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Investigation of Oxygen Exchange in Human Paranasal Sinuses with a Small P_{O_2}-Electrode

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ABSTRACT

A method has been elaborated for the continuous recording of the oxygen content in the human maxillary sinus by using a small P_{O_2}-electrode (Φ 1 mm) which, placed in a cannula, is introduced into the sinus. Model experiment at different P_{O_2} and different temperatures showed that the electrode has satisfactory stability. The response time is 3 seconds. The stability is not changed by introducing the cannula with the electrode through a 2 mm rubber membrane, simulating the perforation of the medial bony wall of maxillary sinus. Measurements in fluid and in gas give almost identical values. Thin layers of albumin or nasal mucus on the electrode do not disturb the results. The presented method has several advantages in comparison with those previously used, but a difficulty sometimes encountered is to get a smooth tight Teflon membrane around the tip of the electrode.

PREVIOUS STUDIES

Gas exchange in the paranasal sinuses has been a matter of discussion since the beginning of this century. In 1909 Hartz (1) assumed an absorption of oxygen in sinuses with obstructed ostium and a replacement by a smaller volume of carbon dioxide. Sluder (2) introduced the term "vacuum headache" as a clinical symptom due to the rarefaction of gases in the sinuses.

In recent decades, the theoretical interest in the gas exchange has been followed by some experimental investigations in animals and humans. Various techniques have been used in these investigations. Doiteau (3) and Flottes et al. (4) performed measurements of the gas exchange in the frontal sinus of the dog. Cannulas were introduced into the sinus through the bony wall of the forehead. The cannulas were connected to each other by a pump and a gas analyser. The sinus was filled with a gas of known composition. Each sample of gas from the sinus was pumped in a closed circuit from the sinus to the gas analyser. The analysing procedure changed the gas composition in the investigated sinus entirely, and the experiment had to be restarted from the beginning after each single measurement.

Kitayama (5) studied the gas composition in maxillary sinuses of patients with chronic sinusitis before Caldwell Luc operation. The samples were obtained through one of two holes in the canine fossa, pouring saline through the other hole into the sinus at the same time. The gas samples were analysed quantitatively with Scholander's method.

Measurements of the oxygen content in the human maxillary sinus have been performed by Drettner (6) with an oxygen analyser and closed circuit. Another method, gas chromatographic analysis of gas samples from the human maxillary sinus, has also been tried (7).

All these mentioned methods have disadvantages which will be discussed later. It therefore seems worthwhile to try to find a more suitable method for studies of the gas exchange. For that purpose a small P_{O_2}-electrode has been tested for measurement of the oxygen exchange in human paranasal sinuses.

P_{O_2}-ELECTRODE

The use of a P_{O_2}-electrode, small enough to be introduced into the human maxillary sinus, has made it possible to perform continuous recordings of change in the antral P_{O_2} (8).

The electrode was a polarographic silver–platinum electrode (Brotzu & Meissl, 1967) with a diameter of 1 mm (9)[1]. The electrode consisted of a platinum thread (Φ 0.0025 mm) moulded into a glass rod which was plated with silver except for at the top (Fig. 1). The platinum acts as cathode and the silver as anode.

[1] The electrode was manufactured by research engineer A. Meissl, Department of Thoracic Surgery, Karolinska Sjukhuset, Stockholm.

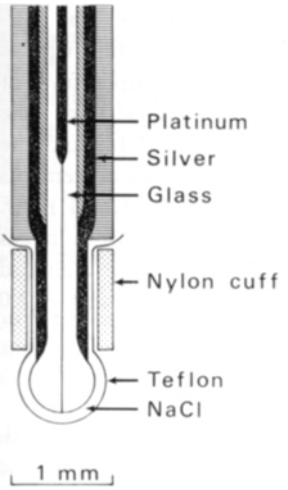

Fig. 1. Schematic drawing of the silver–platinum P_{O_2}-electrode.

Before each experiment the glass tip was covered with a Teflon membrane (fabricated thickness 0.012 mm) keeping a layer of physiologic saline between the Teflon and the glass tip. The Teflon membrane was kept in place by a nylon cuff. A special applicator was used for this procedure. Under magnification it was ascertained that the Teflon membrane was smooth, that the saline did not contain any air and that the nylon cuff fitted tightly around the Teflon membrane. This tightness was also ensured by a special silicone grease. Several applications were sometimes necessary before all the above-mentioned requirements were fulfilled. The functioning of the electrode and the fit of the membrane were checked during calibration, which gave a still better evaluation of the membrane position than did the inspection.

P_{O_2}-MEASUREMENTS

The electrode was connected to a pH-meter with a P_{O_2}-monitor (pH-meter 27 with P_{O_2}-monitor PHA 927b or acid-base analyser PHM 71 b with P_{O_2}-module PHA 930, Radiometer, Copenhagen). The electrode operates at a voltage of approximately 630 mV. Oxygen molecules from the investigated gas pass through the Teflon membrane which is permeable to oxygen by diffusion. The oxygen is reduced at the platinum thread causing a change in the conductivity of the saline inside the Teflon membrane.

The reaction at the cathode occurs in two steps:

1. $2\ H_2O + O_2 + 2\ e^- \rightarrow H_2O_2 + 2\ OH^-$
2. $H_2O_2 + 2\ e^- \rightarrow 2\ OH^-$

The reaction at the anode can be expressed:

$$4\ Ag + 4\ Cl^- \rightarrow 4\ AgCl + 4\ e^-$$

The reduction of O_2 to OH^- changes the conductivity of the electrolyte. The response from the electrode is a current which varies linearly with the P_{O_2} of the sample. The sensitivity, i.e. the current output per mm of P_{O_2}, was adjusted manually on the instrument, 10^{-11} to 10^{-10} A/mmHg of PO_2 was generally used. The response was obtained on an instrument scale and it was also recorded (Cambridge Clearspan P 120 or Philips Automatic Measuring Bridge 2210 U/21 were used as recorders).

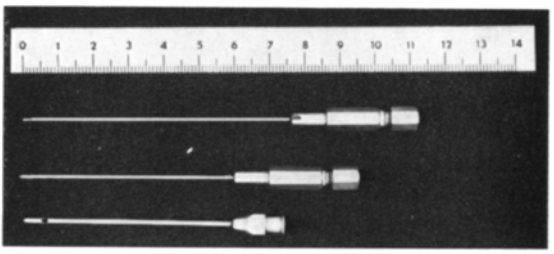

Fig. 2. The electrode without and with Teflon membrane and nylon cuff, and the cannula into which the electrode is introduced.

During all P_{O_2}-measurements the electrode was placed in a cannula with a sharp solid top and a sidehole exactly at the tip of the electrode (Fig. 2). The cannula was applied before calibration and not removed until the whole experiment and a subsequent calibration had been accomplished.

Calibration

Calibration of the electrode was performed before and after each experiment. Two test tubes were used for calibration and both contained saline. One was saturated with nitrogen and the other with air. The tubes were kept at a constant temperature by means of a thermostat. The gases were let into the saline through copper pipes with a length of 2 meters running in spirals in the thermostated bath.

The P_{O_2} in the air can be calculated from the barometric reading (Bp) according to the following formula:

$$P_{O_2} = \frac{20.93(Bp - P_{H_2O})}{100}$$

Saturated vapour pressure at +37°C is 47 mmHg. When Bp is 760 mmHg, the $P_{O_2} = 149$ mmHg if the air is saturated with vapour.

The electrode was first put into the nitrogen-saturated saline and the zero-point of the P_{O_2}-scale of the instrument was adjusted. The electrode was then moved to the air-saturated saline and the sensitivity was adjusted until the meter showed the actual P_{O_2}, usually 149 mmHg.

EXPERIMENTAL TESTS OF THE ELECTRODE

Gas/fluid ratio

The model experiments and the measurements in human sinuses were mostly performed with the

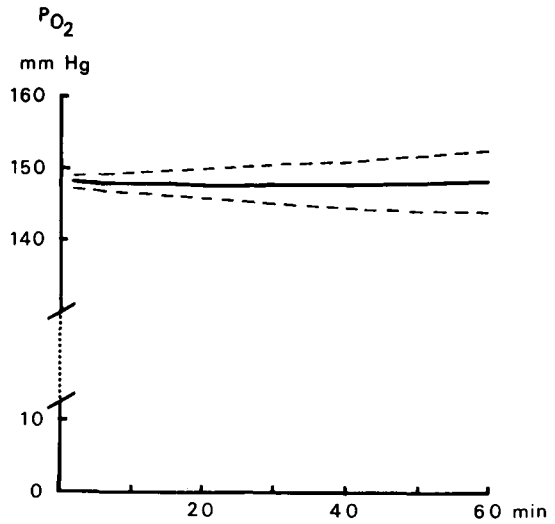

Fig. 3. Mean values and standard deviations of 10 recordings, each during 1 hour with the electrode in saline saturated with air and thermostated to 37.0°C.

electrode in free gas, while calibrations usually were done in saline saturated with nitrogen and air. The gas/fluid ratio was studied with the electrode put first into saline saturated with air and afterwards into a tube with air saturated with vapour. The temperature was 37.0°C in both tubes. The gas/fluid ratio expressed as P_{O_2} gas/P_{O_2} saline varied between 0.97 and 1.01 for different electrodes at a temperature of 37°C. The error due to the gas/fluid ratio was thereafter considered to be small enough to be neglected in the measurements.

Stability

The electrode was tested in different model experiments. In each series, ten experiments were performed.

The stability of the electrode response was tested with the electrode in saline saturated with nitrogen kept at a temperature of 37°C. Recording for 1 hour showed that the standard deviation of a single measurement was less than 1.3 mmHg during the whole experiment.

Experiments in saline with a temperature of 37°C and saturated with atmospheric air coming from a pump showed a standard deviation of the single measurement of ± 1.4 mmHg, ± 2.8 mmHg, ± 4.4 mmHg at 10, 30 and 60 min, respectively (Fig. 3).

To test the stability of the electrode at another temperature a series of experiments was performed with atmospheric air in the same way as previously mentioned, but at a temperature of 24°C both during calibration and testing. The recordings in this series were also stable and the standard deviation for the single measurements remained within ± 2.3 mmHg even after 1 hour.

Another series was made at 37°C with a gas containing 8% O_2 and 92% N_2. The standard deviation of the single measurements was ± 2.0 mmHg after 1 hour.

Temperature dependence

The effect of different temperatures during calibration and measurement was investigated in the following manner. The electrode was calibrated in saline saturated with atmospheric air with a P_{O_2} of 149 mmHg at a temperature of 37.0°C (± 0.1°C) and then kept in this test tube for 5 min. The electrode was thereafter transferred to a similar test tube containing saline saturated with the same atmospheric air as in the calibration test tube, but at a temperature of 24°C and kept there for 5 min. This experiment was performed ten times. The same experiment was then performed at 37°C and 45°C. These series showed that a rise of the temperature of 1.0°C changed the P_{O_2} reading on the radiometer monitor $+1.7$ mmHg, i.e. when the calibration temperature was 36°C and the temperature of the gas in a sinus 37°C the measured value was 1.7 mmHg too high.

Response time

The response time for the electrode was tested when moving the electrode from saline (37°C) saturated with nitrogen to saline saturated with air, i.e. from 0 to 149 mmHg. A paper speed of 25 cm/sec was used as the recorder in this experiment. Full deflection was reached after 3 seconds.

Introduction through a wall

The effect on the electrode of the introduction through the medial antral wall was illustrated in model experiments, where the sinus was replaced by a thermostated bottle with saline on the bottom. The opening of the bottle was covered with a 2 mm thick rubber membrane. Different gases of known composition were per-

fused into the bottle, bubbling through the saline and leaving the bottle through a cannula in the rubber membrane. The electrode in its cannula was introduced through the rubber membrane. Three different series were performed in this model, all at a temperature of 37°C.

In the first series pure nitrogen was used. The standard deviation of the single measurement was less than ± 1.0 mmHg during 1 hour.

The next series was performed with a gas mixture consisting of 8% O_2 and 92% N_2. The standard deviation was ± 2.4 mmHg after 1 hour.

The third series was performed with atmospheric air. The standard deviation after 10 min was ± 2.6 mmHg and after 1 hour ± 3.2 mmHg.

Effect of mucus on the electrode

When the electrode in its cannula is introduced into the human sinuses during sinusitis, it may happen that mucus will cover the electrode. This problem was investigated in a model simulating the nose and the maxillary sinus. The sinus was a plastic syringe with a volume of 10 ml and the nose was a rubber cast from a specimen. The connection between the sinus and the rubber nose simulated the ostium and it had a length of 6 mm and a diameter of 4 mm.

After calibration, the electrode in the cannula was introduced into the sinus model, which was thereupon filled with pure nitrogen. The time for gas exchange by diffusion through the ostium was calculated from the recordings of the exponential increase of the P_{O_2}.

Three kinds of experiments were performed: first with the electrode and cannula clean, then when the cannula and electrode after calibration had been dipped into egg albumin and finally after they had been dipped in nasal mucus. These three recordings were identical.

The effect of a thick layer of mucus in the hole of the cannula was studied with the electrode in the cannula placed in a container filled with 8% O_2 in nitrogen. After a few minutes of recording the hole of the cannula was covered with a thick drop of nasal mucus (c:a 3 mm diameter). The measured P_{O_2} rose immediately 4.5 mmHg and fell afterwards during a period of 4 minutes to the original level where it remained.

DISCUSSION

Only relatively few investigations have been performed about the gas exchange in the paranasal sinuses. This is probably due to the difficulties to obtain a suitable method. The closed circuit method introduced in this field by Doiteau (3) has several disadvantages: each measurement causes a mixing of the gas in the sinus and in the tubes and the experiment has therefore to start from the beginning for each single measurement. This is time-consuming and may also interfere with the results. Further disadvantage with the closed circuit method when using cannulas is the obstruction of the cannula by mucus which often occurs during measurements in patients with sinusitis. This may give a considerable increase in the pressure in the maxillary sinus which may be dangerous due to the risk of air embolism and it also gives completely false values. This method has also been tried in human subjects (6) but it was soon discarded.

Analysis of gas samples taken from a paranasal sinus has a disadvantage in that the reduction of the pressure within the sinus will cause leakage of gas through the ostium giving intermingling with atmospheric air. Kitayama (5) therefore injected saline through another cannula to compensate for the pressure reduction, but he did not discuss the error caused by the gases dissolved in the saline. When similar samples are analysed by gas chromatography it is also difficult to know the pressure within the syringe which interferes with the results. The present authors tried analysis in a Beckman gas chromatograph but leakage through the ostium and lack of knowledge of the total gas pressure made the results unreliable.

The problems mentioned above are avoided when performing measurements with a small electrode introduced into sinus. Continuous measurements are possible with an electrode but not with the other methods mentioned.

The technical problem with the electrode is to get a smooth, tight Teflon membrane around the tip. This membrane often has to be changed before it fits exactly. The membrane can be inspected but it is better to test its function during calibration. Badly-fitting membranes cause unsteadiness of the recordings which can either fluctuate rapidly, or decrease or increase slowly.

The results presented above are obtained with the membrane in a good position.

The gas/fluid factor for the electrode is sufficiently close to 1.0 to permit measurements in sinuses where it is impossible to know if the electrode is situated in gas or in fluid.

Model experiments have shown that the errors in the measurements are sufficiently low to permit reliable results, when measuring in gas or saline. The response time is short enough to follow even very rapid changes of the oxygen content in the maxillary sinus. The stability is also satisfactory. The response is dependent on the temperature and calibration and measurement should therefore be performed at the same temperature.

During all measurements the electrode has been situated within a cannula with a side hole exactly over the membrane. The membrane is therefore protected against disturbances during the introduction of the cannula through the bony medial wall of the maxillary sinus. This has been shown in model experiments where a rubber membrane with a thickness of 2 mm has been used. The rubber membrane will probably have a greater chance to interfere with the membrane than the bony wall.

Experiments when the electrode in its cannula has been dipped in albumin or nasal mucus before recording of the oxygen exchange in a sinus model show that these recordings are identical with those when the electrode and cannula are clean. Thin layers of albumin or mucus on the electrode therefore do not disturb recordings of the oxygen exchange concerning the measured values or concerning the time response.

Thick layers of mucus in the hole of the cannula gave at the moment of application slight increase of the recorded P_{O_2}, when the measurement was performed in 8% O_2. This increase, which probably was due only to higher P_{O_2} of the mucus, was transient and after that the recording was stabile again at the original level.

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