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Continuous In-vivo *Blood-gas Determination in Man:*

Reliability and Safety of a New Device

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The Sentorr® is a gas chromatograph that monitors Pa_{O_2} and Pa_{CO_2} every 4 min from a probe placed through an intraarterial cannula. The accuracy of this device and complications resulting from its use were studied in 46 patients undergoing cardiac surgical procedures with oxygen to nitrous oxide–halothane anesthesia. Sentorr blood-gas values were compared with simultaneous samples analyzed with standard electrodes. During relatively steady states of respiration and circulation, and in the lower (50–125 torr) range of oxygen tensions, the measurements correlated closely (r = 0.92). The device also functioned well during low-flow states, but during hypothermic cardiopulmonary bypass, the correlation was only fair (r = 0.62). When nitrous oxide was present in the inspired gas, Sentorr Pa_{O_2} readings were a third lower than actual P_{O_2} measurements, an effect corroborated by an *in-vitro* experiment. Directional changes of oxygen and carbon dioxide tensions were always correct in all situations. Placement of the probe in a radial artery was unsatisfactory because it significantly interfered with blood pressure measurement and resulted in inaccurate results for this patient population. The brachial artery was a satisfactory site for insertion, although attenuation of the arterial pressure tracing by the presence of a Sentorr probe resulted in systolic pressure readings that averaged 12 torr lower with mean arterial pressure readings 5 torr lower. No increase in morbidity due to use of a Sentorr probe for brachial arterial pressure monitoring could be identified. The most potentially serious complication encountered was transient loss of a palpable pulse without interruption of blood flow in one or more distal arteries after decannulation. This was observed in seven patients (four of whom had diminished distal pulses with normal flow before cannulation). (Key words: Measurement techniques: carbon dioxide; chromatography; electrodes; oxygen. Monitoring: carbon dioxide; oxygen.)

CONTINUOUS MONITORING of arterial blood-gas values is a potentially useful addition to the management of critically ill patients. The Sentorr® (Ohio Medical Products) is a portable gas chromatograph which is connected to, but electrically isolated from the patient by a closed-tipped probe placed in an artery. The present study was designed to evaluate the performance of this device in clinical situations, with special attention to its accuracy and complications resulting from its use. An *in-vitro* experiment was also performed to elucidate the effect of nitrous oxide on accuracy.

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Methods and Materials

Studies were made in 46 patients undergoing elective cardiac surgical procedures with halothane (0.5–1.5 per cent inspired)–nitrous oxide (50–70 per cent inspired) anesthesia and cardiopulmonary bypass. There were 34 men and nine women, whose ages ranged from 31 to 74 years (mean 60 ± 9 SD). Thirteen patients underwent valve replacement, 28 had coronary-artery bypass graft insertion, and five had both procedures. Written informed consent was obtained from the patients, and the study was approved by the University Committee on Studies Involving Human Beings. Preoperatively, the vasculature of each arm was examined by palpating brachial, radial, and ulnar pulses; performing an Allen's test; and, in some patients, applying a Doppler flowmeter (Parks Electronics Laboratory, Model 803®) to the radial and ulnar arteries at the wrist. Flow through the brachial artery was assessed by the systolic pressure difference between arm and forearm. A difference greater than 10 torr between forearm and arm indicates partial brachial arterial occlusion.[1,2]

Using sterile technique, a standard 18-gauge, 4.8-cm-long Teflon® catheter was placed percutaneously into a brachial artery. Arteries previously used for cardiac catheterization were not cannulated. The Sentorr probe was then threaded through the intraarterial cannula. Sentorr probes were 15.2 cm long with an external diameter of .07 cm. The distal 7.6 cm of the probe forms a chamber of non-thrombogenic dimethyl silicone rubber with a heparin-bonded surface that is gas-permeable. The remainder of the probe is fabricated from a non-permeable polymer. Three and a half minutes are allowed for diffusion of gases between blood and membrane, after which the gases are carried by helium through an inner tube into the chromatograph column for analysis. Updated P_{O_2} and P_{CO_2} values are digitally displayed on the front of the chromatograph console every 4 min. These represent the average oxygen and carbon dioxide tension values from the previous 3½ min of equilibration.

A luer-lock Y-connector at the external end of the probe allowed attachment of the intraarterial cannula to standard tubing for simultaneous intraarterial pressure monitoring and blood sampling (fig. 1). In nine patients, pressure tracings from the arterial

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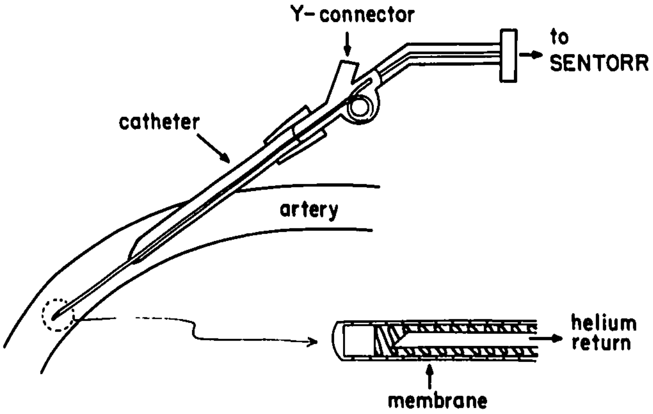

FIG. 1. Schematic diagram of the Sentorr probe, with attention to the probe tip where blood gases diffuse. See text for details.

cannula before and after placement of the probe were recorded. Patency of the arterial cannula was maintained by continuous infusion with heparinized saline solution (2 U heparin/ml saline solution) at 3 ml/h.

The Sentorr chromatograph was set at zero and calibrated once daily according to barometric pressure with oxygen–carbon dioxide (50 per cent each) precision gas that is housed on the chromatograph. For comparison with Sentorr readings, arterial blood samples were drawn preoperatively (while patients were breathing oxygen–nitrogen, F_{IO_2} 0.2–0.4); after induction of anesthesia (breathing oxygen–nitrous oxide–halothane, F_{IO_2} 0.5–1.0); during cardiopulmonary bypass, (F_{IO_2} 1.0); after bypass (breathing oxygen–nitrous oxide–halothane, F_{IO_2} 0.5–1.0); and postoperatively (breathing oxygen–nitrogen, F_{IO_2} 0.21–1.0) for blood-gas analysis using an Instrumentation Laboratories 213® analyzer. The blood-gas analyzer was calibrated before testing each sample with 0 and 12 per cent oxygen. Blood was analyzed immediately after sampling, and results were corrected for body temperature when indicated.[3]

The Sentorr probe was removed either when the arterial cannula was no longer clinically needed or when a complication or malfunction developed. After removal of the probe, the arterial cannula was left in place in some patients, for continuous arterial pressure monitoring. Sentorr probes remained in place an average of 28 ± 12 SD hours (range 1–55 hours). Following arterial decannulation, direct pressure was applied to the puncture site for 5 min. The involved arm was examined on the day of decannulation and every other day thereafter for the duration of the hospitalization, using the same criteria that were used preoperatively. The patients with vascular complications were evaluated for one month postoperatively.

It became apparent that patients breathing nitrous oxide had Sentorr Pa_{O_2} readings that were considerably lower than the values obtained by polarographic electrode measurements. To evaluate this finding *in vitro*, a cardiopulmonary bypass oxygenator was fitted with plastic tubing in a continuous loop which passed through a roller pump. A Sentorr probe was placed through a Y-piece into the tubing, and the system was filled with lactated Ringer's solution. Temperature in the system was kept at 37 C using the heat exchanger of the oxygenator. Releasing compressed air (F_{IO_2} = .21) into the oxygenator at a rate of approximately 5 l/min produced repeated Sentorr readings of 146–151 torr (atmospheric pressure corrected for water vapor = 710.2 torr, with predicted O_2 tension in fully humidified room air being 149.1 torr). By decreasing and increasing fluid flow around 1.1 l/min, we demonstrated that the P_{O_2} readings remained constant. A mixture of oxygen and nitrous oxide in an E cylinder, preanalyzed by mass spectrometry (13.2 per cent O_2 and 86.8 per cent N_2O by two independent analyses), was flowed into the oxygenator at 5 l/min. When repeated Sentorr readings remained constant, a sample of the fluid was analyzed in duplicate by the IL213 polarographic electrode. The test gas was then analyzed directly by the Sentorr chromatograph (thereby bypassing the probe) by placing the E cylinder into the yoke normally occupied by the calibrating gas and operating the device in the "calibrate" mode.

Quantification of gas transfer across the probe was also performed. The helium source tube and the sample draw tube form a loop encompassing the chamber in the tip of the probe. This loop was flushed with helium, and the source tube was closed. A microliter syringe with a soap bubble indicator was inserted into the draw tube and the probe tip placed in three different gas mixtures (table 1). As gas crossed the membrane, its volume was measured by displacement of the soap bubble indicator over 3½ minutes. Data were analyzed for statistical significance using a two-way analysis of variance.

Results

Comparison of 37 electrode and Sentorr measurements of Pa_{O_2} over a range of 50–500 torr showed a close agreement in the steady state. Linear regression analysis yielded a (Pa_{O_2} Sentorr) = [0.982 (Pa_{O_2} electrode) − 0.051] with r = 0.957. Comparison of a further 36 measurements during unstable conditions demonstrated somewhat more variability, with (Pa_{O_2} Sentorr) = [1.123 (Pa_{O_2} electrode) − 37.4] with r = 0.950. Results of Pa_{CO_2} comparison for the same conditions followed a similar pattern. During steady-state conditions (Pa_{CO_2} Sentorr) = [0.99 (Pa_{CO_2} electrode) + 3] with r = 0.921, while unstable conditions showed (Pa_{CO_2} Sentorr) = [0.696 (Pa_{CO_2} electrode) + 11.9] with r = 0.847. The range of Pa_{CO_2}s was 20–49 torr.

During hypothermic cardiopulmonary bypass (temperature 30–33 C) there was more disparity in correlation. Pa_{O_2} values were higher (range 151–515 torr) and linear regression analysis yielded values of (Pa_{O_2} Sentorr) = [0.578 (Pa_{O_2} electrode) + 134.3] with r = 0.524. Pa_{CO_2} (range 21–47 torr) measurements also showed less correlation; (Pa_{CO_2} Sentorr) = [0.796 (Pa_{CO_2} electrode) + 7.3] with r = 0.624. Three of the patients had low-cardiac-output states postoperatively. These patients were being given moderate to high doses of vasopressor drugs postoperatively but were otherwise at a steady state. Data analyzed from these periods demonstrated excellent agreement. Pa_{O_2}s ranged from 66 to 290 torr and (Pa_{O_2} Sentorr) = [1.019 (Pa_{O_2} electrode) − 6.2] with r = 0.989. Pa_{CO_2}s ranged from 33 to 42 torr and (Pa_{CO_2} Sentorr) = [1.063 (Pa_{CO_2} electrode) + 0.199] with r = 0.995.

Data collected 24 hours after insertion showed that duration of probe placement did not affect reliability. Oxygen tensions ranged from 51 to 158 torr and (Pa_{O_2} Sentorr) = [1.04 (Pa_{O_2} electrode) − 3] with r = 0.981. Carbon dioxide tensions ranged from 28 to 47 torr and (Pa_{CO_2} Sentorr) = [0.99 (Pa_{CO_2} electrode) + 3] with r = 0.898.

Whenever nitrous oxide was present in the inspired gas, Sentorr Pa_{O_2}, values were approximately a third lower than the corresponding polarographic values (fig. 2). Carbon dioxide measurements from the same samples when analyzed showed (Pa_{CO_2} Sentorr) = [0.81 (Pa_{CO_2} electrode) + 8] with r = 0.818.

In nine patients, pressure readings from the arterial cannulas were 12 ± 8 SD torr lower immediately following placement of the probe through the arterial cannula. Diastolic pressure reading averaged 1 ± 4 SD torr lower, and mean pressure 5 ± 5 SD torr lower. Damping of the arterial pressure tracing was a recurrent problem in three of 20 patients, and in one patient, the probe had to be removed from the arterial cannula because of excessive damping. Flushing the arterial line usually restored the pressure tracing to normal. Damping did not increase progressively and seemed to become less of a problem the longer the probe remained in place.

In none of the arteries in which cannulas were placed had there been any preoperative evidence of brachial arterial occlusion by arterial palpation or blood pressure difference. In one patient, the amplitude of the radial arterial pulse was diminished,

TABLE 1. Gas Transfer into the Probe in 3½ Minutes

Gas Mixture (Values are Percentages)	Volume (μl) Mean ± SEM (n = 3)
Oxygen, 21; nitrogen, 79 (room air)	8.83 ± 0.16
Oxygen, 12; nitrogen, 83; carbon dioxide, 5	9.0 ± 0.0
Oxygen, 40; nitrous oxide, 60	11.16 ± 0.16*

* Significantly different, $P < 0.05$.

but flow was normal. In six patients, ulnar pulse was diminished, but present, with normal flow. Ecchymoses in seven patients and local stiffness in four patients were transient problems. One patient complained of arm weakness and two others of hand numbness. They had no objective evidence of neuropathy, and these complaints were also short-lived. Pulses were not altered in any patient immediately after insertion of the probe. Postoperative loss of pulses in the cannulated arm occurred in seven patients. Two had complete absence of brachial, ulnar, and radial pulses, while five had loss of the ulnar pulse only. In all seven patients, flow through the involved artery was present as measured by doppler flowmeter and Allen's test. Blood pressure difference between the upper arm and forearm remained less than 10 torr, suggesting the presence of normal flow to the involved hand, which remained warm and pink. The probes and arterial cannulas were removed in the two patients when the complete absence of pulses became apparent. One of those patients died of cardiogenic shock shortly postoperatively. All other patients regained their ulnar pulses within a few days of the operation and remained asymptomatic.

The preanalyzed gas (13.2 per cent O_2 in N_2O) was expected to have a P_{O_2} of 95.6 torr by calculation (P_B humidified = 713.4 torr). With the probe in the simulated circulatory system, the Sentorr showed an average P_{O_2} = 71.2 torr ± 1.9 SD over five consecutive readings, approximately a third lower than expected. A simultaneous sample analyzed by the polarographic electrode showed a P_{O_2} of 98 torr ± 3.9 SD. When the preanalyzed gas was fed directly into the chromatograph in order to bypass the probe, the Sentorr P_{O_2} = 101.8 torr ± 0.8 SD over five consecutive readings. The expected P_{O_2} by calculation (P_B dry = 764 torr) was 102.4 torr.

Results of measurement of gas transfer (table 1) show that when nitrous oxide was present, the amount of gas crossing the membrane was significantly greater. In addition, the volume continued to increase beyond the 3½-min period for all three mixtures, demonstrating that equilibrium had not been attained.

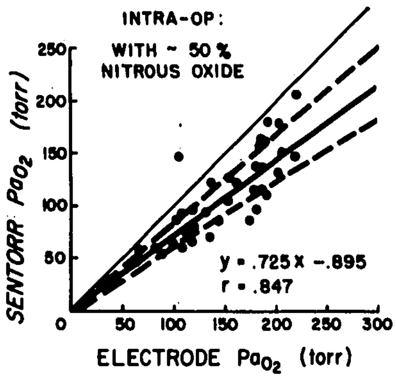

FIG. 2. Linear regression expressing the relationship between Sentorr Pa_{O_2} readings and polarographic analyzer, intraoperatively with an average of 47 per cent N_2O in inspired gas. The thin solid line (45-degree angle) represents the line of identity; the thick solid line is the regression line; the lines consisting of dashes represent 95 per cent confidence levels. Notice that all values but one are below the line of identity, with all Sentorr readings about a third lower than polarographic readings. There are 45 values from 18 patients, whose mean temperature was 35.3 C.

Discussion

Trends in Pa_{O_2} and Pa_{CO_2} were always directionally correct and useful to follow. This was true in all blood-gas ranges, under intraoperative conditions (hypothermia, cardiopulmonary bypass, shock states), postoperatively, and in a patient undergoing extracorporeal membrane oxygenation. A change in Sentorr reading was occasionally the first sign of an important change in gas tension, thereby permitting early intervention. More precise control of O_2 and CO_2 administration was made possible when initiating cardiopulmonary bypass and during active cooling and rewarming of the patient. Earlier adjustments of positive-end expiratory pressure (PEEP) and inspired oxygen concentration were possible in patients when indicated intraoperatively and postoperatively.†

The Sentorr–laboratory correlation was excellent during relatively steady states of ventilation and circulation. Sentorr and laboratory values were most divergent when ventilatory and circulatory changes were occurring. This finding is not surprising, since the chromatograph value is time-averaged (over 3½ min), while the polarographic value reflects an instantaneous sampling. Closer correlation for P_{O_2} was observed in the lower range of oxygen concentration. This is in part due to the two-point calibration (0 and 12 per cent O_2) of the polaragraphic electrode, which favors a linear response in the clinically useful range. The gas chromatograph, however, is reliably linear throughout the entire range. This allows a simple one-point calibration. Discrepancy at high oxygen tensions and during hypothermic cardiopulmonary bypass were also found by Moffitt *et al.*[4]

Accuracy was not affected by duration of placement over the period studied, and fibrin deposition was not observed upon removal (one to six days after insertion). Abnormally low P_{O_2} values (5–8 torr) have been associated with marked hypotension because of insufficient blood flow around the probe.[4] Accuracy in P_{O_2} measurement was maintained in patients in this study during administration of vasopressor drugs, without marked hypotension, which suggests there was adequate blood flow.

In-vivo observations of consistently low oxygen tensions in the presence of nitrous oxide were duplicated in the *in-vitro* experiments, which also suggest that the source of error is related to the sampling mechanism rather than the chromatograph. The observed discrepancy can be explained by the lack of complete equilibration across the membrane and the different rates of gas transfer. The chamber formed by the probe tip is connected to a helium reservoir which is vented to maintain atmospheric pressure. With such an open system, gas continues to transfer so long as there is a partial pressure difference which, in this experiment, was demonstrated by continued gas movement after 3½ minutes. Thus, only partial equilibration is possible in the analyzed sample.

Gas flow across the membrane is a function of permeability, partial pressure, and membrane thickness expressed by:

$$N = (P_m/b)(Pb - Po)$$

where N = gas flux; P_m = permeability of the membrane; b = membrane thickness; Pb − Po = difference in partial pressure across the membrane.[5]

Permeability in the silicone rubber membrane used by the manufacturer for oxygen is 55×10^{-9} ml·cm/sec·cm²·cm Hg and that for nitrous oxide is 365×10^{-9} ml·cm/sec·cm Hg.‡ The higher permeability and partial pressure of nitrous oxide result in a larger sample volume with a disproportionally larger amount of nitrous oxide than oxygen in the sampling chamber before equilibrium is reached.

When the gas sample is composed of oxygen, nitrogen, and carbon dioxide only, a "probe-gain factor" is necessary to account for lack of complete

† Since completing this study, we have had the occasion to use the Sentorr for six consecutive days in a patient with severe respiratory failure. The device functioned well for the duration of its use and there were no complications from the brachial-artery probe.

‡ Unpublished data from Ohio Medical Products.

oxygen equilibration. This factor is part of the calculations used to convert the chromatograph signal to correct oxygen tension readings. Another "gain factor" might be used to yield correct oxygen tension readings in the presence of nitrous oxide.

The potentially most dangerous complication from a device such as Sentorr is vascular occlusion. This was suggested by loss of pulse, which occurred in 15 per cent of the patients. Since in all of these patients, blood flow was present in the involved artery despite the absence of a pulse, the occlusion was incomplete. Clinically detectable occlusion of the brachial artery when it is used as a site for monitoring is uncommon.[1] Addition of the Sentorr probe did not increase the incidence of such occlusion. Partial or complete obstruction of radial or ulnar vessels may be due to fragmentation of brachial thrombi.[1,6] Distal loss of pulse in our patients may represent this phenomenon, but the lack of symptoms and presence of flow suggest limited clinical importance. As a precaution, we would avoid using a brachial artery in which distal arterial flow is already diminished or absent.

Interference with brachial arterial pressure monitoring warranted probe removal in only one of 46 patients. This is in contrast to our findings in pilot studies in which long probes were inserted into a radial artery and positioned in the brachial artery (probes positioned in a radial artery rapidly become inaccurate because of decreased blood flow). The placement of the long probes, however, resulted in such severe damping of the pressure trace that seven of eight probes had to be removed either shortly after insertion or during hypothermic cardiopulmonary bypass. A femoral artery was not used because of the general undesirability of this site for monitoring patients having cardiac surgical procedures.

The Sentorr was found to be a safe and useful device for semi-continuous monitoring of oxygen and carbon dioxide tensions in this group of critically ill patients. Intraoperative accuracy would be enhanced if the effect of nitrous oxide were factored into the calculation of oxygen tension or if total sample equilibration were achieved.

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