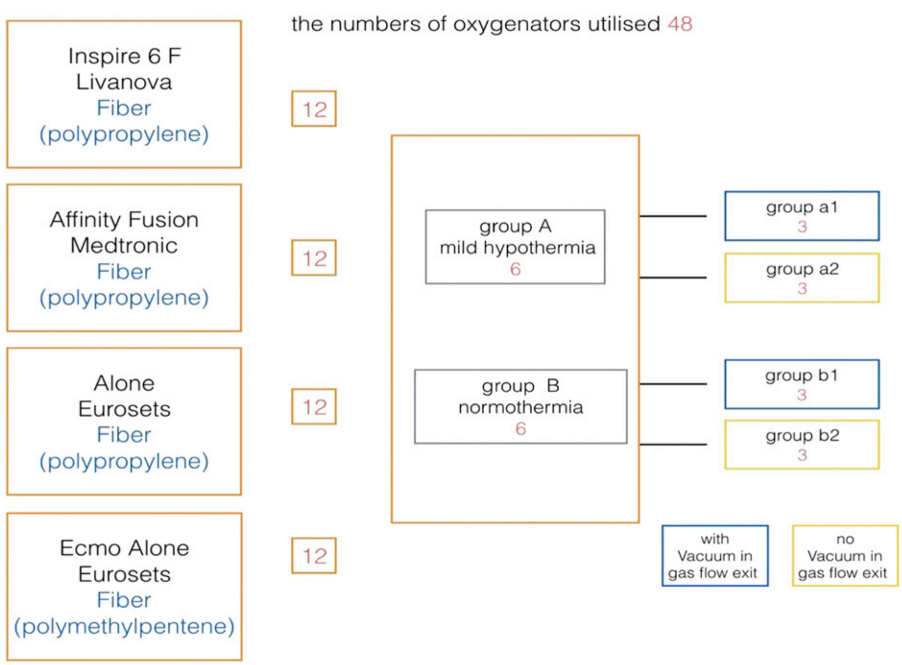

Figure 1. Study design.

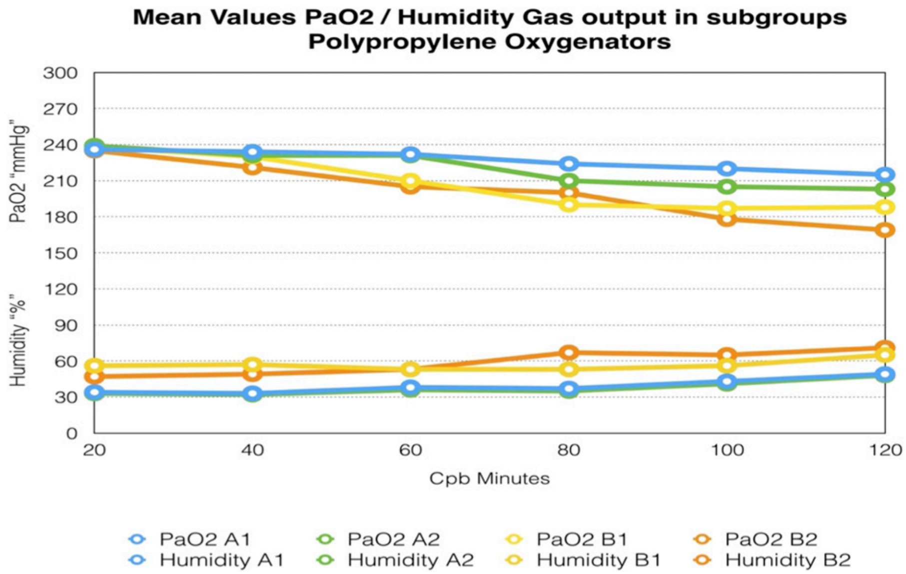

Figure 2. System for negative aspiration for measurement of humidity (%) and temperature (°C) in the oxygenator output.

Institutional approval for the study was obtained. The study was approved without requiring informed consent for the research because all the procedures were part of the routine. A Stockert S5 (Livanova, Italy) heart and lung machine and the same circuit cannula were used in both groups. The priming volume was 1,000 mL in group A and 700 ± 50 mL in group B ($p < .001$). Heparin reversal was obtained with .5–.75 mg of protamine for every 100 units of heparin (2). Anesthesia was obtained by fentanyl, midazolam, and rocuronium. Concentrated red cells were transfused whenever hemoglobin (Hb) concentrations decreases below 6 g/dL during surgery or below 8 g/dL during the intensive care unit stay. A closed circuit for cardioplegia with a heat exchanger with an infusion syringe pump in series was used; Saint Thomas solution with procaine (3) and a DO_2 management monitoring system (Landing Eurosets, Medolla, Italy) (4) were used. During CPB, a centrifugal (pump BioMedicus BPX80 Medtronic) was used to perfuse the patients in each model of the oxygenator (Inspire™ 6 F with an integrated filter Livanova, Affinity Fusion Medtronic, Alone Eurosets with an integrated filter, and Alone ECMO Eurosets). An integral heat exchanger was used, and the

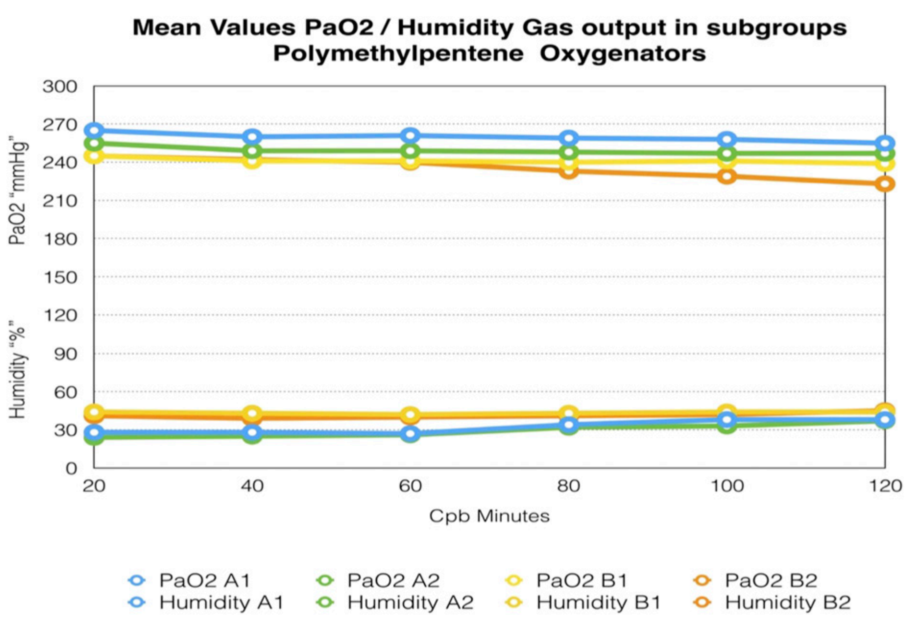

Figure 3. Measurement of humidity (%) and temperature (°C) in the oxygenator output without aspiration.

Figure 4. System for negative aspiration and measurement, which composes of four components: (1) retrofit tank of the heat exchanger for the accumulation of steam.

pump flow had a cardiac index of 2.4 L/m^2 during normothermia, and a mean nadir of $DO_{2indexed}$ (oxygen delivery index) was managed during procedures (298 mL/min/m^2) (4). Gas flow through the oxygenator was adjusted to maintain the laboratory-measured blood gas $PaCO_2$ (partial pressure of carbon dioxide) at 40 mmHg (i.e., alpha-stat management of CPB) (5). Continuous measurement of P (E) CO_2 (oxygenator exhaust PCO_2) during CBP was performed by connecting the catheter of a side stream capnograph (Datex-Ohmeda AS3, Datex-Ohmeda, Helsinki, Finland) end to the side of the oxygenator exhaust, using a short length of silicone rubber tube and a disposable Luer-Lock T-connector (6). The calibration of the capnograph was limited to the manufacturer's routine recommendations (7). The blood gas samples were taken from the arterial port of the oxygenator during bypass and were measured within 10 minutes, with a blood gas analyzer (Radiometer ABL 725, Radiometer Medical A/S Copenhagen, Denmark) set to measure at 37°C (8).

Study Design

The study included 48 patients divided into four groups of 12 each: the first group used an Inspire 6 F oxygenator from the Livanova group, the second group used an oxygenator from the Affinity Fusion Medtronic group, the third group used an Alone oxygenator from Eurosets with polypropylene fiber, and the last group used an Ecmo Alone oxygenator from Eurosets with polymethylpentene fiber (Figure 1). Each group of oxygenators comprising 12 patients was divided into two groups, namely, A and B with six patients in each group. Group A used mild hypothermia during the procedure, and group B of six patients used normothermia. Groups A and B were further subdivided into four subgroups: A1, A2, B1, and B2, each made up of three patients. Subgroups A1 and B1 used negative aspiration (−8 mmHg) measuring the humidity (%) and temperature (°C) in the gas oxygenator output; consequently, a measurement system was necessary to be created. The subgroups A2 and B2 did not use negative aspiration in the oxygenator outlet (9).

Group A of six patients which used mild hypothermia without a warming unit were managed in the first 60 minutes with a nasopharyngeal temperature of 33.9°C and an arterial blood temperature of 33.8 and was heated after 60 minutes, which lasted for 17 minutes by setting the heater unit to 36.7°C, reaching a nasopharyngeal temperature of 36.3°C and an arterial blood temperature of 36.5. Group B of six patients were managed in normothermia, and the heater unit

Table 2. *p*-values subgroups; PaO_2 and humidity during Times 1 and 2.

Subgroup	PaO_2 Polypropylene *p*-Value (Times 1 and 2)	PaO_2 Polymethylpentene *p*-Value (Times 1 and 2)	Humidity in Outlet Oxygenators Polypropylene *p*-Value (Times 1 and 2)	Humidity in Outlet Oxygenators Polymethylpentene *p*-Value (Times 1 and 2)
A1	.078	.098	.086	.086
A2	.068	.071	.076	.069
B1	.046	.066	.038	.049
B2	.036	.046	.032	.048

Table 3. Time 2 (results after 60 minutes during CPB), gas exchanges/humidity gas outlet in subgroups, and mean values.

Oxygenators models (n = 48)	Mild Hypothermia, Vacuum in Outlet Oxygenator, A1 (n = 3)		Mild Hypothermia, No Vacuum in Outlet Oxygenator, A2 (n = 3)		Normothermia, Vacuum in Outlet Oxygenator, B1 (n = 3)		Normothermia, No Vacuum in Outlet Oxygenator, B2 (n = 3)	
	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators
Inspire 6F Livanova (n = 12)	PaO_2 225 ± 2 mmHg	50%	PaO_2 218 ± 4 mmHg	48%	PaO_2 197 ± 4 mmHg	65%	PaO_2 187 ± 1 mmHg	71%
	$PaCO_2$ 40 ± 4 mmHg		$PaCO_2$ 38 ± 2 mmHg		$PaCO_2$ 38 ± 2 mmHg		$PaCO_2$ 43 ± 3 mmHg	
Gas blender	Air/oxygen (1.9 L/min/ 50%)		Air/oxygen (1.9 L/min/ 50%)		Air/oxygen (2.1 L/min/ 50%)		Air/oxygen (2.1 L/min/ 50%)	
Affinity Fusion Medtronic (n = 12)	PaO_2 235 ± 5 mmHg	44%	PaO_2 233 ± 4 mmHg	39%	PaO_2 205 ± 2–3 mmHg	61%	PaO_2 189 ± 2–3 mmHg	59%
	$PaCO_2$ 39 ± 3 mmHg air/ oxygen (1.8 L/min/50%)		$PaCO_2$ 40 ± 2 mmHg		$PaCO_2$ 36 ± 2 mmHg		$PaCO_2$ 37 ± 3 mmHg	
Gas blender	Air/Oxygen L/min/50% (1.8 L/min/50%)		Air/oxygen (1.8 L/min/ 50%)		Air/oxygen (2.2 L/min/ 50%)		Air/oxygen (2.2 L/min/ 50%)	
Alone Eurosets (n = 12)	PaO_2 224 ± 2–3 mmHg	43%	PaO_2 219 ± 2 mmHg	42%	PaO_2 209 ± 2 mmHg	52%	PaO_2 188 ± 2 mmHg	56%
	$PaCO_2$ 39 ± 2		$PaCO_2$ 38 ± 4		$PaCO_2$ 36 ± 2		$PaCO_2$ 39 ± 2	
Gas blender	Air/oxygen (2.5 L/min/ 50%)		Air/oxygen (2.5 L/min/ 50%)		Air/oxygen (2.7 L/min/ 50%)		Air/oxygen (2.7 L/min/ 50%)	
ECMO Alone Eurosets (n = 12)	PaO_2 255 ± 3 mmHg	38%	PaO_2 247 ± 2 mmHg	37%	PaO_2 239 ± 1 mmHg	44%	PaO_2 223 ± 2 mmHg	45%
	$PaCO_2$ 39 ± 3		$PaCO_2$ 36 ± 2		$PaCO_2$ 35 ± 2		$PaCO_2$ 38 ± 2	
Gas blender	Air/oxygen (2.0 L/min/ 50%)		Air/oxygen (2.0 L/min/ 50%)		Air/oxygen (2.2 L/min/ 50%)		Air/oxygen (2.2 L/min/ 50%)	

Table 4. Total accumulated water loss (mL) in subgroups and mean values.

Oxygenators Models (Total n = 48)	A1 (n = 3) Total Accumulated Water Loss (mL)	A2 (n = 3) Total Accumulated Water Loss (mL)	B1 (n = 3) Total Accumulated Water Loss (mL)	B2 (n = 3) Total Accumulated Water Loss (mL)
Inspire 6F Livanova (n = 12)	2.6	3.1	5.1	6.1
Affinity Fusion Medtronic (n = 12)	2.4	2.8	4.3	5.3
Alone Eurosets (n = 12)	1.9	2.3	4.3	5.6
ECMO Alone Eurosets(n = 12)	2.1	2.2	3.2	4.2

was set at a temperature of 36.5°C with nasopharyngeal temperature of 36.2°C and an arterial blood temperature of 36.4 for the duration of CPB. Groups A and B were subdivided into four subgroups, each made up of three patients; subgroups A1–B1 applied negative aspiration (−8 mmHg) with measurement of humidity (%) and temperature (°C) in the gas oxygenator output with a system created (Figures 2 and 3) and composed of four components (Figure 4): retrofit tank of the heat exchanger for the accumulation of steam, connected to a vacuum manometer (Amvex Vacuum Regulators. Amvex®) and inside it was placed a small tank for the loss of water and a thermo hygrometer (vanguard hydroponics). Subgroups A2–B2 did not use negative aspiration in the oxygenator outlet (Figure 4).

Statistical Analysis

The student *t*-test was used to compare continuous variables between groups. A p value of $<.05$ was considered significant. Two measurement times of the parameters were identified in the four subgroups: Time 1 in the first 60 minutes of CPB conduction (in the beginning and half of the procedure), Time 2 after 60 minutes CPB conduction (in the half and end of the procedure). The mean values of gas exchange PaO_2 and $PaCO_2$ were collected in these two time frames; temperature, exhaust PCO_2, and humidity in the gas outlet of oxygenator were measured. After 10 minutes, the procedure suction was placed (−10 mmHg) in the gas outlet of the oxygenator, storing and measuring the residual water in the tank.

RESULTS

The gas flow temperature exiting the gas blender was reported at an average of 18°C with .01% humidity, and the temperature of the operating room was 19°C with 39% humidity. No coagulation problems in the administration of heparin and variation of pressure drop in all oxygenators were shown during the procedures in all study groups.

The total time taken by the oxygenator in the four groups was 120 minutes (mean value), during the procedures, and the hematocrit values were 26% and 28%. The initial ventilation and oxygenation nadir values were set: 50% FiO_2 and 1.9–2.7 liters of air flow per minute, 4.8 L/min of blood flow (mean values). A different variability in the oxygenating performance and production of steam (Tables 2 and 3) and water loss (Table 4) was found in relation to temperature management and humidity evacuation in the four oxygenator models analyzed. No statistically significant difference was found in the first 60 minutes and 60 minutes later in oxygenator use, for PaO_2 and humidity values in polypropylene and polymethylpentene fiber models, during mild hypothermia management with vacuum (subgroup A1) and without vacuum (subgroup A2) in the gas outlet (Table 5). A statistically significant difference for PaO_2 and humidity values in polypropylene and polymethylpentene fiber models was found, in normothermia management with vacuum (subgroup B1) and without vacuum (subgroup B2) in the gas outlet (Table 5) (Figures 5 and 6).

DISCUSSION

The present study shows that all the oxygenator models have presented excellent quality standards during the CPB procedure, in terms of gas and thermal exchange. There are different temperature management techniques during CPB. In this study, we observe during blood heating an increase in humidity and water loss in oxygenator gas outlet and a decrease in PaO_2 (10). The production of condensation and water loss from the gas oxygenator gas output has been treated in various studies (11); however, a strong correlation with gas exchange has never been highlighted (1). Above all, it would seem that each oxygenator model has different parameters and trends in humidity production and oxygenating performance (12). The goal was to describe various approaches to find the most appropriate management for a type and design of the oxygenator that will ensure good gas exchange and performance for long periods of extracorporeal procedures (13). Two temperature managements and two methods have been found for evacuating the condensation from the oxygenator gas outlet, in four models of oxygenators: two types with polypropylene fibers and two types with polymethylpentene fibers because of the microporous nature of the membrane.

Table 5. Time 1 (results of first 60 minutes during CPB), gas exchange/humidity gas outlet in subgroups, and mean values.

Oxygenators models (n = 48)	Mild Hypothermia, Vacuum in Outlet Oxygenator, A1 (n = 3)		Mild Hypothermia, No Vacuum in Outlet Oxygenator, A2 (n = 3)		Normothermia, Vacuum in Outlet Oxygenator, B1 (n = 3)		Normothermia, No Vacuum in Outlet Oxygenator, B2 (n = 3)	
	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators	Gas Exchange	Humidity in Gas Outlet Oxygenators
Inspire 6F Livanova (n = 12)	PaO_2 235 ± 3–6 mmHg $PaCO_2$ 38 ± 4 mmHg	37%	PaO_2 215 ± 4 mmHg $PaCO_2$ 39 ± 2 mmHg	33%	PaO_2 210 ± 2 mmHg $PaCO_2$ 39 ± 2 mmHg	63%	PaO_2 201 ± 2 mmHg $PaCO_2$ 39 ± 3 mmHg	59%
Gas blender	Air/oxygen (1.9 L/min/50%)		Air/oxygen (1.9 L/min/50%)		Air/oxygen (2.1 L/min/50%)		Air/oxygen (2.1 L/min/50	
Affinity Fusion Medtronic (n = 12)	PaO_2 255 ± 2–3 mmHg $PaCO_2$ 37 ± 3 mmHg	34%	PaO_2 235 ± 2–3 mmHg $PaCO_2$ 38 ± 3 mmHg	29%	PaO_2 205 ± 2–3 mmHg $PaCO_2$ 35 ± 3 mmHg	59%	PaO_2 199 ± 2–3 mmHg $PaCO_2$ 37 ± 3 mmHg	55%
Gas blender	Air/oxygen (1.8 L/min/50%)		Air/oxygen (1.8 L/min/50%)		Air/oxygen (2.2 L/min/50%)		Air/oxygen (2.2 L/min/50%)	
Alone Eurosets (n = 12)	PaO_2 234 ± 2–3 mmHg $PaCO_2$ 35 ± 3	36%	PaO_2 224 ± 2 mmHg $PaCO_2$ 38 ± 3	32%	PaO_2 209 ± 2 mmHg $PaCO_2$ 36 ± 2	51%	PaO_2 200 ± 2 mmHg $PaCO_2$ 36 ± 2	46%
Gas blender	Air/oxygen (2.5 L/min/50%)		Air/oxygen (2.5 L/min/50%)		Air/oxygen (2.7 L/min/50%)		Air/oxygen (2.7 L/min/50%)	
ECMO Alone Eurosets (n = 12)	PaO_2 265 ± 3 mmHg $PaCO_2$ 30 ± 3	28%	PaO_2 255 ± 2 mmHg $PaCO_2$ 38 ± 2	24%	PaO_2 245 ± 2 mmHg $PaCO_2$ 38 ± 2	42%	PaO_2 245 ± 2 mmHg $PaCO_2$ 39 ± 2	41%
Gas blender	Air/oxygen (2.0 L/min/50%)		Air/oxygen (2.0 L/min/50%)		Air/oxygen (2.2 L/min/50%)		Air/oxygen (2.2 L/min/50%)	

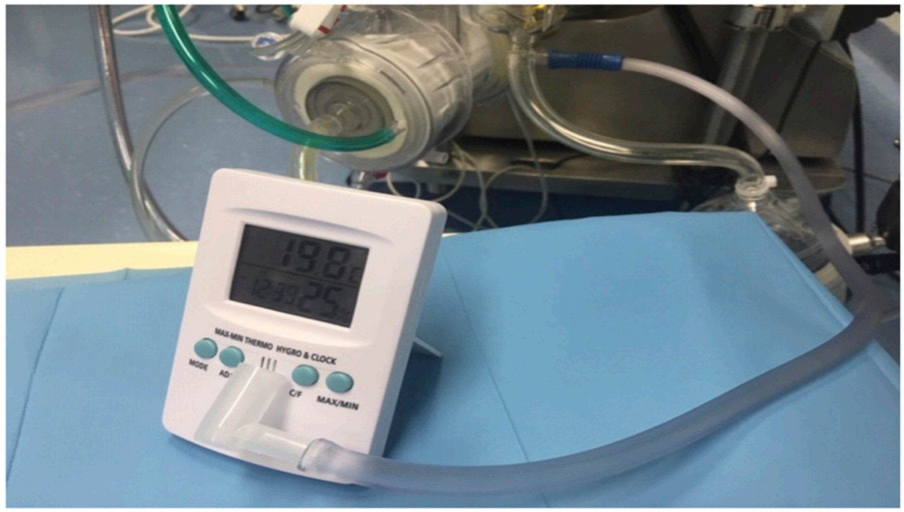

Figure 5. Mean values of PaO_2/humidity gas output in polypropylene oxygenators during procedures.

According to previous studies, blood plasma can evaporate at the liquid–membrane interface and diffuse as water vapor diffuses across the pores into the intraluminal gas phase (14). Despite being supplied as a dry gaseous mixture, because of the large water vapor mass transfer coefficients of the microporous membranes, the gas is expected to become highly saturated within a short fiber length (15).

Another technique that can help solve the problem of low PaO_2 due to the formation of condensation in the fiber is the concept of "Sigh-ing" the oxygenator: turn up the sweep flow to 9–10 LPM for 30 seconds or so and blow out the moisture to improve the PaO_2. It would seem that limiting the use of the heat exchanger and the association of a negative pressure of −8 mmHg to continuously remove the production of steam from the gas outlet improves the values of PaO_2 for the standard FiO_2 (50%) in all types of fibers and models of oxygenators. Limitations of this study are as follows: the formation of condensation and water loss are very complex mechanisms, the samples examined are few in number, and the times of extracorporeal circulation are relatively short. It is necessary to confirm these data in more samples and longer procedure times as ECMO.

CONCLUSION

The result of this study shows an inversely proportional correlation between gas exchange and condensation in statistically significant values. In polypropylene and polymethylpentene fiber oxygenators, the production of condensation was increased at the oxygenator gas outlet during

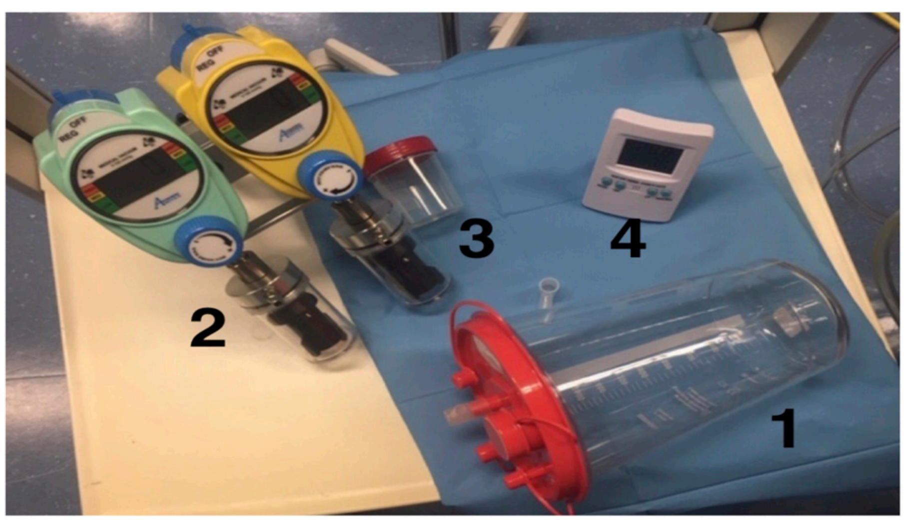

Figure 6. Mean values of PaO_2/humidity gas output in polymethylpentene oxygenators during procedures.

the use of normothermia. Limiting the use of heat exchanger time during CPB would seem to reduce the production of water loss and condensation and improve the stability of exchanges in terms of PaO_2 in the long-term extracorporeal circulations. The aspiration use in the gas outlet could favor the elimination of the condensation, particularly in the polymethylpentene oxygenators, and favor gas exchanges. However, further studies are needed to validate these preliminary results.

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