SIMULTANEOUS RECORDING OF LOCAL ELECTRICAL ACTIVITY, PARTIAL OXYGEN TENSION AND TEMPERATURE IN THE RAT HIPPOCAMPUSS WITH A CHAMBER-TYPE MICROELECTRODE. EFFECTS OF ANAESTHESIA, ISCHEMIA AND EPILEPSY

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Abstract—A miniature multiple thin-film recording sensor was used to measure simultaneously the electrical activity, oxygen content and temperature of brain tissue. The chamber-type potential sensor was an Ag/AgCl electrode covered by a Si3N4 (silicon nitride) chamber. The chamber-type oxygen sensor consisted of an Au-Ag/AgCl two-electrode electrochemical cell embedded in an electrolyte-filled Si3N4 chamber. The temperature sensor was a thin-film germanium resistor. The different sensors were spaced 300 μm apart.

Anaesthetics (pentobarbital, chloral hydrate, chloronembutal, halothane) were shown to depress electrical activity and to increase local oxygen tension in the hippocampus. Halothane, but not the other anaesthetics, also increased the current output of the oxygen sensor when tested in saline bath, indicating that the apparent increase in measured oxygen levels during halothane anaesthesia was partly due to an electrochemical effect of halothane on the oxygen sensors. The decrease of tissue oxygen consumption produced by the other anaesthetics is likely to be the result of metabolic depression.

Cerebral ischemia, evoked by cauterization of the vertebral arteries and occlusion of the carotid arteries for 30 min, resulted in the disappearance of both spontaneous and evoked electrical activity in the hippocampus and a decrease of both local temperature and oxygen tension. There was a marked overshoot of the oxygen tension to above preocclusion level following the release of the carotid arteries. As soon as electrical activity returned, the oxygen tension fell again, often below the lowest level seen during the ischemic period. This secondary decrease of oxygen level could be reversed by administration of supplementary small doses of anaesthetic. The anaesthetic-induced increase in oxygen tension was accompanied by a marked decrease in electroencephalogram amplitude and frequency.

During electrically induced seizures a decrease in hippocampal oxygen content occurred and was accompanied by an increase of local temperature. Since the rectal temperature was kept constant, the changes in temperature are likely to reflect changes in blood perfusion of the recorded area. These findings are in agreement with previous observations made with conventional electrodes. In addition, the miniature size of the chamber-type microelectrode assembly allows a correlated monitoring of parallel physiological changes with high spatial and temporal resolution during anaesthesia, ischemia and epilepsy.

The understanding of the relationships between electrical activity, oxygen consumption and blood flow in the brain is crucial for the treatment and prevention of several brain disorders. There are, however, technical limitations in monitoring the changes of physiological parameters locally, in specific brain areas. The total brain oxygen consumption, blood flow, electrical activity and their relationships are routinely investigated with indirect techniques, or by indirect correlation of separate measurements. Each of these physiological parameters, as well as the vulnerability of cells to certain pathophysiological conditions, shows great regional variation. Therefore, it is important to follow local events within a certain micro-area by techniques which have high spatial resolution, e.g. microelectronic recordings of oxygen tension, blood flow and electrical activity, or by gas-sampling microprobes coupled to mass spectrometry. The latter measurements have the advantage of great accuracy, but do not have a temporal resolution high enough to follow changes during rapidly occurring events.

Thin-film and solid-state multiple potential sensors for recording bioelectric activity of nerve tissue and muscle have been developed and used successfully. Thin-film and thick-film oxygen sensors have also been reported. The major disadvantages of these designs are that (1) there are limits to reducing their size, because of the increasing electrode-electrolyte impedance and the inevitable increase in signal disturbances connected therewith, and (2) the electrodes are in direct contact with the living tissue which may result in severe disturbances during long-term voltammetric recordings. These dis-
advantages can be overcome by the chamber-type electrochemical sensors. The new chamber-type design improved the recording qualities of the potential sensors and permitted the integration of oxygen and temperature sensors onto the same probe. In the chamber-type electrode a thin Si$_3$N$_4$ (silicon nitride) layer forms a chamber with the glass substrate carrying the recording thin-film metal electrodes and connections. The chamber is filled with an electrolyte, thus separating the recording electrode surface from the nervous tissue. Microholes in the chamber form the actual recording sites.

In the present experiments we applied this commercially available assembly of chamber-type microelectrodes, measuring electrical activity, oxygen tension and temperature, to study (i) the relative changes of these variables under anaesthesia; (ii) the local oxygen and temperature changes accompanying the disappearance and reappearance of electrical activity in the hippocampus upon blockage and restoration of blood supply to the forebrain; (iii) the relative levels of these variables during complete electrical silence; and (iv) the changes of oxygen tension and temperature during epileptic afterdischarges. The experiments were carried out in the rat hippocampus, since a great deal of information is available on the spatial distribution of its spontaneous and evoked potential characteristics and because the hippocampus of the rat has been extensively studied in epilepsy, circulatory and metabolic investigations and in models of forebrain ischemia.

EXPERIMENTAL PROCEDURES

Animals and surgery

The experiments were carried out on 34 male Wistar rats (Charles River) weighing 200-300 g. They were anaesthetized with Equithesin (chlornembutal, 3 ml/kg, 18 animals) or halothane (16 animals). Halothane was vaporized in air (0.5-2%), and was administered via a nose mask or directly through a tracheal cannula after tracheotomy. The body temperature of the animals was kept constant (37 °C) throughout the experiment by a homeothermic blanket system (Harvard Apparatus Ltd), using a rectal probe.

Recording and data processing

A miniaturized multiple thin-film recording device was used to simultaneously measure the electrical activity, oxygen content and temperature of the hippocampus (Fig. 1). The two potential sensors, 0.9 mm from one another, were positioned to record activity from the hilus of the dentate gyrus and the CA1 region. The potential sensors were Ag/AgCl electrodes covered by chambers formed by thin layers of Si$_3$N$_4$. The amperometric oxygen sensor consists of an Au-Ag/AgCl, two-electrode electrochemical cell (B, C), embedded in an Si$_3$N$_4$ chamber filled with electrolyte. The chambers are visible on the low-power photograph (arrowheads in A). The temperature sensor is a thin-film germanium transistor based on the principle of a resistance thermometer. For a detailed description and characterization of these sensors see Refs 42, 43. The tip of the glass substrate is pulled into an approximately 3-mm-long needle, which can be broken off at the desired length. Scales: A, 500 μm; B, C, 100 μm.

Fig. 1. Light micrographs of the Ottosensors electrode probe at low power in (A), and at higher magnification in (B) and (C). The sensors are placed 300 μm from each other in a sequence of potential (P:1, deepest), oxygen (O:1), temperature (T:1), potential (P:2), oxygen (O:2), temperature (T:2, highest). The potential sensors are Ag/AgCl electrodes in chambers formed by thin layers of Si$_3$N$_4$. The amperometric oxygen sensor consists of an Au–Ag/AgCl, two-electrode electrochemical cell (B, C), embedded in an Si$_3$N$_4$ chamber filled with electrolyte. The chambers are visible on the low-power photograph (arrowheads in A). The temperature sensor is a thin-film germanium transistor based on the principle of a resistance thermometer. For a detailed description and characterization of these sensors see Refs 42, 43. The tip of the glass substrate is pulled into an approximately 3-mm-long needle, which can be broken off at the desired length. Scales: A, 500 μm; B, C, 100 μm.
layers of Si₃N₄. The advantage of the chamber-type electrode is that chloride ion concentration changes do not affect the recordings, because of the electrolyte buffer. The temperature sensor was a thin-film germanium resistor based on thermistor measurement principles. The amperometric oxygen sensor consisted of an Au–Ag/AgCl two-electrode, electrochemical cell embedded in an Si₃N₄ chamber filled with electrolyte. The chamber type oxygen sensor has a negligible diffusion error and a better spatial and temporal resolution than the traditional Clark sensors. Its response time is 0.25–1.00 s.42

The outputs of the oxygen and temperature devices were connected to LED voltmeters and a polygraph (Grass). Due to the limitations of the number of recording channels of the polygraph, two potential sensors, one temperature and one oxygen sensor, were recorded on the polygraph; the other oxygen and temperature sensors were monitored only on the LED voltmeters. The angular bundle was stimulated at 0.1 Hz with single pulses (0.2 ms) at an intensity (10–50 V) to evoke population spikes in the dentate gyrus. Epileptic discharges were elicited by 5–10-s-long trains of 15–30 Hz, in 14 animals. Forebrain ischemia was produced in 32 animals by the four-vessel occlusion model of Pulsinelli and Todd et al.59 The alar foramina on each side were drilled to expose the vertebral arteries running in the foramen transversarium, and then they were cauterized and split under direct visual control.

Oxygen sensor tests

The electrochemical effects of halothane, chloral hydrate, pentobarbital and Equithesin were assessed, using physiological saline as a medium, bubbled with N₂, air or O₂ for several hours. In N₂-saturated saline, where the partial O₂ tension is close to zero, the sensors showed a residual current of 3–6 pA. The maximum oxygen tension values measured in vitro were in a range of 40–45 pA, but typically they were between 15–25 pA under normal physiological conditions and light Equithesin anaesthesia. In vivo "zero checks" (e.g. ventilating the animal with N₂) were not performed, since the animals were also used later, following perfusion, to study morphological changes evoked by ischemia or epileptic discharges. The in vivo changes of oxygen tension are, therefore, given as percentage changes without correcting for residual current. Consequently, the changes expressed as percentage values, and indicated on the figures, are smaller than in reality, i.e. if the residual current had been subtracted.

The addition of 0.2% liquid halothane or bubbling 0.5% halothane vaporized in air through saline solutions (gassed previously with either air or N₂) increased the current output of the oxygen sensors dramatically (see Fig. 3C and D), probably due to an electrochemical reduction of halothane on the gold electrode.16,36 Addition of pentobarbital (0.02% w/v), chloral hydrate (0.02% w/v) or Equithesin (1% w/v) did not change significantly the current output of the oxygen sensors.

RESULTS

Potential recordings

Stimulation of the angular bundle evoked short-latency (2.5–4.0 ms), large positive potentials in the hilus. With higher intensity pulses a negative-going population spike, riding on the positive field potential, was also observed. Occasionally a positive potential with a latency of 12–18 ms was also present in the shallow electrode, reflecting the trisynaptic activation of the CA1 field. These characteristic waveforms have been repeatedly described using conventional microelectrodes.1,6,36 By decreasing the level of anaesthesia and/or stroking the back of the rat, rhythmic slow waves (theta pattern) appeared in the shallow (CA1) electrode coupled with large amplitude irregular waves in the hilus (Fig. 2).

Effects of anaesthesia

Since in pilot experiments we found that the level of anaesthesia had a conspicuous effect on the hippocampal electroencephalogram patterns, we systematically followed the local partial oxygen tension, temperature and electrical changes in rats anaesthetized with Equithesin or halothane. Decreasing or increasing the level of anaesthesia resulted in reproducible decreases or increases, respectively, of oxygen tension without noticeable changes of the local temperature (Figs 3A, 4A and B). The changes in oxygen tension were substantial, often reaching 30% of the baseline value obtained during deep anaesthesia. Both anaesthetics, especially halothane (Fig. 3A), decreased the rate of respiration, therefore arterial pO₂ probably decreased while the tissue oxygen tension increased. The i.p. injections of saline did not influence either the rate of respiration or the tissue oxygen level.

![Fig. 2. Recordings by the deep (dentate hilus) and shallow (CA1 region) potential sensors of the same probe. Demonstration of rhythmic slow waves (theta pattern) in the CA1 region (upper trace), and large-amplitude irregular waves in the dentate hilus (lower trace) during lighter anaesthesia while stroking the back of the animal.](image)
The pattern of electroencephalogram also varied depending on the level of anaesthesia, and changed parallel with the oxygen tension. When halothane anaesthesia was light, touching or stroking the animal's back usually resulted in the appearance of rhythmic slow (theta) activity. Under deep halothane or Equithesin anaesthesia high-voltage irregular waves dominated (Figs 3A, B and 5). The tests carried out in saline showed that halothane increased the current output of the oxygen sensors (Fig. 3C and D), but Equithesin did not (see Experimental Procedures). Therefore, the fluctuation of oxygen tension with halothane anaesthesia could be due, at least in part, to the electrochemical action of halothane directly on the oxygen electrode. This is unlikely to be the only cause of oxygen tension increase under halothane anaesthesia, since halothane anaesthesia is accompanied by metabolic depression, e.g. a reduction of oxygen consumption and electrical activity. The relative contribution of these two effects of halothane cannot be established in vivo, therefore halothane anaesthesia was not used in subsequent ischemia experiments.

Tests in saline showed that Equithesin anaesthesia is unlikely to produce any electrochemical reaction on the oxygen sensors. Therefore, the detected increase in oxygen tension in vitro is likely to be associated with metabolic depression. As the animals were recovering from an initial high dose of Equithesin, the oxygen tension slowly decreased, while small supplementary doses (20–25% of the initial dose) resulted in a rapid rise of oxygen tension. This was paralleled by changes in the electroencephalogram, which showed a decrease both in frequency and amplitude in response to small doses of the anaesthetic. These changes were more pronounced after, than before a 30 min ischemic episode (Figs 4A, B and 5). The small increase in the rate of respiration is likely to increase arterial pO2. The decrease of tissue oxygen tension upon recovery from Equithesin anaesthesia at constant arterial pO2 would be, therefore, even greater.
Potential, oxygen tension and temperature recordings in rat hippocampus

Fig. 4.
Effects of complete forebrain ischemia

Forebrain ischemia, produced by the four-vessel occlusion method, resulted in a rapid cessation of spontaneous and evoked electrical activity in the hippocampus (Figs 4A, B, 5 and 6). Background activity decreased to isoelectric level within 20–30 s. The monosynaptic-evoked response in the dentate gyrus and the trisynaptically-evoked potential in the CA1 region began to decrease 20–40 s after the cessation of the spontaneous electroencephalogram, and disappeared completely in 1–2.5 min. It is not clear whether some residual flow remained, even in those animals with no electrical activity. 7 In animals where the evoked potential did not disappear completely, the ischemia was regarded incomplete. Nevertheless, the disappearance of the evoked responses was always preceded by the reversal of the polarity of the CA1 response and a transient (5–30 s) burst of high frequency (20–50 Hz) spindle (Figs 4A, B, 5 and 6).

The rapid reduction of the electrical activity was paralleled by a decrease of the local temperature, due to the blockade of forebrain circulation. In cases of incomplete ischemia the magnitude of temperature decrease was much smaller, occasionally less than 50% of the usual complete ischemic temperature drop (5–6°C). In these animals some electrical activity always remained.

The local partial tension of oxygen decreased together with the temperature, however, it rarely decreased to a level lower than that observed under light anaesthesia and normal blood supply. Occasionally,
Potential, oxygen tension and temperature recordings in rat hippocampus

Fig. 6. Electroencephalogram, oxygen tension and temperature recording from the hippocampus of rat El/14 at the onset (large arrow) of 30-min ischemia produced by the four-vessel occlusion method and preceded by 1-min asphyxia. The deep potential sensor was recorded from the hilus (upper trace), the other from the CA1 region. One oxygen and one temperature sensor situated between the two potential sensors was monitored. The occlusion resulted in the cessation of spontaneous electrical activity within 25 s. Evoked field potentials (asterisks) produced by stimulation of the angular bundle (10 V, 0.1 Hz) disappeared within 75–80 s both in the hilus (monosynaptic) and in the CA1 region (trisynaptic). In the latter the evoked potential reversed polarity for 25 s before disappearing. In both regions the disappearance of the evoked potential was accompanied by a brief (30–35 s) high-frequency (25–50 Hz) spindle.

Both the local oxygen tension and the temperature decreased rapidly following occlusion.

the oxygen level started to rise slowly before the release of the carotid arteries (Fig. 4). This may have been the result of residual blood flow reaching the hippocampus via non-occluded collateral vessels, although the temperature continued falling in each case. In contrast, releasing one of the carotid clamps for only 2–3 s caused a marked increase in temperature.

Following release of the carotid arteries the temperature rose suddenly, increasing above the pre-

Fig. 7. Records of epileptic afterdischarge evoked by trains of high-frequency stimuli (15–20 Hz, 50 V) delivered to the perforant path input to the hippocampus (angular bundle). Local oxygen tension is decreased and the temperature slightly increased by the afterdischarges (use broken line as reference constant value).
occlusion level. This overshoot lasted for 15–20 min.
The partial tension of oxygen also showed a steady increase. Upon the recovery of the spontaneous and/or the evoked electrical activity (10–15 min after release) the oxygen tension fell rapidly, faster, and often even to a lower level, than following the carotid artery occlusion (Fig. 4A and B). This postsischemic decrease of the partial oxygen tension occurred at a normal or even at elevated local temperature. The decrease could be stopped and reversed by giving a small dose of anaesthetic (0.2 ml Equithesin), which at the same time reduced the electroencephalogram amplitude and frequency (Figs 4A and 5). One to three hours after the ischemic period a slow recovery from Equithesin anaesthesia was still accompanied by a marked increase in EEG amplitude and frequency, and by a decrease of oxygen tension. These changes were smaller than immediately after the ischemic period, and they were similar to that seen before the ischemic episode (Figs 4A and 5).

Effects of evoked epileptic afterdischarges

The relationships among increased neuronal firing, local partial tension of oxygen and local temperature were further investigated in experiments in which increase in neuronal activity was produced by electrical stimulation and epileptic discharges (Fig. 7). Trains of stimuli delivered to the perforant path input resulted in epileptic afterdischarges, and they were invariably accompanied by a decrease of the partial tension of oxygen and a small increase in temperature (Fig. 7). Both changes were determined by the intensity and duration of epileptic discharges. Stimulus trains without epileptic discharges were usually ineffective.

DISCUSSION

Technical considerations

The present experiments demonstrate that local electrical activity, temperature, and partial tension of oxygen can be recorded in parallel. Each of the parameters can vary independently, depending on the physiological conditions used to induce the changes. The results also support the selectivity of the recording system and rule out the possibility that the observed changes are due to "crosstalk" or to just a common denominator.

The advantage of the chamber-type electrode is its very small size, minimizing tissue damage, and high spatial resolution. No other available system possesses both of these important features. Parameters of several modalities can be obtained simultaneously, thus data collection is much faster and more reliable than with traditional single electrodes. In addition, the on-line measurements reveal important time relations which may lead to cause-effect deductions.

The spontaneous and evoked potentials recorded by the hybrid probe were similar to those obtained with conventional microelectrodes.1,7,12,29,62 There was usually some difference between the absolute values of current output of the deep and shallow oxygen sensors. This difference may be explained by the fact that the oxygen tension varies considerably in the brain even within a very short distance, but in a small area under normal physiological conditions it stays remarkably constant.4,6,34,54 The residual currents showed only slight differences. The difference between the current output of the two oxygen sensors was negligible in measurements taken in saline. The induced changes in oxygen tension, when expressed as percentages, were very similar on the two sensors of the same electrode.

There was no significant difference in the temperature changes measured by the two temperature sensors.

Oxygen tension; a secondary fall following ischemia

Following carotid artery occlusion or asphyxia the oxygen tension in most cases changed towards the expected direction,4,15,30,34,41,53 until the release of the carotid arteries. The occasional rise of oxygen tension 5–10 min before the release of the carotid arteries may be due to increased residual blood flow.16 However, the steady decrease of the temperature indicated that very little, if any, increase in the residual blood flow took place in the recorded area, thus the apparent increase in oxygen tension may be due to as yet unknown factors.

In contrast to earlier studies,15,30,34 we did not see a complete disappearance of tissue oxygen even if the electroencephalogram became isoelectric. Several reasons may account for this apparent discrepancy. Firstly, with decreased oxygen availability, there is a reduction in tissue oxygen consumption,35 especially when the electrical activity is stopped. The unconsumed oxygen carried by the calculated 3% residual flow present in the hippocampus of all four-vessel occluded rats45 may be detected by our electrode. Secondly, the disappearance rate of oxygen may be slowed by a continuous release of oxygen from oxyhaemoglobin,30,34 which may allow time for other factors to silence the neurons (see below). Further evidence for residual oxygen tension during ischemia comes from the secondary fall of oxygen tension, which was often greater than during ischemia (Fig. 4A, and see below).

The remarkable overshoot in oxygen tension upon the release of the carotid arteries has also been reported following very short ischemic episodes30,34 and hypoxia.4,5 It can be explained by an initial hyperaemia, and a very low rate of tissue oxygen consumption as a result of electrical silence. The return of the evoked field potentials coincided with a dramatic fall of the tissue oxygen tension, which occurs while the temperature record still shows hyperaemia. The capillary microflow, however, may not have been fully restored, resulting in a subnormal oxygen supply to the tissue. The oxygen consumption
of the tissue has been shown to increase at this stage. 18

The presence of a secondary fall of oxygen tension back to the ischemic or to even lower levels during the restoration of electrical activity shows that the nervous tissue is capable of an almost complete extraction of the available oxygen in order to maintain electrical activity after recovering from an ischemic episode. This raises the question of what factor is the initial cause of the disappearance of electrical activity at the onset of ischemia. The usual explanation is that the lack of oxygen causes a depletion of high-energy phosphates and consequently a membrane failure (i.e. breakdown of the \( \text{Na}^+ \), \( \text{K}^+ \)-pump). Another possibility is that electrical silence is produced by a protection mechanism localized within the nervous tissue, which at a certain hypoxic threshold could silence the neurons by depolarization, e.g. by releasing potassium from the cells. 4 This mechanism, if present, may be unoperational after ischemia, since oxygen levels even below the ischemic level did not silence the neurons. Alternatively, the alarm signal for the protection mechanism is not the level of oxygen tension, but some other factor, for example high tissue \( \text{CO}_2 \) tension and/or low pH. 16, 19

The duration of this secondary relative hypoxic state could not be determined under our conditions, since the animals were given supplementary doses of anaesthetic (0.2 ml Equithesin) as they became sensitive, and this caused an increase in oxygen tension paralleled by decrease in electroencephalogram amplitude and frequency. This is in agreement with previous studies on the relationship of anaesthesia, cerebral metabolism and the electrical activity. 20, 21, 27, 34, 35-58

The rapid fall of temperature during ischemia and its rapid rise following the release of the carotid arteries is probably due mainly to the cessation and reinstatement of blood flow, but local metabolic changes may also play some part. Monitoring the local temperature during ischemia is important especially if the extent of neuronal injury is to be studied, since low brain temperature during ischemia was shown to have a powerful protective effect. 10 The postischemic overshoot in temperature correlates well both in magnitude (about 20% of the magnitude of decrease seen during ischemia) and duration (15-20 min) with the hyperaemic period reported to occur after ischemia in different models. 17, 28, 31, 45 Our measurements, however, do not show any secondary decrease in temperature correlating with the hypoperfusion period, which usually follows hyperaemia. 17, 28, 31, 45 This may be because in our animals there was no hypoperfusion, or its effect on the temperature was compensated by increased local metabolic activity, i.e. by rebuilding the high-energy phosphate reservoir. 16, 46, 48, 49

### Relative hypoxia and hyperaemia during epileptic discharges

The decrease of partial oxygen tension and increase of local temperature (i.e. increase of perfusion) during and following epileptic discharges is in agreement with previous reports using different models and measuring systems. 15, 27, 39 It has been shown that there is a close and inverse relationship between electrical activity and tissue oxygen level. 23, 15, 34, 27, 38, 40, 56 Increased electrical activity results in higher rates of oxygen extraction/consumption, which is seen by our electrode as a decreased oxygen tension. This leads to an increase in blood flow, 27, 35 which can in most cases satisfy and even overcompensate for the increased oxygen demand. 27, 38, 39 This increase in blood flow was reflected in our temperature recordings.

### CONCLUSION

These findings indicate that the complex interactions between electrical activity, cellular metabolism and cerebral blood flow can be readily analysed by the chamber-type potential/oxygen/temperature electrode probe, and the high spatial and temporal resolution of the measurements can provide new insights into the pathophysiological processes which take place during ischemia and epilepsy.

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### REFERENCES


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