Clinical evaluation of an instrument to measure carbon dioxide tension at the oxygenator gas outlet in cardiopulmonary bypass

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This paper presents the clinical testing of a new capnograph designed to measure the carbon dioxide tension at the oxygenator exhaust outlet in cardiopulmonary bypass (CPB). During CPB, there is a need for reliable, accurate and instant estimates of the arterial blood CO_2 tension (P_aCO_2) in the patient. Currently, the standard practice for measuring P_aCO_2 involves the manual collection of intermittent blood samples, followed by a separate analysis performed by a blood gas analyser. Probes for inline blood gas measurement exist, but they are expensive and, thus, unsuitable for routine use. A well-known method is to measure $P_{ex}CO_2$, ie, the partial pressure of CO_2 in the exhaust gas output from the oxygenator and use this as an indirect estimate for P_aCO_2.

Based on a commercially available CO_2 sensor circuit board, a laminar flow capnograph was developed. A standard sample line with integrated water trap was connected to the oxygenator exhaust port. Fifty patients were divided into six different groups with respect to oxygenator type and temperature range. Both arterial and venous blood gas samples were drawn from the CPB circuit at various temperatures.

Alfa-stat corrected pCO_2 values were obtained by running a linear regression for each group based on the arterial temperature and then correcting the $P_{ex}CO_2$ accordingly. The accuracy of the six groups was found to be ($\pm$SD): $\pm$4.3, $\pm$4.8, $\pm$5.7, $\pm$1.0, $\pm$3.7 and $\pm$2.1%. These results suggest that oxygenator exhaust capnography is a simple, inexpensive and reliable method of estimating the P_aCO_2 in both adult and pediatric patients at all relevant temperatures. *Perfusion* (2006) **21,** 21–26.

Introduction

This paper presents the clinical testing of a new capnograph designed to measure the carbon dioxide tension at the oxygenator exhaust outlet in cardiopulmonary bypass (CPB).[1] During CPB, there is a need for reliable, accurate and instant estimates of the arterial blood CO_2 tension (P_aCO_2) of the patient. Currently, the standard practice for measuring P_aCO_2 during CPB involves the manual collection of intermittent blood samples, followed by a separate analysis performed by a blood gas analyser. This approach substantially delays the acquiring of data, as well as having undesirable manual steps. Probes for inline blood gas measurements exist, but they are expensive and, thus, unsuitable for routine use.

A well known method is to measure $P_{ex}CO_2$, ie, the partial pressure of CO_2 in the exhaust gas output from the oxygenator used in the CPB circuit, and use this as an indirect estimate for P_aCO_2.[2–4] However, previous presentations use capnographs designed for patients on mechanical ventilation, thus, are made for normothermia and pulsatile flow. Therefore, the aim of this study was to perform a clinical evaluation of a new capnograph designed to measure the carbon dioxide tension at the oxygenator exhaust outlet.

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Materials and methods

Technical overview

It was decided to find an accurate, cheap and controllable pCO_2 sensor that could be used with laminar flow at the oxygenator gas outlet in the CPB circuit. A vast number of CO_2 sensors are available on the market, but most have limitations regarding our three initial demands. Searches were made, and two good candidates from Square One Technology, later Dolphin Medical Sensors (Hawthorn, CA, USA), and CardioPulmonary Technologies, Inc.

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(Sussex, WI, USA) were found. Both could offer a small, low power and fully digitalized infra-red (IR) sidestream gas analyser for a reasonable price. Square One's 2125 CO_2/N_2O sensor was chosen, mainly because of the excellent command functions and good technical support. The gas analyser was then built into a housing to protect the electronics from excessive fluids and blood. Figure 1 shows an overview of how the capnograph and the computer were connected to the heart-lung machine.

The gas analyser is connected to the exhaust outlet from the oxygenator through a disposable sample line with an integrated water trap. Gas is sampled continuously from the oxygenator gas outlet port and the results are digitalized and transferred to a computer (PC) through an RS-232 interface. No pulsatile CO_2 levels are expected and no apnea alarms or any non-laminar effects will occur. When results are acquired on the PC, calculations and rendering is performed and the actual CO_2 value is presented on the computer screen as a virtual instrument. All information exchange performs automatically, the only action needed from the perfusionist is to switch on the device and insert the sample line into the oxygenator.

Methods

The Avant oxygenator (Sorin Group, Mirandola, Italy) was selected as the main oxygenator for testing because it is the standard oxygenator for adult patients in our department. The patients were divided into six different groups with respect to oxygenator type and patient category. The groups are summarized in Table 1 and were divided as follows: *Group I*: 20 adult CPB patients on moderate hypothermia and the Avant oxygenator were randomly selected into this group. $P_{ex}CO_2$ readings from the capnograph were recorded at intervals of 32–35–38°C. Venous and arterial blood gas samples were drawn from the CPB circuit and both pump-flow and oxygenator sweep gases were recorded. *Group II*: Five patients undergoing deep hypothermia with the Avant oxygenator were randomly selected to this group. $P_{ex}CO_2$ readings were recorded at intervals of 20–28–36°C. Arterial blood gas samples were drawn from the oxygenator. *Group III*: Five patients were randomly selected to the Lilliput oxygenator (Sorin Group, Mirando La, Italy). $P_{ex}CO_2$ readings were recorded at intervals of 32–35–38°C. Arterial blood gas samples were drawn from the oxygenator. *Group IV*: Five adult CPB patients on moderate hypothermia and the Avant oxygenator were randomly selected into this group. $P_{ex}CO_2$ readings were recorded at intervals of 32–35–38°C. Arterial blood gas samples were drawn from the oxygenator. *Group V:* Seven patients were randomly selected to the Spiralgold oxygenator (Maquet Cardiopulmonary, Hirrlingen, Germany). $P_{ex}CO_2$ readings were recorded at intervals of 32–35–38°C. Arterial blood gas samples were drawn from the oxygenator. *Group VI*: Eight patients on moderate hypothermia and the Affinity oxygenator (Medtronic Inc., Minneapolis, MN, USA) were randomly selected into this group. $P_{ex}CO_2$ readings were recorded at intervals of 32–35–38°C. Arterial blood gas samples were drawn from the oxygenator.

The only exclusion criterion for all groups was patients in need of emergency surgery. All statistical evaluations in this paper were performed with the SPSS 12 software (SPSS Inc., Chicago, IL, USA).

The ABL 700 series blood gas analyser (Radiometer Medical A/S, Copenhagen, Denmark) was used as reference.

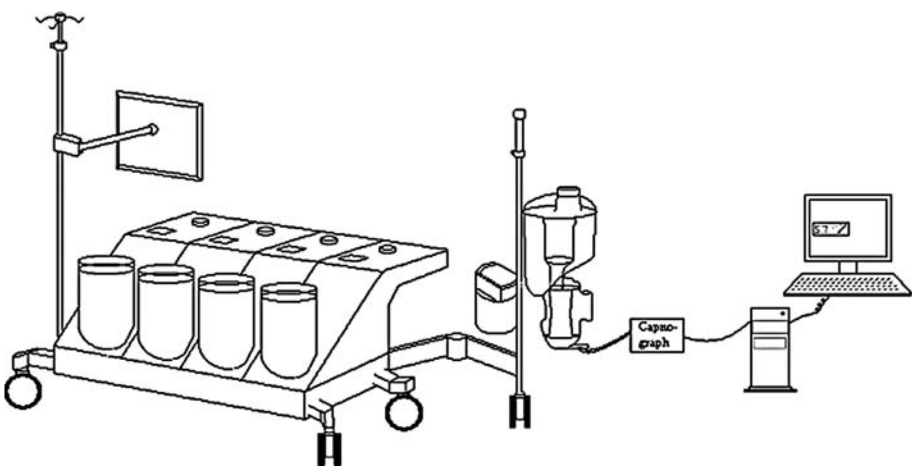

Figure 1 Schematic overview of the capnography set-up.

Table 1 Summary of data acquired from the six different groups

Group	*Oxygenator*	*No. of patients*	*Sample temperature (°C)*	*Samples collected*
I	Avant	20	32–35–38	Arterial and venous blood gas
II	Avant	5	20–28–36	Arterial blood gas, $P_{ex}CO_2$
III	Lilliput	5	32–35–38	Arterial blood gas, $P_{ex}CO_2$
IV	Avant	5	32–35–38	Arterial blood gas, $P_{ex}CO_2$
V	Spiralgold	7	32–35–38	Arterial blood gas, $P_{ex}CO_2$
VI	Affinity	8	32–35–38	Arterial blood gas, $P_{ex}CO_2$

Results

Fifty patients were divided into six different groups with respect to the oxygenator used and temperature range. A total of 150 blood gas samples were analysed.

Group I

The following measurements were collected from the CPB circuit with an Avant oxygenator: arterial pO_2, arterial pCO_2, arterial saturation, venous pO_2, venous pCO_2, venous saturation, pump flow, oxygenator gas flow, venous temperature and capnograph $P_{ex}CO_2$. A multiple regression analysis was applied on the 20 patients in Group I in order to find the best predictor of P_aCO_2. Both arterial temperature and venous temperature showed high correlation with changing P_aCO_2, but arterial temperature proved the highest correlation ($R = 0.937$, Pearson correlation). This is not a surprising discovery, since most modern membrane oxygenators have the heat exchanger placed in front of the gas-exchange mechanism. The correction factor was then implemented as a function of the arterial temperature taken from the oxygenator. A linear regression analysis was performed based on arterial temperature and the difference between the uncorrected $P_{ex}CO_2$ reading from the capnograph and the P_aCO_2 from the blood gas sample (ΔpCO_2). The regression line derived was $\Delta pCO_2 = -8.47 + 0.250$*a-temp. Figure 2 displays the deviation between blood gas P_aCO_2 and the uncorrected $P_{ex}CO_2$ plotted with respect to the arterial temperature for Group I.

The regression line $\Delta pCO_2 = -8.47 + 0.250$* a-temp was then utilized to find corrected values for alfa-stat use of the capnograph ($P_\alpha CO_2$). The accuracy was found to be $\pm 4.35\%$.

Group II

Samples of the deep hypothermia group were collected as stated in Table 1 using an Avant oxygenator. A linear regression analysis was performed based on the arterial temperature and the difference between the uncorrected $P_{ex}CO_2$ reading from the capnograph and the P_aCO_2 from the blood gas sample. The regression line derived was $\Delta pCO_2 = -7.95 + 0.246$*a-temp. The regression line was then utilized to find corrected values for alfa-stat use of the capnograph. The accuracy was found to be $\pm 4.82\%$. The deviation between corrected $P_\alpha CO_2$ and blood gas P_aCO_2 as a function of arterial temperature is plotted in Figure 3.

Group III

Samples of the pediatric group were collected as stated in Table 1 using a Lilliput oxygenator. A linear regression analysis was then performed based on the arterial temperature and the difference between the uncorrected $P_{ex}CO_2$ from the capnograph and the blood gas P_aCO_2. The regression line derived was $\Delta pCO_2 = -8.79 + 0.248$*a-temp. The regression line was then used to find the corrected values for alfa-stat use of the capnograph. The

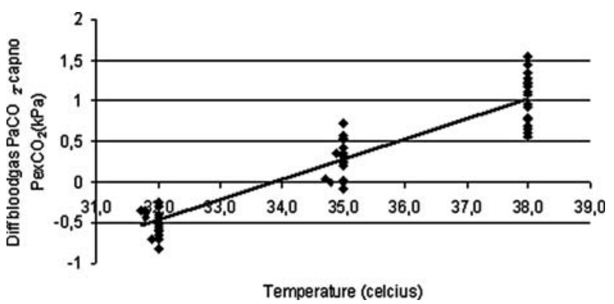

Figure 2 Deviation between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature for Group I.

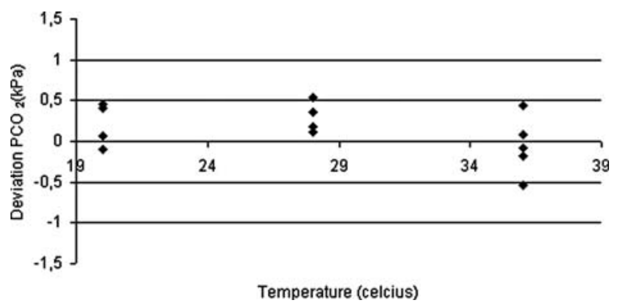

Figure 3 Deviation between corrected $P_\alpha CO_2$ and blood gas P_aCO_2 as a function of arterial temperature, using an Avant oxygenator for patients undergoing deep hypothermia.

accuracy was found to be ±5.70%. The difference between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature is plotted in Figure 4.

Group IV

Samples for Group IV were collected as stated in Table 1 using an Avant oxygenator.

The regression line was found to be $\Delta pCO_2 = -8.21 + 0.245$*a-temp. The regression line was then used to find the corrected values for alfa-stat use of the capnograph. The accuracy was found to be ±1.02%. The difference between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature is plotted in Figure 4.

Group V

Samples for Group V were collected as stated in Table 1 using a Spiralgold oxygenator. A linear regression analysis was then performed based on the arterial temperature and the difference between the uncorrected $P_{ex}CO_2$ reading from the capnograph and the P_aCO_2 from the blood gas sample. The regression line derived was $\Delta pCO_2 = -6.21 + 0.187$*a-temp.

The regression line was then used to find the corrected values for alfa-stat use of the capnograph. The accuracy was found to be ±3.74%. The difference between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature is plotted in Figure 4.

Group VI

Samples for Group VI were collected as stated in Table 1 using an Affinity oxygenator. A linear regression analysis was then performed based on the arterial temperature and the difference between the uncorrected $P_{ex}CO_2$ from the capnograph and the blood gas P_aCO_2. The regression line derived was $\Delta pCO_2 = -9.15 + 0.277$*a-temp. The regression line was then used to find the corrected values for alfa-stat use of the capnograph. The accuracy was found to be ±2.14%. The difference between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature is plotted in Figure 4.

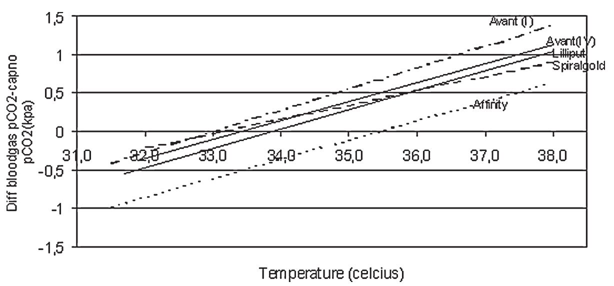

Figure 4 Deviation between blood gas P_aCO_2 and uncorrected capnograph $P_{ex}CO_2$ as a function of arterial temperature for Groups I and III–VI.

The results obtained from all six groups are shown in Table 2.

Discussion

Oxygenator exhaust capnography is an indirect measurement of the patient arterial carbon dioxide tension. The measuring principle is based on an assumption that the oxygenator pCO_2 and the blood pCO_2 reach equilibrium during the passage through the oxygenator. Recent presentations on the subject have concluded that this is not the case.[3] In opposition to this, our results suggest that $P_{ex}CO_2$ and P_aCO_2 indeed reach equilibrium during passage through the oxygenator. We do not know if this equilibrium occurs in all areas of the exhaust region. The important aspect for us is that the equilibrium is reached in time to give dependable measurements at the exhaust port where the sample line is located.

The CDI instrument from Terumo (Terumo Cardiovascular Systems Corporation, Ann Arbor, MI, USA) is considered one of the best in the category of CPB inline monitoring. Several studies have been presented on the CDI instrument, and its accuracy for P_aCO_2 is reported in the range ±5–10%.[5,6] The results presented in this study are even more accurate than those reported on the CDI 500 instrument and can be obtained at a much lower cost. A complete setup of sensors and disposables for a CDI 500 costs approximately 100€, while a water trap with a sample line costs about 20€. It is important to note that a CDI 500 will give more parameters than the capnograph, and thus, complicates any attempts of comparison of the two methods. On the other hand, if P_aCO_2 is the desired parameter, a simple water trap with a sample line is obviously a cheaper solution than an inline probe. Finally, the capnograph is a non-invasive method as opposed to the CDI 500, reducing the risk of contaminating the bloodstream.

Two major improvements were discovered during the testing period of the first three groups: how to place the sample line in the oxygenator exhaust port and implementing a sample line with integrated water trap and moist filter.

During the first three groups, a T-connector was fitted onto the exhaust port of the oxygenator to deliver the sample gas to the capnograph, as shown on the right side of Figure 5. However, statistical evaluation of the results obtained from the first three

Table 2 Results from the six different groups

Oxygenator	*Regression line*	*No. of patients*	*±SD (kPa)*	*±SD (%)*	p-*value**
Group I, Avant	−8.47+0.25*a-temp	20	0.23	4.35	NS
Group II, Avant Hypo.	−7.95+0.246*a-temp	5	0.27	4.82	NS
Group III, Lilliput	−8.79+0.248*a-temp	5	0.30	5.70	NS
Group IV, Avant	−8.21+0.245*a-temp	5	0.05	1.02	NS
Group V, Spiralgold	−6.21+0.187*a-temp	7	0.19	3.74	NS
Group VI, Affinity	−9.15+0.277*a-temp	8	0.11	2.14	NS

*Paired *t*-test.

groups showed that the accuracy of the capnograph was somewhat dependent of the amount of gas flow through the oxygenator. A possible explanation for this may be that false room air is sucked into the sample line. To test this thesis, it was decided to plasma-sterilize the sample line and put it slightly into the exhaust chamber of the Avant oxygenator for five follow-up patients. The new placement of the sample tubing into the Avant oxygenator is shown on the left side of Figure 5. As shown under the results from Group IV, this improvement leads to even more accurate results. This technique was so successful that it was also applied to the last two groups in the project. The exact position of the sample line might vary slightly from case to case, with an approximate position of the end of the sample line 5–10 mm inside the exhaust chamber. A piece of adhesive tape was used to ensure the position of the sample line. In the future, a standardized connection is desired. All the different oxygenators were connected with the sample line in the same way. From our results, this variation in position inside the chamber is negligible. The major difference seems to be if the sample line is placed inside or outside the exhaust chamber, not the relative position inside.

A second object for improvement that became apparent during the testing of the first three groups was the big spread in the $P_{ex}CO_2$ readings during the rewarming phase of the perfusion. This is particularly visible for the samples collected at 38°C in Figure 3. A possible explanation for this may be that the big difference between the oxygenator gas and the blood temperature causes moisture to build up in the exhaust chamber. This moisture is then transported out of the exhaust port into the sample line and ends up in the capnograph IR chamber. In the IR chamber, this leads to varying energy absorption and, thus, a greater spread in the pCO_2 readings. Because of this, a water trap with integrated moist filter was used for the last three groups in the project. The possible relationship between room temperature and the regression line was not investigated in this study, mainly because it is the difference between gas temperature and blood temperature that creates condensation, but also because the results are significant even without compensating for this possible source of error.

Looking at the summary of the five groups with the same temperature range in Figure 4, it seems that all the oxygenators from the same producer have an equal slope in the regression line. A possible conclusion from this is that the slope of the regression line is fibre-dependent and the amount of fibre inside the oxygenator decides the crossover point with the Y-axis. The regression line needs to be calculated once for every oxygenator type, not for each oxygenator. When it comes to the other variables, such as patient, temperatures and surroundings, the regression line seems to be independent.

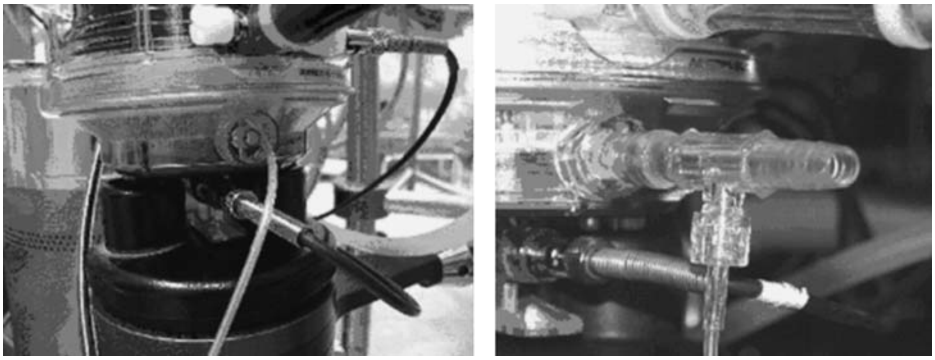

Figure 5 Placement of the sample tubing in the oxygenator exhaust port, the method to the left gives the most reliable results.

Referring to the schematic overview of the set-up in Figure 1, the equipment might seem a bit extensive. Adding a computer to a heart-lung machine increases the weight and complicates handling of the machine. However, in order to implement a data logger, a computer had to be placed on the heart-lung machine anyway. The only new device was the plastic box housing the CO_2 sensor. This plastic box was placed under a shelf close to the oxygenator, safe from liquids and dirt, also being kept out of the way for the perfusionist.

Conclusion

Our results suggest that oxygenator exhaust capnography is an easy, inexpensive and reliable method of estimating the P_aCO_2 in both adult and pediatric patients at all relevant temperatures.

References

1 Høgetveit JO, Kristiansen F, Pedersen TH. Development of an instrument to indirectly monitor asterial pCO_2 during cardiopulmonary bypass. *Perfusion* 2006; **21**(1): 13–19.
2 Potger KC, McMillan M, Southwell J, Dano H, O'Shaughnessy K. Membrane oxygenator exhaust capnography for continuously estimating arterial carbon dioxide tension during cardiopulmonary bypass. *J Extra-Corpor Technol* 2003; **35**: 218–23.
3 O'Leary MJ, MacDonnel SP, Ferguson CN. Oxygenator exhaust capnography as an index of arterial carbon dioxide tension during cardiopulmonary bypass using a membrane oxygenator. *Br J Anaesth* 1999; **82**(6): 843–46.
4 McCloskey DB, Strickler RF, Reusch GW. Alfa-stat capnography for the Sorin Monolyth oxygenator. *J Extra-Corpor Technol* 1994; **26**: 64–67.
5 Svenmarker S, Lindhol R, Haggmark S *et al*. Clinical evaluation of the CDI system 400 blood gas monitor. *Perfusion* 1994; **9**: 71–76.
6 Trowbridge CC, Vasques M, Stammers AH *et al*. The effects of continuous blood gas monitoring during cardiopulmonary bypass: a prospective, randomized study – part I. *J Extra-Corpor Technol* 2000; **32**: 120–28.