Superoxide (\(\cdot O_2^-\)) Production in CA1 Neurons of Rat Hippocampal Slices Exposed to Graded Levels of Oxygen

Dominic P. D’Agostino,1 Robert W. Putnam,2 and Jay B. Dean1

1Department of Molecular Pharmacology and Physiology, College of Medicine, University of South Florida, Tampa, Florida; and 2Department of Neuroscience, Cell Biology and Physiology, College of Medicine, Wright State University, Dayton, Ohio

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D’Agostino DP, Putnam RW, Dean JB. Superoxide (\(\cdot O_2^-\)) production in CA1 neurons of rat hippocampal slices exposed to graded levels of oxygen. J Neurophysiol 98: 1030–1041, 2007. First published June 6, 2007; doi:10.1152/jn.01003.2006. Neuronal signaling, plasticity, and pathologies in CA1 hippocampal neurons are all intimately related to the redox environment and, thus, tissue oxygenation. This study tests the hypothesis that hyperoxic superfusate (95% O2) causes a time-dependent increase in superoxide anion (\(\cdot O_2^-\)) production in CA1 neurons in slices, which will decrease as oxygen concentration is decreased. Hippocampal slices (400 \(\mu\)m) from weaned rats were incubated with the fluorescent probe dihydroethidium (DHE), which detects intracellular \(\cdot O_2^-\) production. Slices were loaded for 30 min using 10 \(\mu\)M DHE and maintained using one-sided superfusion or continuously loaded using 2.5 \(\mu\)M DHE and maintained using two-sided superfusion (36°C). Continuous loading of DHE and two-sided superfusion gave the highest temporal resolution measurements of \(\cdot O_2^-\) production, which was estimated by the increase in fluorescence intensity units (FIUs) per minute (FIU/min ± SE) over 4 h. Superoxide production (2.5 \(\mu\)M DHE, 2-sided superfusion) was greatest in 95% O2 (6.6 ± 0.4 FIU/min) and decreased significantly during co-exposure with antioxidants (100 \(\mu\)M melatonin, 25 \(\mu\)M MnTMPyP) and lower levels of O2 (60, 40, and 20% O2 at 5.3 ± 0.3, 3.3 ± 0.1, and 1.6 ± 0.2 FIU/min, respectively). CA1 cell death after 4 h (ethidium homodimer-1 staining) was greatest in 95% O2 and lowest in 40 and 20% O2. CA1 neurons generated evoked action potentials in 20% O2 for >4 h, indicating viability at lower levels of oxygenation. We conclude that \(\cdot O_2^-\) production and cell death in CA1 neurons increases in response to increasing oxygen concentration product (\(\Delta_{\text{PO}_2} \times \text{time}\)). Additionally, lower levels of oxygen (20–40%) and antioxidants should be considered to minimize superoxide-induced oxidative stress in brain slices.

INTRODUCTION

Superoxide anion (\(\cdot O_2^-\)), generated from the mitochondria, is the most abundant form of reactive oxygen species (ROS) in neurons (Emerit et al. 2004; Nicholls 2004; Sugawara and Chan 2003). Its levels are tightly regulated under normal conditions because it can, paradoxically, have both physiological and pathophysiological effects on cellular function (Drobe 2002; McCord 1995). For example, in the CA1 hippocampus, \(\cdot O_2^-\) and other ROS act as signaling molecules in processes such as long-term potentiation (LTP) (Gahtan et al. 1998; Klann and Thiels 1999; Klann et al. 1998; Knapp and Klann 2002) and oxidative preconditioning induced by cerebral ischemia (Furuichi et al. 2005; Ravati et al. 2000) and breathing hyperbaric oxygen (Nie et al. 2006). Excess production of \(\cdot O_2^-\), however, can occur as a result of mitochondrial dysfunction with deleterious consequences for neurons (Emerit et al. 2004). In fact, there is a selective vulnerability of the CA1 pyramidal neurons to \(\cdot O_2^-\)-induced oxidative stress, which is thought to be critical in producing neuronal damage (Weinstock and Shoham 2004; Wilde et al. 1997). For example, \(\cdot O_2^-\) is reduced sequentially to form hydrogen peroxide and hydroxyl radicals. Excess \(\cdot O_2^-\) also reacts with nitric oxide to form peroxynitrite. All of these \(\cdot O_2^-\)-derived reactive species are highly toxic to neurons in excess concentrations (Emerit et al. 2004; Moncada and Bolanos 2006).

In the present study, we examined the effect of sustained oxygen exposure on \(\cdot O_2^-\) production in CA1 hippocampal neurons in tissue slices. The PO2 in the intact CNS ranges from <10 to 35 Torr for a rat breathing normobaric air (reviewed in Dean et al. 2003). Therefore tissue PO2’s exceeding 35 Torr in the CNS are, presumably, hyperoxic. Work from our lab has demonstrated that the tissue PO2 profiles measured in 300–400-\(\mu\)m-thick brain slices (rat) equilibrated with ≥20% O2 are also hyperoxic from the surface to the core (Dean et al. 2005; Mulkey et al. 2001). Surprisingly, nearly all experiments using the in vitro brain slice are performed with solutions equilibrated with 95% O2-5% CO2 which produces a tissue PO2 of ~440 to ~300 Torr (from surface to core, 150 \(\mu\)m deep), which is the equivalent of a rat breathing >2.0 atmospheres absolute (ATA) O2 (Dean et al. 2003). These supraphysiologically high PO2’s likely perturb redox homeostasis, which is intimately linked to cellular excitability (Drobe 2002). In fact, recent evidence from our lab shows that normobaric and hyperbaric hyperoxia increases the excitability of CA1 neurons in hippocampal slices and activates neural plasticity (Dean et al. 2004; Garcia et al. 2004).

In this study, we hypothesized that 95% O2 causes a significant time-dependent increase in \(\cdot O_2^-\) levels in the CA1 region in hippocampal slices relative to lower levels of oxygen (60, 40, and 20% O2). The results of this study demonstrate that 95% O2 significantly increases the rate of \(\cdot O_2^-\) production and caused the greatest cell death over 4 h relative to lower levels of oxygen. These findings suggest that lower levels of control oxygen (e.g., 20 or 40%), supplemental antioxidants or both procedures should be considered for use with brain slices.
Generating and scavenging superoxide

Superoxide anion production was stimulated with FCCP (1 μM), which has been shown previously to stimulate mitochondrial \( \text{O}_2^- \) production in vitro (Bindokas et al. 1996; Scanlon and Reynolds 1998; Sengpiel et al. 1998). MnTMPyP is a cell-permeable superoxide dismutase (SOD) and catalase (CAT) mimic and has been used at a concentration of 25 μM to quench \( \text{O}_2^- \) production (Dantas et al. 2002; Wang et al. 2004). Light-inactivated MnTMPyP (25 μM, 12 h visible light) was used to control for possible nonspecific effects of MnTMPyP on fluorescence intensity. Melatonin was used at a concentration of 100 μM as a broad spectrum antioxidant, which has been shown to be particularly effective at scavenging \( \text{O}_2^- \) (Uchida et al. 2004).

Visualization and measurement of superoxide in hippocampal slices

Relative rate of \( \text{O}_2^- \) production was measured by monitoring an increase in ethidium fluorescence over time generated by the oxidation of DHE by \( \text{O}_2^- \) (Bindokas et al. 1996; Nakamura et al. 2001; Zhao et al. 2003). DHE is oxidized to the fluorescent product ethidium (intracellular \( \text{O}_2^- \), which intercalates with the cell’s DNA and is thought to further enhance its fluorescent properties. Cellular fluorescence was imaged using a Nikon extra long working distance (ELWD, 16 mm) Plan Fluor ×10 infinity-corrected objective (0.30 NA) with Hoffman modulation contrast optics.2 The oxidized product of DHE (ethidium) was visualized by alternatively exciting dye-loaded cells at 525 nm and then capturing their fluorescence emission at 590 nm. Baseline measurements of FIU were initiated within 15 min of transferring the slice to the tissue bath chamber. Measurements of FIU of individual neurons were taken every 1–5 min thereafter with minimum exposure times (200 ± 50 ms) to limit phototoxicity and photobleaching. Observations lasted 30 min to 4 h, depending on the experimental protocol. Images were captured using a digital camera (CoolSnap HQ, Roper Scientific, Tucson, AZ) and processed using MetaFluor software (Universal Imaging, Sunnyvale, CA).

Data analysis

During each DHE experiment, several cells within the CA1 pyramidal region were selected to monitor real-time production of \( \text{O}_2^- \) and to gauge the outcome of the experiment. Subsequently, experiments were analyzed off-line using MetaFluor to measure changes in FIU of individual neurons, which are reported here. Several criteria were used to select cells for off-line analysis. In preincubated slices (10 μM DHE × 30 min) only cells with an initial baseline of 400–600 FIU were analyzed. A baseline FI of <300 units presumably reflected poor retention of DHE in cells, whereas a baseline FI >600 units appeared to indicate early oxidative stress, possibly from cells damaged near the surface of the slice; these cells were more apt to lyse and disappear before the experiment ended. Cells that disappeared (lysed) within the first 60 min of measurement were excluded from analysis. Average FIU for each cell was calculated as the change in fluorescence from baseline, \( \Delta \text{FI} = (\text{FI} - \text{FI}_b) \), where \( \text{FI}_b \) is the baseline fluorescence defined by FI at the start of the experimental recordings. Superoxide production was reported as a change in absolute FIU at a given time point, or as a slope of the fluorescence intensity over time (\( \Delta \text{FIU}/\text{min} \)), which reflected the rate of \( \text{O}_2^- \) production. Each cell served as its own control. Fluorescence values were measured using MetaFluor software and were analyzed and plotted using Excel, SigmaPlot and KyPlot software packages. Statistical comparisons of

1Experiments (Figs. 1-5) and initial analyses were conducted at Wright State University, Dayton, OH. The final analyses, manuscript preparation and additional experiments requested after peer review (Figs. 6 and 7) were conducted at the University of South Florida, Tampa, FL, using the same research equipment.

2Hoffman modulation contrast (HMC) optics were not required for these experiments however. The slit aperture in the HMC modified objective, which would reduce the amount of transmitted light, was not a problem when working with DHE because neutral density filters were still required to avert photobleaching during repeated DHE excitation.
absolute FIU and slopes of \(O_2^-\) production (\(\Delta FIU/\text{min}\)) between graded \(O_2\) concentrations were made using an unpaired Student’s \(t\)-test and \(P < 0.05\) was considered significant. One-way ANOVAs were performed on the slope of the FIU/time, and multiple comparison tests were performed using a Tukey-Kramer’s test for pairwise comparisons (\(P < 0.05\)). All FIU values are reported as the means ± SE. All summary data were collected from at least three and ≤12 independent experiments in different slices.

**Visualization and measurement of cell death in CA1 cell layer**

Relative levels of CA1 cellular viability in hippocampal slices exposed to graded levels of oxygen (0–4 h) were assessed using ethidium homodimer-1 (EH-1, 12 mM stock in DMSO) at a final concentration of 6 \(\mu\)M. EH-1 fluorescence increases with increased numbers of dead cells and has been used to qualitatively estimate relative tissue viability in hippocampal slices (Bickler and Hansen 1998; Pinheiro et al. 2006). After recovery from sectioning (60 min in 95% \(O_2\)), brain slices were exposed to 95, 60, 40, or 20% \(O_2\) in 5% \(CO_2\) and balance \(N_2\) for 0–4 h. After incubation with EH-1, the slices were washed for 15 min and transferred to the imaging chamber. Images were captured using the same excitation/emission filters and ELWD (×10) objective used with DHE. Five individual brains (4 slices/brain) were used for each level of oxygen (\(n = 20\) slices/level of \(O_2\)) with slices sampled at times 0 and 4 h. EH-1 fluorescence was quantified by measuring the average EH-1 fluorescence within an 800 \(\times\) 80 \(\mu\)m area positioned over the CA1 pyramidal region. Summary data are presented as the group average FIU ± SE, and significance was evaluated for time 0 versus 4 h at each level of \(O_2\) using a Student’s unpaired \(t\)-test.

**Intracellular recordings of CA1 neurons during and after exposure to 20% \(O_2\)**

Intracellular recordings were made in CA1 pyramidal neurons using sharp-tipped, high-resistance (50–110 M\(\Omega\)) microelectrodes filled with 3 M potassium acetate in bridge-balance mode using an Axoclamp 2A amplifier (Molecular Devices). After recovery from slicing in 95% \(O_2\) (1 h, 22°C) and incubation in 20% \(O_2\) (4 h, 22°C), slices were transferred to a recording chamber and superfused continuously with ACSF equilibrated with 20% \(O_2\) (36°C). Action potentials of CA1 neurons were evoked using positive current injection (0.2–1.0 nA; 250 ms). Experimental recordings were maintained up to an additional 5 h in 20% (36°C) after the initial 4-h incubation (22°C). Data were recorded and analyzed off-line using AxoScope 9 (Molecular Devices). In some experiments, oxygen-dependent excitability of CA1 neurons was assessed by briefly (10 to 20 min) switching from ACSF equilibrated with 20% \(O_2\)-95% \(O_2\).

**RESULTS**

**Pharmacological manipulation of CA1 hippocampal superoxide production in slices exposed to one-sided superfusion after 30-min DHE preloading**

Data in Fig. 1 were obtained from slices preincubated with 10 \(\mu\)M DHE for 30 min, washed, and then exposed to ACSF equilibrated with 95% \(O_2\) for an additional 45 min during imaging. The DHE-loaded cells at the bottom of the slice were visualized and single-cell traces of 10 CA1 neurons in the same slice show a rapid time-dependent increase in FIU, which reflects increased \(O_2^-\) production during the 45-min exposure to 95% \(O_2\). Note the considerable variability in the rate of \(O_2^-\) production between CA1 neurons (Fig. 1A). The absolute increase in FIU from \(t = 0\) to 45 min ranged from 65 to 165 FIU. In actuality, this period represents the final 45 min during 90 min of exposure to 95% \(O_2\) if the time from slicing (0–45 min) plus the duration of the experimental run (46–90 min) are considered.

Figure 1B shows the summary data from six to eight hippocampal slices per condition during application of FCCP, MnTMPyP, or melatonin for 45 min while superfused with ACSF equilibrated with 95% \(O_2\). Superoxide production in 95% \(O_2\) alone is also shown for comparison. The mitochondrial uncoupler, FCCP, was used as a positive control (\(n = 80\) cells) to establish that DHE is sufficiently sensitive to detect increases in \(O_2^-\) and to determine if the mitochondria were a source for \(O_2^-\) production in our experiments. Adding FCCP to the superfusate during 95% \(O_2\) resulted in a peak value of 143 ± 19 FIU and at a rate of 3.0 ± 0.8 FIU/min during the first 45-min period. Superoxide production with FCCP was not significantly higher, however, than that with 95% \(O_2\) alone, which caused a peak increase of only 85 ± 15 FIU at a rate of 2.8 ± 0.6 FIU/min over 45 min. Exposure to FCCP for >60 min caused a decrease or plateau in the slope of FI, the significance of which is discussed in the following text.

To determine the relative specificity of DHE for \(O_2^-\) in the CA1 hippocampus, control experiments were performed in...
95% O2 with the $^{\cdot}O_2^-$ scavenger and SOD and CAT mimetic, MnTMPyP ($n = 60$ cells). Slices were exposed to MnTMPyP prior to (10 min) and during $^{\cdot}O_2^-$ measurements. MnTMPyP significantly reduced $^{\cdot}O_2^-$ production relative to 95% O2 alone ($P < 0.001$). Notice that the slope of FIU/min was negative ($-1.3 \pm 0.2$ FIU/min) with the $^{\cdot}O_2^-$ scavenger, indicating that little or no $^{\cdot}O_2^-$ was being produced. This was expected considering that previous reports indicate that MnTMPyP is a highly specific $^{\cdot}O_2^-$ scavenger (Klann 1998; Wang et al. 2004). Additionally, the broad spectrum antioxidant melatonin ($n = 60$ cells) significantly decreased the rate of $^{\cdot}O_2^-$ production ($-1.3 \pm 0.2$ FIU/min) during exposure to 95% O2 after a modest increase ($30 \pm 8$ FIU) during the first 20 min of the experiment ($P < 0.001$).

Superoxide production during graded O2 exposure using 30-min DHE preloading and one-sided superfusion

Figure 2, A–D, shows a comparison of fluorescence images of the CA1 region of individual hippocampal slices exposed to graded levels of oxygen over 0, 1, and 4 h (from left to right). These $^{\cdot}O_2^-$ measurements were made in hippocampal slices using one-sided superfusion and exposure (from top to bottom) to 95, 60, 40, and 20% O2 after 30 min of preincubation with 10 $\mu$M DHE. Notice the apparent increase in FIU of each consecutive image at 95% O2, which is considerably greater than that observed with lower levels of oxygen (Fig. 2, A–D). Summary data show that peak measurements of $^{\cdot}O_2^-$ production during 4 h exposure to 95, 60, 40, and 20% O2 were 193 ± 27 ($n = 80$), 61 ± 10 ($n = 60$), 51 ± 15 ($n = 60$), and 12 ± 6 FIUs ($n = 60$), respectively (Fig. 2E). Notice that the slope of FIU/min in 95% O2 was greatest during the first 45 min of $^{\cdot}O_2^-$ measurement, which was followed by a plateau in FI after 60 min. At levels of O2 <95%, the slope of $^{\cdot}O_2^-$ production became negative (60 and 40%) after ~60 min or less (20%; Fig. 2E).

To better assess the oxygen-dependent effect on $^{\cdot}O_2^-$ production using preloaded slices and one-sided superfusion we analyzed the slopes of $^{\cdot}O_2^-$ production within the initial 45 min of exposure to 95, 60, 40, and 20% O2. The rate of $^{\cdot}O_2^-$ production with 95% O2 was significantly different ($P < 0.001$) than 60, 40, and 20% O2. However, the rates of $^{\cdot}O_2^-$ production with 60, 40, and 20% O2 were not significantly different from each other ($P > 0.05$); refer to Fig. 5B.

We attributed the plateau and negative slopes in FIU/min after 45 min were due to: leakage of DHE from the intracellular...
These observations support the role of the mitochondria as a source of intracellular superoxide production during exposure to 95% O₂ along with light inactivated MnTMPyP (n = 60; 25 μM) significantly reduced -O₂⁻ production during exposure to 95% O₂ (P > 0.001). Light-inactivated MnTMPyP (n = 50; 25 μM) reduced -O₂⁻ production during exposure to 95% O₂ but was significantly higher than activated MnTMPyP (P > 0.001).

Superoxide production in 10 individual cells is shown in Fig. 3A as a time-dependent increase in FI over 4 h during exposure to 95% O₂. Notice that the increase in -O₂⁻ production over time does not plateau and that the response is essentially linear (Fig. 3B, 95% O₂ trace). Also notice that the rate of -O₂⁻ production and absolute change in peak fluorescence significantly exceeds that measured using one-sided superfusion and DHE preloading (cf. Fig. 2E, 95% O₂ trace); see following text, Fig. 5. Figure 3B shows the summary data from hippocampal slices following the application of FCCP, MnTMPyP, and melatonin for 1 h while superfused with ACSF equilibrated with 95% O₂. Superoxide production in 95% O₂ alone was estimated at 5.7 ± 0.7 FIU/min (n = 60 cells) with a peak fluorescence after 1 h of 688 ± 29 FIU. Adding FCCP further increased -O₂⁻ production (P < 0.001) in 95% O₂ to 992 ± 24 FIU over 1 h and resulted in a greater rate of superoxide production at 8.3 ± 0.8 FIU/min (n = 80 cells). These observations support the role of the mitochondria as a source of intracellular -O₂⁻ production as reported by others (Bindokas et al. 1996). Exposure to FCCP for longer periods of time (>120 min) resulted in cell death (lysing) and a gradual plateau in FI (not shown).

In studies using antioxidants, the slices were briefly pre-treated with MnTMPyP and melatonin (10 min) prior to and during subsequent -O₂⁻ measurements. During exposure to 95% O₂, application of MnTMPyP caused only a very modest increase of 98 ± 3 FIU over 1 h at the rate of 0.8 ± 0.1 FIU/min (n = 60 cells), which was significantly decreased (P < 0.001) relative to 95% O₂ alone. Light inactivation (12 h) of MnTMPyP (25 μM) rendered the antioxidant less effective as a SOD and CAT mimetic: -O₂⁻ production was significantly lower in CA1 neurons (n = 50) during exposure to 95% O₂ (P > 0.001), but it was only ~30% of the inhibition of -O₂⁻ production that occurred using normally active MnTMPyP. Likewise, melatonin (100 μM) caused a similar inhibition of -O₂⁻ production in 95% O₂ as light inactivated MnTMPyP and significantly decreased -O₂⁻ production (P < 0.001) causing an increase of 344 ± 27 FIU over 1 h at the rate of 2.9 ± 0.1 FIU/min (n = 60 cells).

Superoxide production during graded O₂ exposure using continuous DHE loading and two-sided superfusion

Figure 4 shows a comparison of fluorescence images of the CA1 region of individual hippocampal slices exposed to 95, 60, 40, and 20% O₂ over 0, 1, and 4 h (from left to right). Note the dramatic increase in fluorescence relative to the initial baseline and that the fluorescence is proportional to the level of oxygen over the entire 4 h of study (Fig. 4, A–D). In these studies, exposure to 95, 60, 40, and 20% O₂ produced an increase in peak fluorescence of 1,265 ± 65, 813 ± 45, 535 ±
The rates of $\mathrm{O}_2^-$ production were significantly different between 95, 60, 40, and 20% $\mathrm{O}_2$ ($P < 0.001$). In addition, this method resulted in no plateau in FI over the 4-h study period (cf. Fig. 2E).

**Comparison of one-sided versus two-sided superfusion and method of DHE loading**

Comparison of summary data for hippocampal slices shows the rate of $\mathrm{O}_2^-$ production during exposure to FCCP, MnTMPyP, and melatonin in 95% $\mathrm{O}_2$ with two- and one-sided superfusion (Fig. 5A). Notice that with two-sided superfusion the rate of $\mathrm{O}_2^-$ production was significantly higher during exposure to FCCP ($P < 0.001$) and significantly lower with MnTMPyP and melatonin ($P < 0.001$). Conversely $\mathrm{O}_2^-$ production with FCCP using one-sided superfusion was not significantly different from 95% $\mathrm{O}_2$ alone ($P > 0.05$). However, experiments using one-sided superfusion showed that both MnTMPyP and melatonin significantly reduced $\mathrm{O}_2^-$ production in 95% $\mathrm{O}_2$ relative to 95% $\mathrm{O}_2$ alone ($P < 0.001$).

The rate of $\mathrm{O}_2^-$ production during the first 45 min was directly proportional to oxygen level in the ACSF using the two-sided superfusion, and the rate of $\mathrm{O}_2^-$ production was significantly different between all levels of oxygen ($P < 0.001$). Using the one-sided superfusion we observed a significant difference in the rate of $\mathrm{O}_2^-$ production during the first 45 min in 95% $\mathrm{O}_2$ relative to lower levels of oxygen. However, no oxygen-dependent effect on $\mathrm{O}_2^-$ production was detected at 20, 40, and 60% using one-sided superfusion (Fig. 5B). A comparison of absolute $\mathrm{O}_2^-$ production in response to 95, 60, 40, and 20% $\mathrm{O}_2$ using one- and two-sided superfusion is shown in Fig. 5C. Data from experiments with two-sided superfusion (2-SP, ■, $n = 260$ cells) and one-sided superfusion (1-SP, ○, $n = 260$ cells) are grouped into four columns representing (left to right) 95% $\mathrm{O}_2$, 60% $\mathrm{O}_2$, 40% $\mathrm{O}_2$, and 20% $\mathrm{O}_2$ with 6 slices/O2 level. Time 0 includes 60 min of incubation in 95% $\mathrm{O}_2$ after slicing, without DHE. Thus the total time the slices were exposed to 95% $\mathrm{O}_2$ was 5 h. Refer to the text for further details.

**Oxygen dose and cell death during two-sided superfusion**

EH-1 staining was used to determine if greater CA1 cell death occurred at lower levels of oxygen due to hypoxia and/or

![Image](https://example.com/image.png)
higher levels of oxygen due to hyperoxia. Figure 6, A–D, shows EH-1 staining in hippocampal slices before (left) and after 4-h exposure (right) to (top to bottom) 95, 60, 40, and 20% O₂ at 36°C. As shown in panel E, the highest level of cell death was observed after 4-h exposure to 95% O₂ (t = 0 vs. t = 4 h, Student’s unpaired t-test, P < 0.001). Sixty-percent O₂ caused a modest but significant increase in cell death (P < 0.05), and no time-dependent increase in cell death was observed using 40 and 20% O₂. This pattern of hyperoxia-induced cell death is similar to that which others have reported using the organotypic hippocampal slice preparation (Graulich et al. 2002; Pomper et al. 2001) and suggests that hyperoxia (60% O₂) may increase oxidative-stress-induced cell death.

Cellular viability in 20% O₂: electrophysiological recordings of evoked action potentials

Intracellular recordings from a total of 12 neurons in six hippocampal slices were used to determine if CA1 neurons remain functional after prolonged exposure to 20% O₂. We postulated that if action potentials could be measured in CA1 neurons during and after 4-h exposure to the lowest level of O₂ (20%), then this would confirm that CA1 neurons were indeed viable. It also would be further evidence that the decrease in O₂⁻ production in 20% O₂ was not due to increased CA1 cell death at the lowest level of oxygenation.

A representative electrophysiological experiment in 20% O₂ shown in Fig. 7, A–C, demonstrates evoked action potentials in a CA1 neuron in response to a 0.4-nA positive current pulse (250 ms). This particular recording was made at 36°C after incubation in 20% O₂ for 4 h (22°C). A brief exposure to 95% O₂ (10 min) increased evoked action potential frequency (Fig. 7B). Switching back to 20% O₂ reversed the oxygen-dependent increase in excitability (Fig. 7C). Figure 7, D–F, shows evoked action potentials from three individual neurons maintained in 20% O₂ for 7, 8, and 9 h, respectively (36°C). These data demonstrate that neurons are viable after extended incubation in 20% O₂. These findings are consistent with previous studies from our lab (Garcia et al. 2005) that have demonstrated that lowering oxygen decreases neuronal excitability but does not abolish it.

DISCUSSION

This study provides a comprehensive description of superoxide (O₂⁻) production in cells of the CA1 hippocampal slice exposed to sustained, graded oxygenation. There were five important findings. First, two methods for loading DHE and maintaining the slices (preincubation with 10 μM DHE followed by 1-sided superfusion and continuous loading with 2.5 μM DHE and 2-sided superfusion) gave quantitatively different results for estimating oxygen-dependent O₂⁻ production in the brain slice. The latter scenario—2-sided superfusion and
continuous DHE loading—gave the best temporal resolution of \( \cdot \mathrm{O}_2^- \) production. Second, we observed that under control conditions used for maintaining slices (95% \( \mathrm{O}_2 \), 36°C), \( \cdot \mathrm{O}_2^- \) production in the CA1 hippocampus is significantly increased during 4 h relative to lower levels of oxygen that are not hypoxic, at least as defined by the absolute value for tissue \( \mathrm{PO}_2 \). Third, \( \cdot \mathrm{O}_2^- \) production during hyperoxia (95% \( \mathrm{O}_2 \)) is minimized by adding the antioxidants melatonin or MnTMPyP to the ACSF. Fourth, cell death is likewise greatest after 4 h of exposure to 95% \( \mathrm{O}_2 \). No significant time-dependent increase in CA1 cell death occurred in hippocampal slices maintained at \( \sim 36^\circ \mathrm{C} \) in ACSF equilibrated with 20 and 40% \( \mathrm{O}_2 \). Finally, CA1 neurons remain viable—that is, capable of generating action potentials—during and after prolonged exposure (\( \geq 4 \) h) to 20% \( \mathrm{O}_2 \) at \( \sim 36^\circ \mathrm{C} \).

Measurement of oxygen-dependent hippocampal superoxide production

Oxygen-dependent \( \cdot \mathrm{O}_2^- \) production in the CA1 hippocampus was characterized using two methods of \( \cdot \mathrm{O}_2^- \) measurement. For one-sided superfusion, the brain slice was supported against the glass coverslip at the bottom of the tissue slice chamber. CA1 cells were visualized from the bottom after 30 min of loading with 10 \( \mu \mathrm{M} \) DHE. A drawback to this method was that the surface of the slice being imaged was not directly exposed to the oxygenated ACSF. Additionally, the rate of increase in DHE fluorescence reached a plateau before 60 min (95% \( \mathrm{O}_2 \)). At lower levels of \( \mathrm{O}_2 \), DHE fluorescence decreased over time, and no differences were noted in the rate of \( \cdot \mathrm{O}_2^- \) production as a function of \( \mathrm{O}_2 \) level (20–60% \( \mathrm{O}_2 \)). A decrease in the plateau of DHE fluorescence likely occurred from irreversible oxidation and/or cellular leakage of the probe, and thus \( \cdot \mathrm{O}_2^- \) production may have been underestimated using this method.

These limitations were addressed by using two-sided superfusion and continuous loading with a lower concentration of DHE (2.5 \( \mu \mathrm{M} \)). By raising the slice up off the floor of the tissue bath on a nylon mesh, the cells being imaged on the bottom surface of the slice were brought into direct contact with a constant flow of oxygenated ACSF. Using a \( \times 10 \) objective enabled suitable resolution and working distance to image neurons in the CA1 region. Using two-sided superfusion, we...
determined that \( \text{O}_2^- \) production in CA1 cells was proportional to the "\( \text{O}_2 \) concentration product," which is defined as \( \text{PO}_2 \times \text{duration of exposure to } \text{O}_2 \) (Fig. 4E). This method improved diffusion of oxygen to the slice and enabled detection of a higher resolution fluorescence signal that neither plateaued nor decreased over time. The maximum change in FIU with 95% \( \text{O}_2 \) after 4 h was approximately seven times greater using two-sided superfusion and continuous loading. Furthermore, because DHE is potentially toxic to cells at high concentrations \((>50 \, \mu\text{M})\) (Zhao et al. 2003), using a lower concentration \((2.5 \, \mu\text{M})\) applied immediately before visualizing cells likely minimized toxicity. We also attempted to use one-sided perfusion with continuous DHE loading \((2.5 \, \mu\text{M}, \text{data not shown})\), but the images quickly became blurry, and it was difficult to visualize individual neurons within the CA1 region. This likely occurred because the oxidized DHE became trapped between the bottom surface of the slice and cover glass during one-sided superfusion. It’s important to note that the \( \text{PO}_2 \) profiles of slices maintained in one- and two-sided superfusion are considerably different (Dean et al. 2005).

**Cell death and cellular viability as a function of \( \text{O}_2 \) tension**

Using EH-1 staining and electrophysiology, we show that the lower rate of \( \text{O}_2^- \) production with 60, 40, and 20% \( \text{O}_2 \) as compared with 95% \( \text{O}_2 \) was not due to increased cell death from hypoxia (Fig. 6). To the contrary, the highest level of EH-1 staining and thus cell death was observed after 4-h incubation in 95% \( \text{O}_2 \). These data suggest that CA1 neurons in hippocampal slices are vulnerable to oxidative stress from prolonged exposure \((\leq 4 \, \text{h})\) to hyperoxic control conditions (Fessel et al. 2002; Rice 1999) This finding supports the earlier findings of Pomper et al. (2001), who showed that CA1 cell death in organotypic slice cultures, prepared from younger rats, was greatest in 95% \( \text{O}_2 \) and less in 20% \( \text{O}_2 \). Likewise, cell death was greatest in hippocampal and cerebral cortical neuronal cultures incubated in 95 and 21% \( \text{O}_2 \) and less in 9% \( \text{O}_2 \) (Brewer and Cotman 1989; Kaplan et al. 1986).

Our electrophysiological measurements from individual CA1 neurons in slices maintained in 20% \( \text{O}_2 \) provided further evidence that CA1 neurons remained viable during prolonged exposure to the lowest level of \( \text{O}_2 \) tested; that is, they continue to generate action potentials that overshoot 0 mV. Excitability, however, was lower during exposure to 20% \( \text{O}_2 \) and increased during brief exposure to 95% \( \text{O}_2 \). Similar observations have been made previously in our lab when comparing CA1 neuronal excitability of hippocampal slices maintained in 95, 60, and 40% \( \text{O}_2 \) (Garcia et al. 2005). It is our opinion (Dean et al. 2003) and others (Bingmann and Kolde 1979; Bingmann et al. 1982; Fessel et al. 2002; Pomper et al. 2001; Shibata and Blatteis 1991) that neuronal activity that is traditionally characterized as "normal" in 95% \( \text{O}_2 \) has in fact been altered by an underlying level of oxidative stress due to hyperoxia. We propose that the brain slice preparation has increased excitability from the general stimulatory effects of hyperoxia (Dean et al. 2003; Garcia et al. 2005; this study, Fig. 7). It is likely that the lower level of excitability observed using lower levels of \( \text{O}_2 \) reflect the reduced excitability of the deafferented in vitro brain slice preparation rather than a hypoxic condition. Further studies are needed to determine if slice procedures and recovery from slicing should be done in lower oxygen. The findings of the present study, however, indicate that this possibility should be considered.

The relationship between hyperoxia and decreased cell viability needs to be assessed in a rigorous study in which the neuroprotective effects of various antioxidants and \( \text{O}_2 \) levels are established using a combination of electrophysiology, real-time measurements of ROS and measurements of cell death. This is especially important because the levels of certain endogenous antioxidants are reduced during incubation and superfusion of brain slices with ACSF (Rice 1999; Rice et al. 1994).

**Source of superoxide production**

Increasing the concentration of molecular \( \text{O}_2 \) provides a source for the generation of ROS (Katoh et al. 1997; Li et al. 2004). The general consensus is that the mitochondria appear to be the primary source of \( \text{O}_2^- \) production in neurons (Emerit et al. 2004). In fact, several investigators have reported that \( \text{O}_2^- \) production in hippocampal neurons is generated from the mitochondria under physiological and pathological conditions (Bindokas et al. 1996; Li et al. 2004; Murakami et al. 1998). Our data support this by demonstrating that uncoupling mitochondrial respiration with FCCP increases the production of \( \text{O}_2^- \) in hippocampal neurons as previously reported (Bindokas et al. 1996). An increase in ethidium fluorescence indicates probe oxidation by \( \text{O}_2^- \); however, increased ethidium fluorescence does not rule out further reactions that \( \text{O}_2^- \) may undergo to produce additional ROS and reactive nitrogen species: hydrogen peroxide, hydroxyl radical, peroxynitrite and nitrogen dioxide (Bindokas et al. 1996). Regardless, for purposes of this study, DHE enables us to estimate oxygen-dependent \( \text{O}_2^- \) production.

**Considerations with fluorescence measurement of superoxide**

Several methods of ROS detection exist, but the most accurate and sensitive method for detecting intracellular ROS in cells and tissues involves fluorescence-based techniques (Budd et al. 1997; Castilho et al. 1999; Gomes et al. 2005; Zuo and Clanton 2002). The fluorogenic probe most commonly used for intracellular \( \text{O}_2^- \) detection is DHE, and it has been extensively used to measure intracellular \( \text{O}_2^- \) in the hippocampus (Bindokas et al. 1996; Kawase et al. 1999; Kovacs et al. 2001; Muranyi and Li 2006; Peterson et al. 2002). Intracellular oxidation of DHE yields the two-electron oxidized product, ethidium, which binds to DNA and enhances the fluorescence signal \((\lambda_{em} = 480 \, \text{nm}; \lambda_{em} = 586 \, \text{nm})\). The ethidium fluorescence resulting from the oxidation of DHE is inhibited by endogenous and exogenous \( \text{O}_2^- \) scavengers, including superoxide dismutase and melatonin (Bindokas et al. 1996; Budd et al. 1997; Castilho et al. 1999; Uchida et al. 2004). However, like all fluorogenic probes, there are a number of caveats associated with using DHE, including the probe’s specificity. To our knowledge, no fluorogenic probe is exclusively oxidized by a specific ROS, but DHE is a fairly specific probe for detecting intracellular \( \text{O}_2^- \) (Bindokas et al. 1996), and its use has been reviewed and critiqued (Budd et al. 1997; Zuo and Clanton 2002). To test the specificity of DHE for \( \text{O}_2^- \) production, we confirmed that \( \text{O}_2^- \) production was inhibited completely by a \( \text{O}_2^- \) scavenger MnTMPyP. Light-inactivated
MnTMPyP, by contrast, was only 2/3 as effective at inhibiting \( \text{O}_2^- \) production. The remaining one-third of \( \text{O}_2^- \) scavenging activity exhibited by light-inactivated MnTMPyP could indicate an insufficient amount of light was used or that DHE is reacting with another form of ROS family. We also were able to demonstrate a further increase in \( \text{O}_2^- \) production during 95% \( \text{O}_2 \) with FCCP, which was consistent with other studies (Bindokas et al. 1996; Prehn 1998).

With regard to our fluorescence measurements, DHE is permanently oxidized by \( \text{O}_2^- \), and the signal produced is irreversible after oxidation, which occurs in all ROS-sensitive probes. In theory, the signal should never decrease, only increase during \( \text{O}_2^- \) production or plateau when no \( \text{O}_2^- \) is generated. Therefore the decrease in ethidium fluorescence that we observed is presumably indicative of probe leakage and/or photobleaching and resulted in a negative slope of FIU/min. Last, DHE should only be used as a qualitative measure of \( \text{O}_2^- \) production because the yield of ethidium produced per \( \text{O}_2^- \) radical is not stoichiometric (Benov et al. 1998). Therefore our data were reported as an estimate of oxygen-induced \( \text{O}_2^- \) production.

**Implications of hyperoxia-induced superoxide formation**

Recent experiments in our lab using the hippocampal slice preparation have shown that normobaric hyperoxia (95% \( \text{O}_2 \)) and hyperbaric oxygen (HBO) increase synaptic activity and firing rate in CA1 neurons, resulting in increased excitability (Dean et al. 2003; Garcia et al. 2004). For example, HBO often induces one or more secondary population spikes in CA1 neurons, referred to as mild epileptiform activity. At higher levels of hyperoxia, these excitatory effects of HBO on synaptic activity are often only partially reversible, resulting in oxygen-induced potentiation of the synaptic response. Increased excitability of hippocampal neurons during HBO is attenuated by \( \text{O}_2^- \) scavenger MnTMPyP (Garcia et al. 2003). This is consistent with studies from Klann et al. (1998), which show MnTMPyP inhibited the induction of hippocampal LTP, and that \( \text{O}_2^- \) is an important signal transduction molecule in its induction (Kishida et al. 2005; Knapp and Klann 2002). Therefore evidence supports the role for \( \text{O}_2^- \) in mediating hyperoxia-induced hyperexcitability in hippocampal slices.

The pathological consequences of increased ROS production are well known (Lynn et al. 2005; Serrano and Klann 2004). In fact, the hippocampus is particularly vulnerable to hyperoxia-induced oxidative stress (Fukui et al. 2001; Onodera et al. 2003; Serrano and Klann 2004; Shimabuku et al. 2005), and this can be prevented by an overexpression of superoxide dismutase in transgenic rats (Chan et al. 1998). In addition, supplemental antioxidants (e.g., melatonin) decrease lipid peroxidation, increase glutathione peroxidase activity, and prevent cognitive deficits in the rat hippocampus under conditions of oxidative stress (Baydas et al. 2005; Gonenc et al. 2005; Maharaj et al. 2005). Our results show that melatonin (100 \( \mu \)M) significantly reduces hippocampal \( \text{O}_2^- \) production during hyperoxia, suggesting that supplemental melatonin may reduce excess oxidative stress that likely occurs in hippocampal slices over the time spent in 95% \( \text{O}_2 \). Melatonin, when used at a concentration of 10 to 100 \( \mu \)M, significantly protects hippocampal slices from ischemic damage due to excess \( \text{O}_2^- \) production (Uchida et al. 2004).

In conclusion, using DHE we have demonstrated that \( \text{O}_2^- \) production in the CA1 hippocampus is tightly coupled to tissue oxygen concentration ranging from 20 to 95% and that 95% \( \text{O}_2 \) causes the greatest level of \( \text{O}_2^- \) production over the duration of a 4-h experiment. Superoxide production in 95% \( \text{O}_2 \), however, is significantly reduced using the antioxidant melatonin or MnTMPyP. Considering that neurons are sensitive to their redox environment, it is likely that 95% \( \text{O}_2 \) perturbs normal redox signaling, especially because endogenous antioxidants are significantly reduced in this preparation (Brahma et al. 2000; Rice 1999; Rice et al. 2002). Thus 95% \( \text{O}_2 \) may lead to hyperexcitability (Garcia et al. 2005) and hyperoxic preconditioning (Dong et al. 2002; Freiberger et al. 2006), which may confound certain types of experiments in neurons. These data indicate that hippocampal \( \text{O}_2^- \) production is proportional to oxygen concentration, and thus investigators seeking to minimize oxidative stress in the brain slice preparation should consider using a lower level of control oxygen, supplemental antioxidants, or both.

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