A clinical catheter for continuous blood gas measurement by mass spectrometry

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1976—A new Teflon catheter for continuous in vivo measurement of blood gases by mass spectrometry has an outer diameter of 0.032 in. and can be inserted through percutaneous puncture with an 18 gauge needle. Response time (63% of a total change) is 40 s for oxygen and 65 s for carbon dioxide. When calibrated in analyzed gas at 37°C, the catheter-mass spectrometer system has been shown to analyze tonometered blood with an error of 1.6% for oxygen and 1.9% for carbon dioxide. Temperature dependence is 2.9% per °C for oxygen and 1.6% per °C for carbon dioxide. The catheter was thromboresistant during in vivo use in seven dogs and measurements compared favorably with results of blood sample analyses by standard hospital methods. Compared with previous devices, the new catheter provides size and convenience, advantages that make it more applicable for routine clinical use.

oxygen; carbon dioxide; monitoring systems

PREVIOUS EXPERIENCE has shown that continuous in vivo blood gases can be measured by mass spectrometry utilizing Silastic (3) or Teflon (2) diffusion membrane catheters. These catheters, however, have inherent features that make routine clinical use difficult. Silastic catheters are made thromboresistant by TDMAC-heparin coating (5), whose gradual deterioration limits the catheter shelf life. The earlier Teflon catheters have a diameter unacceptably large for clinical use. Both catheters are provided unsterilized because of difficulty in calibrating without contamination.

This paper describes a new Teflon catheter that has a diameter acceptably small for percutaneous insertion. A quick method of calibration without contamination allows it to be provided presterilized. Compatible with various medical mass spectrometers, this catheter makes continuous blood gas measurement by mass spectrometry more acceptable as a routine clinical technique.

MATERIALS AND METHODS

Minute amounts of gases are sampled through a Teflon diffusion membrane mounted at the end of an indwelling catheter. The new catheter geometry, presented in schematic and photograph in Figs. 1 and 2, incorporates structural advantages allowing smaller overall diameter and greater mechanical strength when compared with previous catheters. The catheter is constructed of flexible 22-gauge annealed stainless steel needle tubing with the 0.002 in. Teflon membrane providing an overall outer diameter of 0.032 in. The catheter can be inserted through a standard 18-gauge percutaneous arterial puncture.

With the membrane end in blood and the opposite end connected to the vacuum system of the mass spectrometer (Perkin-Elmer Corp., model MGA-1100), a minute amount of gas is continuously withdrawn through the diffusion membrane at a sampling rate of about $3 \times 10^{-6}$ ml/s. No blood is withdrawn: only dissolved gases are drawn through the membrane in quantities proportional to their partial pressures, pass along the helical groove, enter the catheter, and pass into the mass spectrometer where they are continuously analyzed according to molecular weight.

For the evaluation of these catheters a calibrating device provided a slow flow of analyzed gas at a controlled temperature of 37°C. The sterile delivery device of Fig. 3 allowed the catheter to be exposed to the calibrating gas without contaminating its sterility. The total time required to achieve calibration would vary with different mass spectrometers but averaged about 10 min in this study.

In vitro pulsatile-flow circulating system similar to previous studies (2, 3) was constructed and experiments done at a controlled temperature (1) to determine relative permeabilities in gas and liquid, (2) to develop a calibrating procedure for new catheters, (3) to investigate the flow dependence of the catheters, (4) to assess temperature dependence, (5) to determine the response time of the system, and (6) to confirm a quantitative accuracy equivalent to previous larger catheters.

Three cylinders of accurately known mixtures (Scholander analysis) of oxygen, carbon dioxide, and nitrogen were obtained and each in turn was equilibrated with blood and water in the circulating system. After the catheter and mass spectrometer were calibrated to measure accurately in the gas phase at 37°C, the catheter was placed in the tonometered circulating system and spectrometer readings made in water and blood at flow rates of 25–30 cm/s.

In vivo studies were done for periods of 4–6 h in a series of seven nonheparinized dogs to assess the thromboresistance of the Teflon catheters. Each dog was anesthetized with sodium pentobarbital (Nembutal 25 mg/kg), intubated, and ventilation was controlled by respirator. The Teflon catheter was positioned in the abdominal aorta through percutaneous femoral artery puncture and measurements initiated. Different blood gas levels were investigated by changing the inspired gas tensions and respirator settings. Arterial blood samples were collected in glass syringes and immediately transported to the Pulmonary Laboratory at the University of Utah Medical Center where comparison blood gases were measured with less than five minutes delay by independent laboratory personnel using the London Co. MK-3 micro-blood gas system. Dogs were killed at the end of the period, the abdomens opened, and the catheters were dissected in situ and observed for thrombus.

RESULTS

In vitro data are presented in Table 1 showing the response of the Teflon catheter in analyzing known standards in the gas phase and analyzing flowing water, flowing blood, and static
In Fig. 4, the various pump flow speeds are plotted against mass spectrometer response to demonstrate the flow dependence of the Teflon catheters. Normal arterial blood flow rate is in the range of 30–40 cm/s, well up on the “flat” portion of the flow curve in which even large variations in blood flow rate have little effect on measurements.

Temperature dependence of the Teflon catheters over the range 26–45°C was 2.0% per °C for PO₂ and 1.6% per °C for PCO₂. The temperature dependence is due to the higher permeability of the Teflon membrane at higher temperatures.

The in vitro system has also shown that a sudden step-function change in gas tension is reflected by the membrane-mass spectrometer system with a response time (1e or 63% of total change) of about 40 s for oxygen and 65 s for CO₂, while 96% of total change occurs in 80 s for oxygen and 130 s for CO₂. These response times are also influenced by the length and diameter of the cannula connecting the catheter to the mass spectrometer, and in the in vivo situation, the course of physiological changes may add some delay. Figure 5 illustrates the in vivo response time and stability of the catheter-mass spectrometer system during changes in respirator settings.

Typical comparisons with sample measurements done with The London Co. MK-3 micro-blood gas system are given in Fig. 6. Differences averaged 3.5% for PO₂ and 5.0% for PCO₂.

TABLE 1. Response of Teflon catheter in gas, flowing water, flowing blood, and static water

<table>
<thead>
<tr>
<th>Analyzed Gas Mixture</th>
<th>Mass Spectrometer Percent Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO₂</td>
<td>PCO₂</td>
</tr>
<tr>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>77</td>
<td>51</td>
</tr>
<tr>
<td>126</td>
<td>26</td>
</tr>
<tr>
<td>37</td>
<td>76</td>
</tr>
</tbody>
</table>

All data from a single catheter (n = 1).

TABLE 2. Mass spectrometer measurements of flowing blood tonometered with calibration standards

<table>
<thead>
<tr>
<th>Analyzed Gas Mixture</th>
<th>Mass Spectrometer</th>
<th>Percent Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO₂</td>
<td>PCO₂</td>
<td>PO₂</td>
</tr>
<tr>
<td>119.2</td>
<td>25.0</td>
<td>118.5</td>
</tr>
<tr>
<td>72.3</td>
<td>48.9</td>
<td>71.5</td>
</tr>
<tr>
<td>35.0</td>
<td>71.8</td>
<td>36.1</td>
</tr>
</tbody>
</table>

All data from a single catheter (n = 1)

FIG. 4. Flow dependence of the catheter in water is demonstrated in the in vitro system. Slight flow dependence is caused by some reduction of gas in the film of blood surrounding the catheter in static condition and low flow.
DISCUSSION

Accuracy. Traditional hospital blood gas analyses unfortunately do not provide an absolute standard against which to compare measurements with the mass spectrometer. To assess directly the accuracy of hospital analyses available to the present study, measurements of split blood samples were made on four separate instruments by the laboratory personnel of three independent local institutions (1). Results from these hospital laboratories showed a standard deviation of 5-7% for PO₂ and 10-15% for PCO₂ (1). Comparisons of mass spectrometer results with blood gas measurements by the University of Utah Pulmonary Laboratory yielded average differences of 3.5% for PO₂ and 5.0% for PCO₂ (Fig. 6, A and B). This variation includes error contributions from both mass spectrometer and hospital instruments and is within the accuracy of the hospital equipment itself.

Evaluation of the accuracy of the catheter-mass spectrometer technique requires measurements of a more reliable standard such as the analyzed cylinders of gas mixtures. When the catheter is used to measure blood tonometered with these precise standards, an accuracy of 1.6% for PO₂ and 1.9% for PCO₂ has been routinely achieved (Table 2).

Both in vitro and in vivo measurements are similar to the accuracy achieved in blood measurements with the previous larger catheters (2, 3). The PO₂ range of the present study and the identical response in water and blood demonstrate that the method is independent of hemoglobin and the dissociation curve. Studies with the larger catheters have shown linear response to 700 mmHg PO₂. Although the present catheters

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**FIG. 5** Response time and stability of the catheter-mass spectrometer system are demonstrated in a dog study in which a range of PO₂ and PCO₂ values are explored by changes in respiratory gas, tidal volume, and respiratory rate.

**FIG. 6.** Comparison of in vivo mass spectrometer measurements with sample analyses by the Radiometer method yields an average difference of 3.5% for PO₂ (A) and 5.0% for PCO₂ (B).
were not tested above a \( \text{PO}_2 \) of about 150, the previous experience with the larger catheters should be directly applicable because of the identical polymer (Teflon) and the identical diffusion membrane principle.

**Catheter design.** Although Silastic catheters made thrombo-resistant by the TDMAC-heparin treatment of Grode and co-workers (5) function quite well for blood gas measurements (3), the coating appears to deteriorate with time. G. A. Grode has stated that no formal studies of "shelf life" of the TDMAC-heparin coating have been completed. In his experience, coatings as old as 6 mo have shown no decline in thromboresistant properties; however, there is no information available beyond 6 mo (personal communication). The limiting factor of TDMAC-heparin shelf-life is the relative instability of the biological compound heparin. One might speculate that refrigeration or freezing might improve stability, but again no formal studies have been completed.

Two catheters were tested to explore this problem, one 6 mo and the other 12 mo after heparinization. After 24 h in the canine abdominal aorta, the 6-mo catheter was free of thrombus while the 12-mo catheter was clotted. Although these formal studies have been completed. In his experience, coatings as old as 6 mo have shown no decline in thromboresistant properties; however, there is no information available beyond 6 mo (personal communication). The limiting factor of TDMAC-heparin shelf-life is the relative instability of the biological compound heparin. One might speculate that refrigeration or freezing might improve stability, but again no formal studies have been completed.

In the seven dog studies reported here, catheter clotting did not occur; however, if the guidelines are not followed, some chance of clotting exists with any type of catheter.

**Clinical use.** The present catheter is the first Teflon catheter of its type small enough for percutaneous radial artery insertion. Artifical thrombosis is the most serious complication of radial artery catheterization of any type. In several dog studies, a small thrombus was observed at the site of arterial puncture, a normal body mechanism to seal the rent. Total arterial occlusion becomes particularly important in the absence of a functioning ulnar artery. For this reason, patency of the ulnar artery should routinely be assessed by Allen's test or by Doppler ultrasonic flowmeter before the catheter is inserted. Complications following use of the blood gas catheters should parallel those observed with other types of indwelling radial artery catheters. Gardner et al. (4) reported a series of 536 patients having indwelling Teflon radial artery catheters for a mean duration of 3.4 days. Partial occlusions detected by Doppler ultrasonic flowmeter occurred in 19.3%. Only three patients required thrombectomies, and these complete arterial occlusions were associated with hypotension, use of vasconstrictive drugs, and prolonged catheterization (4).

The present Teflon catheters are compatible with a number of medical mass spectrometers currently available. The size and convenience advantages of these new catheters should make continuous blood gas measurement by mass spectrometry more acceptable as a routine clinical technique.

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