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# The Measurement of $pO_2$ by $O_2$ Electrode in the Presence of Changing $pCO_2$

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Studies on the transport of $O_2$ and $CO_2$ in the alveoli and blood have focused on simultaneous measurements of the two gases with classical instruments; an interaction between the two gases has been assumed (see Bohr Effect and Rahn-Otis Plot). Nevertheless, of late years with wide use of the Kimmich-Kreuzer Oxygen Electrode in liquids and gases, the measurements have included oxygen alone. These small (2mm) polarographic catheter electrodes have been used in both physiologic and bioengineering applications. Within a particular range of polarization voltage, the electrode current is limited by $O_2$ diffusion across a membrane; i.e., at a constant polarization voltage, current is linearly related to $pO_2$. Since it is often the case that measurements of $pO_2$ are taken while $pCO_2$ is changing, $CO_2$ effects on the electrode current should be known and corrected for. In the present experiments, electrical currents at 5% and 21% $O_2$ with varying amounts of $CO_2$ were measured. Polarograms (a plot of current v. voltage) made in the presence and absence of $CO_2$ were compared. The $pO_2$ measurement is significantly affected by $CO_2$ at 21% $O_2$, but not a 5% $O_2$; i.e., the $O_2$ value changed with different $CO_2$ levels. These results are particularly interesting since the electrode membrane is a physical model of the alveolar membrane.

INDEX DESCRIPTORS: Oxygen measurements; catheter electrodes; gas analysis.

## Introduction

There is considerable interest among respiratory physiologists in the topic of the relationship between carbon dioxide transport and oxygen transport in lungs and blood. The following examples of the importance of the interrelationship are given:

A) In simple laboratory experiments for student teaching, one can record variations in percent of oxygen in the alveoli (independent of the variation in carbon dioxide) from 13.6% to 17.6% and variations in the carbon dioxide (independent of simultaneous variations in oxygen) from 3.5% to 5.9%.
B) When blood transport is considered, the well-known Bohr effect upon the dissociation curve will illustrate the influence of carbon dioxide upon oxygen transport.
C) To elucidate the relationship between respiratory carbon dioxide and oxygen, two respiratory physiologists devised a plot which, although useful at sea level, is particularly useful when respiratory gases are analyzed at higher altitudes. This is referred to as the Rahn-Otis plot for alveolar $pO_2$ and alveolar $pO_2$ (Folk, p. 323, 1974).

Simultaneous variations in carbon dioxide and oxygen were originally studied using the Haldane gas analyzer for alveolar samples and the Van Slyke apparatus for blood samples. However, these earlier instruments have been replaced in some physiological work by single measurements of a single gas (Kimmich and Kreuzer, 1977). One of the most popular instruments is the Kimmich-Kreuzer catheter oxygen electrode, which is not only used for measurements of percent of oxygen in respiratory gas mixtures (Beneken Kolmer and Kreuzer, 1968, 1969), but also in blood and other liquids (Jank, *et al.*, 1975; Kimmich and Kreuzer, 1969a; Kreuzer and Nessler, 1958). The electrode has been used in masks for recording during exercise (Kimmich, 1969). Furthermore, other forms of oxygen electrodes have replaced the Warburg apparatus for oxygen-consumption measurements of tissues.

In spite of the popularity of the catheter oxygen electrode, which now has an international use in a variety of forms from a large size down to hypodermic needle size, the influence of carbon dioxide upon this instrument has not been recorded. There are two criteria which warrant such a study. In the first place, the membrane of the oxyen electrode acts as a physical model of the alveolar membrane. Secondly, many of the publications using the oxygen electrode have ignored the possibility of effects due to variable carbon dioxide. Therefore, we began to make careful measurements of oxygen percents in variable carbon dioxide environments. The task proved challenging because of the following technical difficulties:

1) The catheter electrode is extremely temperature-sensitive; current increases with increases of temperature (Schuler and Kreuzer, 1969). Changes of a fraction of a degree were noticeable on recordings of electrode current. A water bath was used to eliminate as much as possible this artefactual change of current.
2) The care of the electrode is extremely important. During cleaning and polishing of the electrode, changing of the membrane, and filling with buffer solution, there are many steps in which errors are easily made. Instruction in proper maintenance is not sufficient; only with time and experience are the necessary manual skills acquired. Also, the catheter electrodes are very small, and therefore, quite easily damaged.
3) An obstruction to the outflow of gas from the chamber results in increasing pressure, which is interpreted as increased concentration of gas, and must be avoided. In our apparatus, gas outflow was completely open to the atmosphere; any momentary increase in pressure would have been immediately equilibrated with room atmosphere.
4) Evaporation of buffer solution and possibly also effects on the Teflon membrane occur with long-term use of the electrode (i.e., greater than 24 hours), in effect narrowing the distance between membrane and cathode, plus altering the concentration of the buffer. This problem can be eliminated by using humidified gas or, as we did, changing membrane and buffer each evening, then soaking the electrode with new membrane overnight in buffer solution.
5) The Wosthoff gas pumps used in this experiment, because of their mechanical design, deliver a slightly inconstant, oscillating gas mixture, which is reflected in the electrode current. This oscillation, though noticeable, is too small to have a significant impact on electrode current. Average current was used in all measurements.
6) Electrode current is not perfectly stable. A slight drift of current sometimes occurred. This was monitored and the baseline was corrected.
7) Response time is a function of both electrode properties and chamber/gas pump properties, i.e., the speed with which a pump can deliver a new gas mixture plus the time required to replace the chamber volume with a new gas mixture limit the response time. Thus, any change in chamber volume or gas flow alters response

time. A paper recorder was used to assess the end point at which current was stable; the time required was about 20-30 minutes.

## MATERIALS AND METHODS

The Kimmich-Kreuzer catheter oxygen electrode is designed according to the principle of polarography. If the electrode current is plotted as a function of increasing voltage at any constant $pO_2$, the resulting curve (known as a polarogram) shows an initial increase in current, then a plateau during which current remains constant despite increasing voltage, and finally a second steep increase in current with increasing voltage. In the voltage range of the plateau, current is limited by diffusion of oxygen across membrane, and is hence proportional to the partial pressure of oxygen (Kimmich and Kreuzer, 1969b).

Figure 1 illustrates the construction of the Kimmich-Kreuzer catheter oxygen electrode, custom-made in the laboratories of Kimmich and Kreuzer in Nijmegen, the Netherlands. The platinum cathode is covered with a cylinder of polyvinyl chloride, leaving only the surface of the cathode tip exposed to a buffer solution. A 6μm thick (± 0.5 μm) Teflon membrane is attached by a small ring at the tip. The electrode measures 7mm × 2mm; electrodes and their currents vary slightly (Schuler and Kreuzer, 1967).

Normal maintenance of the electrode involves cleaning the cathode and anode, and changing the membrane daily. The outer surface of the anode is polished about once a week, while the cathode is polished less frequently. The electrolyte is a phosphate buffer solution adjusted to pH 8.

Gases were mixed from cylinders using one or two Wosthoff gas pumps. These gas pumps are able to fractionate two sources of incoming gas; the delivered gas mixture might be 21% from cylinder A and 79% from cylinder B, or whatever whole percentage mixtures are desired. Several samples of gas mixtures were analyzed by Scholander apparatus; the results agreed within 1.1% with the calculated value of the samples. The pumps deliver a mixture of gases which slightly oscillates in composition (±0.07%). The dry gas mixture was warmed to 37° C, flowed past the $O_2$ electrode, and was released to the atmosphere. Flow of gas was maintained at a level sufficient to prevent back-diffusion of gas. The gas exit was open to the atmosphere.

### Experimental Design

Two series of experiments were performed to investigate the effect of $CO_2$ on the oxygen electrode. The first involved determining the electrode current with 5% $O_2$ and comparing this with the current observed at the same $pO_2$ in the presence of varying levels of $CO_2$. The baseline value of $CO_2$-free current was rechecked after each change of $CO_2$. The second involved rerunning the series with 21% $O_2$.

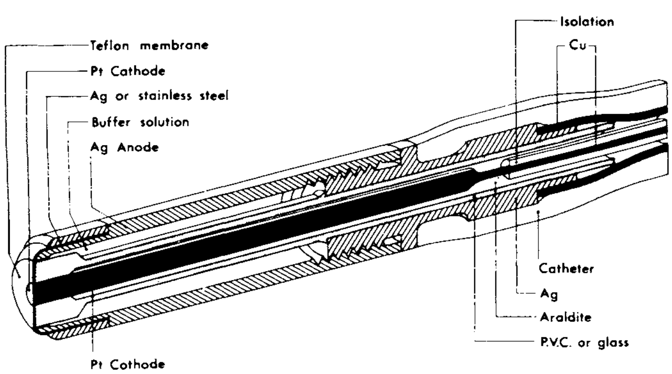


Fig. 1 The Kimmich-Kreuzer catheter oxygen-electrode. It has a single wire cathode (400 μ in diameter) for use in the gas phase (Kimmich, H.P., 1969).

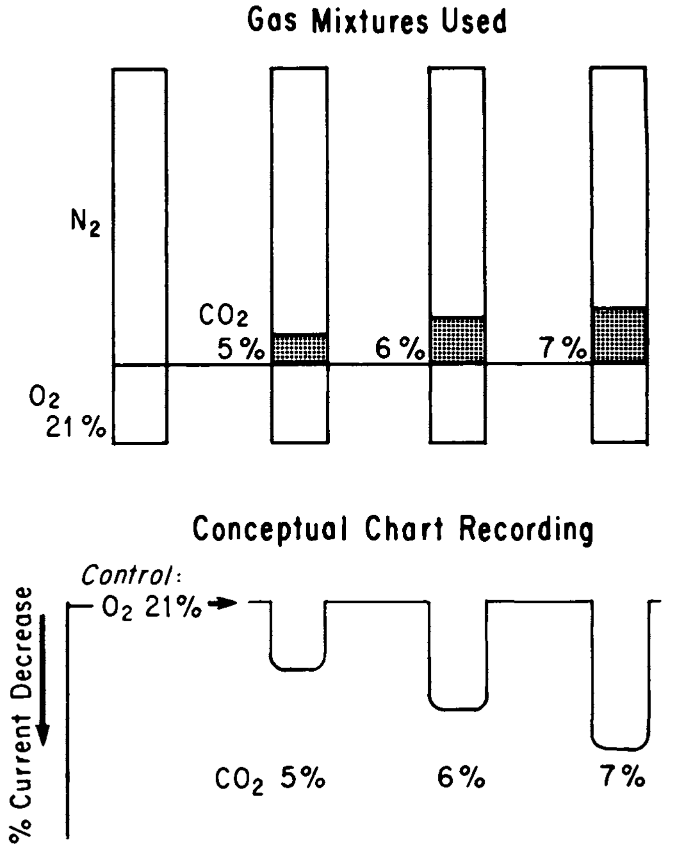


Fig. 2 Conceptual chart recording of the error in the catheter $pO_2$ electrode in the presence of $CO_2$ mixtures.

The polarization voltage for these experiments was −0.8V, and a recorder was used to determine when the current was stable. After a stable $O_2$ current was reached, $CO_2$ was introduced in varying amounts to the gas mixture (keeping $O_2$ as constant as possible) and the new current recorded when stable. The gas mixtures used and a typical chart record of a hypothetical run are shown in Figure 2. Following each trial, the current of the $CO_2$-free gas mixture was again recorded. Since at −0.8V polarization, the current is a linear function of $O_2$ concentration, calculations could be made to correct for the slight change in oxygen concentration (e.g., 0.1%) which occurred in some circumstances.

For polarograms, the elecrode was polarized for 30 mins. at −0.9V, then polarization voltage was varied between −0.01V and −1.2V using an automatic voltage supply. A custom-built difference amplifier was used, which gave results as voltage rather than current. Results were recorded on an X-Y plotter (Fig. 3).

The effect of varying levels of $CO_2$ on nitrogen current was also examined but there was no effect.

## RESULTS

At 5% oxygen, the effect of zero to 10% carbon dioxide was negligible. In contrast, even small amounts of carbon dioxide caused a large drop in current at 21% oxygen. At 21% oxygen, the polarogram is shifted down and slightly to the right in the presence of 4% carbon dioxide, and even more so with 7% carbon dioxide (Fig. 3). The drop in current of the plateau region of the polarogram was approximately 6% and 8% respectively. This represents false $O_2$ readings of 19.8% and 19.2% rather than the actual 21% oxygen. The results of further testing of the electrode at 21% oxygen, and the resulting decreases in current as a function of increasing carbon dioxide are shown in Figure 4. Each number represnts an experimental replicate with the same electrode, done on different days. That is, false readings for $pO_2$ ranged from 20.7% to 17.9% depending upon how much $CO_2$ was present. The sharpest decrease in current seems to occur from 0-5% $CO_2$; from 5-7% $CO_2$ the effect does not increase as dramatically. These results are a sample of approximately 15 total experimental replicates.

Carbon dioxide had no effect on the nitrogen current in concentrations from zero up to 10%; 20% and 100% $CO_2$ caused a negligible current increase.

## DISCUSSION

This work demonstrates that carbon dioxide has a significant effect on the cathode oxygen electrode at 21% $O_2$, but not at 5% $O_2$. Our data regarding the percentage decrease in current as a function of the percent of $CO_2$ in the gas mixture are adequately fitted by both linear and quadratic regression models within 95% confidence limits. This effect could be a source of error under some experimental and clinical conditions; under such circumstances simultaneous measurements of $CO_2$ and $O_2$ must be made so that a correction can be applied.

The mechanism by which $CO_2$ produces these effects upon the $O_2$ electrode is still not understood. Since the electrode membrane is a physical model of the alveolar membrane, knowledge of this mechanism may prove to be physiologically as well as technically useful.

Classical physiological instruments measured both $CO_2$ and $O_2$; under those conditions, we were acknowledging the possible interaction of the two gases. Apparently, today we pay a penalty under some circumstances when we use an instrument which measures only one gas, because this interaction is neglected.

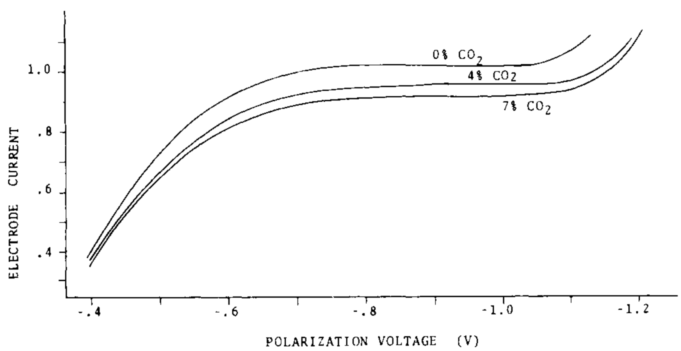


**Fig. 3 The effect of $CO_2$ on the 21% $O_2$ polarogram. An X-Y recorder was used.**

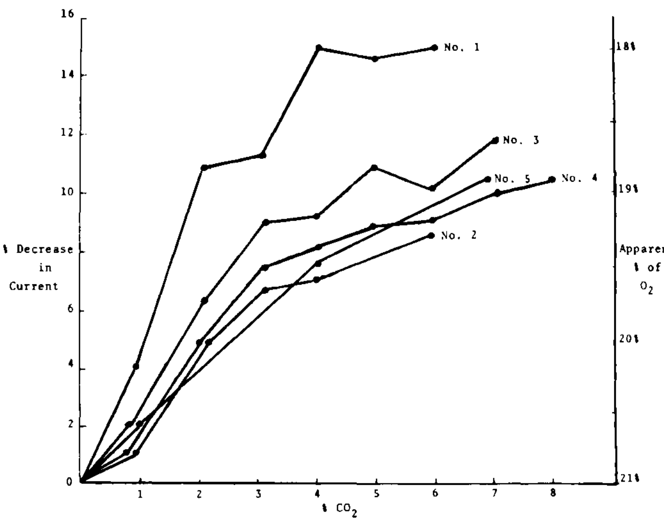


**Fig. 4 Five replicates on successive days with different membranes from catheter $pO_2$ electrode using a chart recorder with 21% $O_2$ and variable $CO_2$ mixtures. These results fall within calculated lines for 95% confidence limits for the linear and the quadratic regression models.**

## ACKNOWLEDGEMENTS

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