

NO Synthesis, Unlike Respiration, Influences Intracellular Oxygen Tension

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Received December 10, 2001

We have developed a new phosphorescent probe, PdTCPPNa₄, whose luminescence properties are affected by local variations of intracellular oxygen tension (PO₂). Spectrofluorometric measurements on living human umbilical venous endothelial cells loaded with this molecule show that a decrease in extracellular oxygen tension induces a decrease of PO₂, illustrating the phenomenon of oxygen diffusion and validating the use of this probe in living cells. Moreover, KCN- or 2,4-dinitrophenol-induced modifications of respiration do not lead to detectable PO₂ variations, probably because O₂ diffusion is sufficient to allow oxygen supply. On the contrary, activation by acetylcholine or endothelial nitric oxide synthase (eNOS), which produces NO while consuming oxygen, induces a significant decrease in PO₂, whose amplitude is dependent on the acetylcholine dose, i.e., the eNOS activity level. Hence, activated cytosolic enzymes could consume high levels of oxygen which cannot be supplied by diffusion, leading to PO₂ decrease. Other cell physiology mechanisms leading to PO₂ variations can now be studied in living cells with this probe. © 2002 Elsevier Science

Key Words: endothelium; intracellular oxygen tension; porphyrin; fluorescence.

In the cellular respiratory function, part of the energetic metabolism is accompanied by an oxygen intake and a CO₂ discharge in the environment (1). In addition, nonmitochondrial enzymes, not involved in the respiratory function, can also use oxygen: nitric oxide synthase (NOS) is a cytoplasmic enzyme which produces a vasomodulator and neuromodulator gas, nitric oxide (NO), from the precursor L-arginine, while consuming oxygen (2). In animal

cells, extracellular oxygen influx occurs by diffusion through the cell membrane and the intracellular medium, according to the gradient of concentration existing because O₂ is consumed into cells. Using data from the literature (3, 4), the maximum oxygen flow entering a cell (diameter: 10 μm) by simple diffusion can be calculated in the range of 3×10^{-15} mol O₂ · s⁻¹ · cell⁻¹.

In biological tissues, various means can be used to measure oxygen, such as spectrophotometry (5), oxygen microelectrodes (6, 7) and oxygraphy, the latter technique having allowed calculation of basal respiratory O₂ consumption in human umbilical vein endothelial cells (HUVEC): 4×10^{-17} mol O₂ · s⁻¹ · cell⁻¹ (8). Also, noninvasive molecular probes, whose luminescence properties are affected by oxygen, have also been developed to study intracellular (PO₂) or extracellular oxygen tension. For instance, the phosphorescent albumin-bound-Pd meso-tetra (4-carboxyphenyl) porphyrin, has been intravenously injected for *in vivo* tissue PO₂ measurements in Hamster Skinfold (9) and in rat skeletal muscle (10). Recently, other investigators have measured intracellular PO₂ modifications in response to variations of extracellular PO₂ in isolated dead muscle skeletal fibers (poisoned with 2 mM NaCN) from *Xenopus laevis* by microinjection of albumin-bound Pd meso-tetra (4-carboxyphenyl) porphyrin (11).

In the present work, we have improved the solubility of the phosphorescent oxygen probe Pd-meso-tetra (4-carboxyphenyl) porphyrin (12) by using a chemically-prepared and purified tetra sodium salt derivative (PdTCPPNa₄). In contrast to the porphyrin microinjection technique used by Lo *et al.* in their studies on poisoned cells (12), our probe presents the capability of being loaded noninvasively in living cells. On living human umbilical venous endothelial cells (HUVEC), we have studied the relative impacts on PO₂ of two physiological intracellular mecha-

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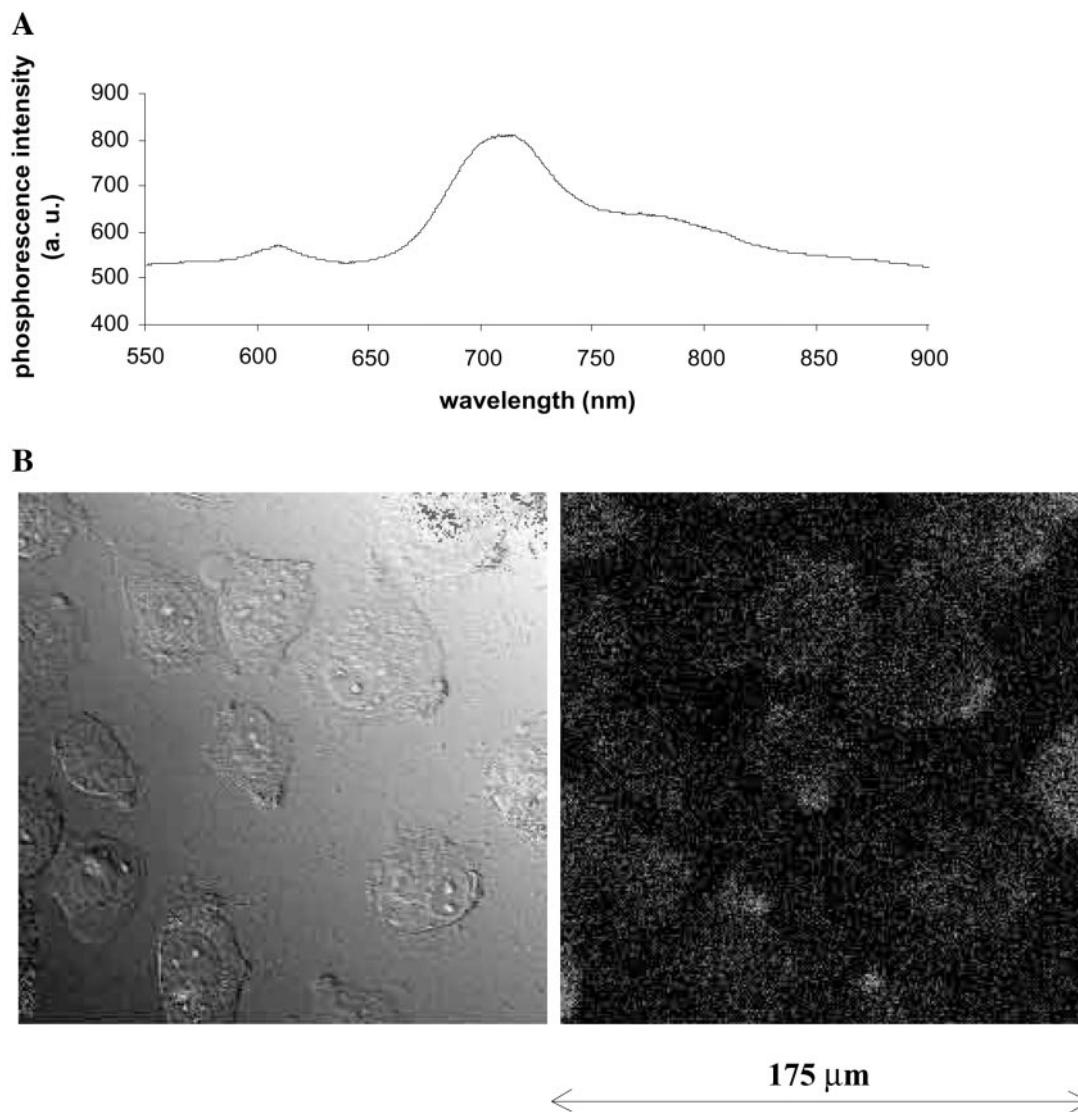


FIG. 1. Emission spectrum of the water soluble PdTCPPNa₄ illuminated by a 514-nm laser beam (A). Adherent HUVEC loaded with PdTCPPNa₄ observed by confocal laser scanning microscopy in differential interferential contrast (left) and fluorescence (right) (B). The images presented are representative of two experiments.

nisms consuming O₂, i.e., mitochondrial respiration and extramitochondrial NO synthesis, together with the effect of hypoxia on the intracellular PO₂, induced by a decrease of the extracellular PO₂.

The spectrofluorometry measurements indicate that both extracellular PO₂ decrease and endogenous endothelial nitric oxide synthase (eNOS) activation induce a transient decrease in intracellular PO₂, whereas modulation of the mitochondrial respiration does not result in a significant variation of PO₂. These findings lead to the hypothesis that maximal O₂ diffusion across the cell membrane is sufficient for continuous oxygen supply in mitochondrial respiration, whereas O₂ diffusion is insufficient to continuously provide with O₂ the

activated cytoplasmic enzymes, such as eNOS, that consume high levels of O₂.

MATERIALS AND METHODS

Pd-meso-tetra (4-carboxyphenyl)porphyrin tetra sodium salt derivative. Pd-meso-tetra (4-carboxyphenyl)porphyrin (0.185 g) (Porphyrin Products) was neutralized by addition of 13 ml NaOH (0.065 N). The resulting red solution was stirred for 2 h at room temperature and filtered, before being evaporated near to dryness (≈0.5 ml). The precipitate, Pd-meso-tetra (4-carboxyphenyl)porphyrin tetra sodium salt (PdTCPPNa₄), was filtered off, washed with ethanol, and dried under vacuum. Yield, 90%, 169 mg.

Intrinsic luminescent properties of the initial molecular phosphorescent probe are not affected by this treatment: emission spectra of

PdTCPPNa₄ in water solution, obtained with a 514-nm laser beam, also shows a maximum emission peak at 710 nm (Fig. 1A).

Similar to previously published investigations (13, 14), the O₂-dependence of the probe phosphorescence is described by the Stern-Volmer relationship: $\tau_0/\tau = 1 + k_q \tau_0 PO_2$, where τ_0 and τ are the phosphorescence lifetimes (decay) in the absence of O₂ and at a given PO₂, respectively, and k_q (the quenching constant) is a second-order rate constant that is related to the frequency of collisions between O₂ and the excited triplet state of PdTCPPNa₄. An intracellular oxygen tension (PO₂) decrease in the environment increases the phosphorescence intensity (I) and lengthens the phosphorescence decay (τ) of PdTCPPNa₄, and inversely. Here, I and τ were followed, as markers of the PO₂ variations, in acellular solutions or in PdTCPPNa₄-loaded endothelial cells.

Human umbilical venous endothelial cells (HUVEC). HUVEC were used for several reasons. The endothelial cells have a glycolytic potential enabling them to stand hypoxia or short duration anoxia (15). Also, endothelial cells allow the investigation of three different mechanisms for inducing potential changes in PO₂: (i) decrease in extracellular oxygen (by argon bubbling), (ii) use of uncouplers and inhibitors of the mitochondrial respiration, and (iii) stimulation or blockade of eNOS.

HUVEC were obtained according to a protocol derived from the Jaffe's method and, for investigations of PO₂ by fluorescence confocal microscopy, HUVEC were cultured on dishes whose bottom was a glass slide coated with 0.25 mg · ml⁻¹ fibronectin (16, 17).

Determination of optimal active concentrations of KCN and DNP using the oxygraphy technique. Respiration rate of HUVEC suspended in PSS (2 ml, 5 × 10⁶ cells · ml⁻¹) was measured polarographically in a stirred oxygraph vessel (37°C) including a Clark oxygen electrode. Different concentrations of the respiration inhibitor potassium cyanide (KCN) or of the uncoupler of mitochondrial phosphorylative oxidation 2,4-dinitrophenol (DNP) were then added and the effect on cellular O₂ consumption was recorded.

Control of probe penetration in the cells. Fluorescence images of adherent HUVEC were acquired by using a Zeiss LSM 410 confocal laser scanning microscope (Zeiss). Excitation, 514 nm; dichroic, 560 nm; emission collection, 665 nm long pass. Each image (optical sections passed through the nuclei) is the average of four successive image acquisitions.

Intracellular oxygen measurement in suspended HUVEC. Subconfluent adhering HUVEC were washed twice with PSS and trypsinized. Trypsinization was stopped by addition of PSS containing 50% human serum. Cells were then centrifuged 5 min at 200g and resuspended in 6 ml PSS with 0.45 mg · ml⁻¹ pluronic F-127, 5 mg · ml⁻¹ BSA added. Sixty microliters of a 10 mM PdTCPPNa₄ solution was added to a 6-ml cell suspension (final concentrations: 100 μM PdTCPPNa₄) before a 60-min incubation at 37°C, 5% CO₂, humid atmosphere, in the dark. The cells were then washed of the extracellular fluorescent probe by four centrifugation cycles (5 min, 200g) and pellet resuspension in 6 ml PSS containing 4 mM octanoate (≈10⁶ cells · ml⁻¹).

eNOS is activated using 0.1, 1, and 10 μM acetylcholine (Ach) (18) or inhibited using 10 μM *N*-ω-nitro-L-arginine methyl ester (L-NAME), an analogue of the precursor L-arginine which cannot be used by eNOS (19). L-NAME was added to the HUVEC suspension during PdTCPPNa₄ incubation (60 min). The cell suspension was then washed out of the probe and L-NAME by centrifugation and resuspension in PSS before measurement.

In addition, to evaluate the interaction between PdTCPPNa₄ and the chemicals used in this study, the chemicals were added to a 10 μM PdTCPPNa₄ solution (without cells) during the phosphorescence emission acquisition.

Two different parameters were measured, depending on the experimental condition: phosphorescence intensity (I) and phosphorescence decay (τ). τ and I were obtained using a pulsed water cooled continuous wave ArGa laser excitation (514 nm) and a

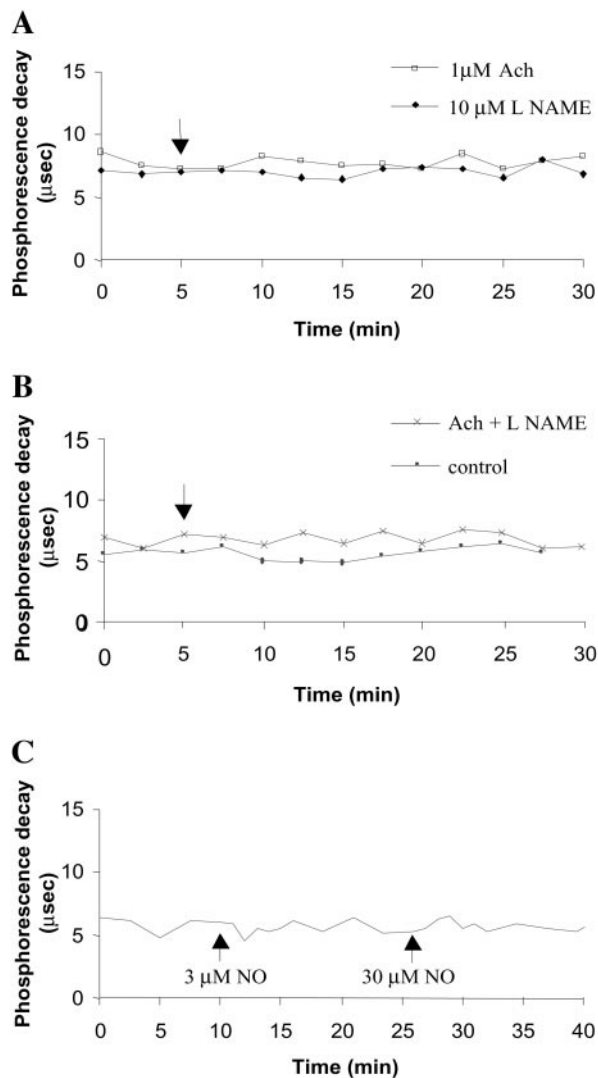


FIG. 2. Absence of interaction of NO, Ach, and L-NAME on the luminescence properties of PdTCPPNa₄ (10 μM) in PSS. (A) Effects of 1 μM acetylcholine or 10 μM L-NAME on the 10 μM porphyrin solution. (B) Effects of 1 μM acetylcholine and 10 μM L-NAME on the 10 μM porphyrin solution and corresponding control tracing. (C) Sensitivity of the porphyrin probe (10 μM) to successive additions of 10 and 100 nmol NO. Arrows, product addition. A representative tracing is shown ($n = 2$ in each case).

continuous laser beam (514 nm), respectively, and the 90° phosphorescence emission was detected at 710 nm with a AsGa photomultiplier.

Probe and chemicals. Chemicals were obtained from Sigma except potassium cyanide (KCN) and 2,4-dinitrophenol (DNP) provided by Merck. PdTCPPNa₄ is prepared as reported above.

Computer analysis. Exponential decay curve analysis was performed by using the Origin 5.0 Microcal Origin software. For suspended HUVEC intracellular origin measurements, phosphorescence acquisition was performed by using software written by the authors. Averaging of 100 successive exponential decays was used to measure τ .

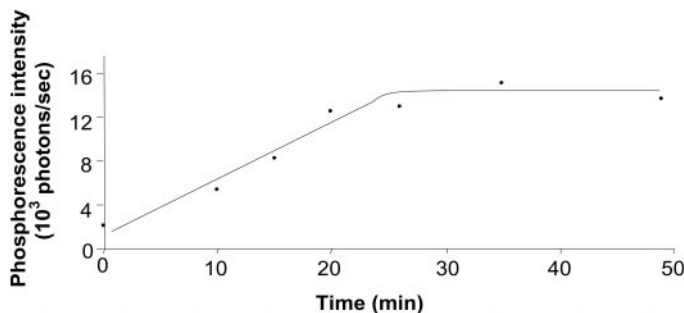


FIG. 3. Effect of argon bubbling on the phosphorescence intensity of PdTCPPNa₄-loaded HUVEC suspension. The argon bubbling starts at time 0 min.

RESULTS

Optimization of Experimental Conditions

Validation of the loading protocol. Figure 1B illustrates that PdTCPPNa₄ enters human umbilical venous endothelial cells (HUVEC), as seen from the fluorescence confocal microscopy signal (optical slices passing through the nuclei). The weakness of the intracellular fluorescence is expected because of the low quantum yield of this probe.

The strong photobleaching due to the repeated laser scanning of the whole microscopic field did not allow further sequential acquisition of images using the confocal microscopy technique. Consequently, all further experiments were carried out on HUVEC suspensions.

Optimal concentrations of KCN and 2,4-dinitrophenol for modulation of mitochondrial respiration in endothelial cells. On HUVEC suspension, using the oxygraphy technique, uncoupling by 100 μ M DNP stimulates the respiratory rate up to 2-fold within a few seconds, and 1 mM KCN is an optimal concentration which induces almost an immediate 10-fold inhibition of respiration. However, 1 mM KCN also induces a rapid morphological deterioration of cells observed in confocal microscopy. Since 100 μ M KCN does not induce cell morphological changes while still inhibiting the respiratory rate by 2-fold (data not shown), 100 μ M KCN and 100 μ M DNP have been used as respiration modulators in the following experiments.

Lack of interaction between the PdTCPPNa₄ and the chemicals added. It has been verified that acetylcholine and L-NAME do not directly affect the optical properties of PdTCPPNa₄ by direct molecular interaction in an acellular physiological solution (Figs. 2A and 2B). Besides, we have observed that the average values of the measured probe phosphorescence decays are different in physiological solution and in cells (about 6 and 90 μ s, respectively).

This can result from the different molecular environment around the probe. In accordance with the literature (12), we have observed, using bovine serum albumin (BSA) addition to PdTCPPNa₄ solutions, that the presence of protein induces an increase in the probe luminescence. The same phenomenon likely occurs when the probe is loaded in the protein-rich cytoplasm of the cell.

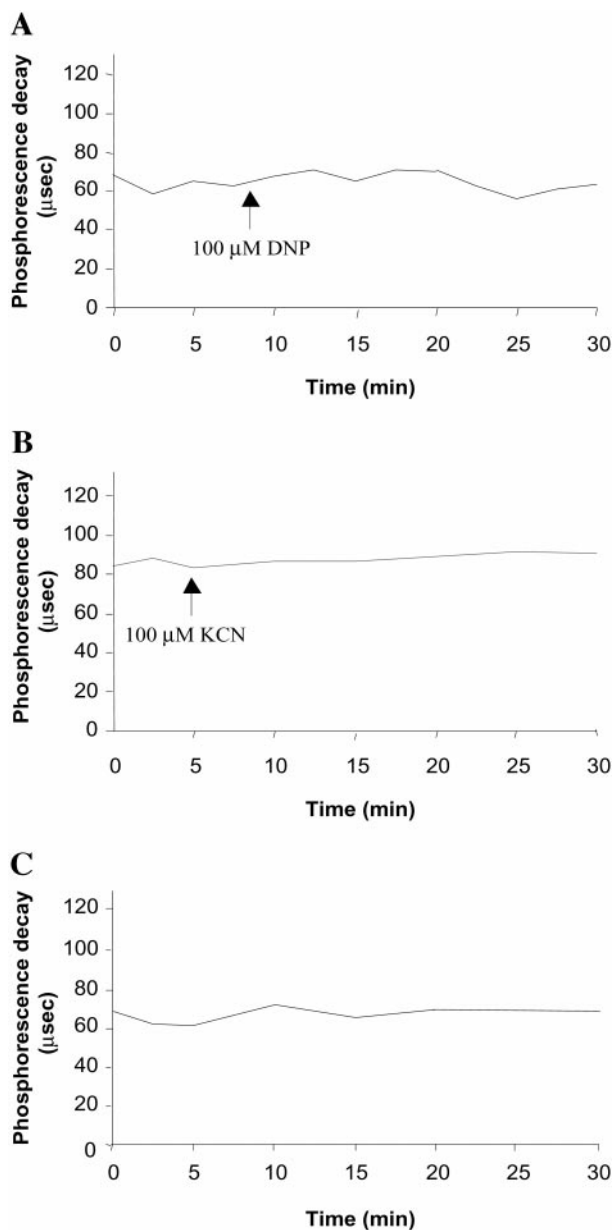


FIG. 4. Effect of 100 μ M DNP (A) and 100 μ M KCN (B) on the phosphorescence decay of 100 μ M PdTCPPNa₄-loaded HUVEC suspension. A control tracing is shown in C. A representative tracing is shown ($n = 2$ in each case).

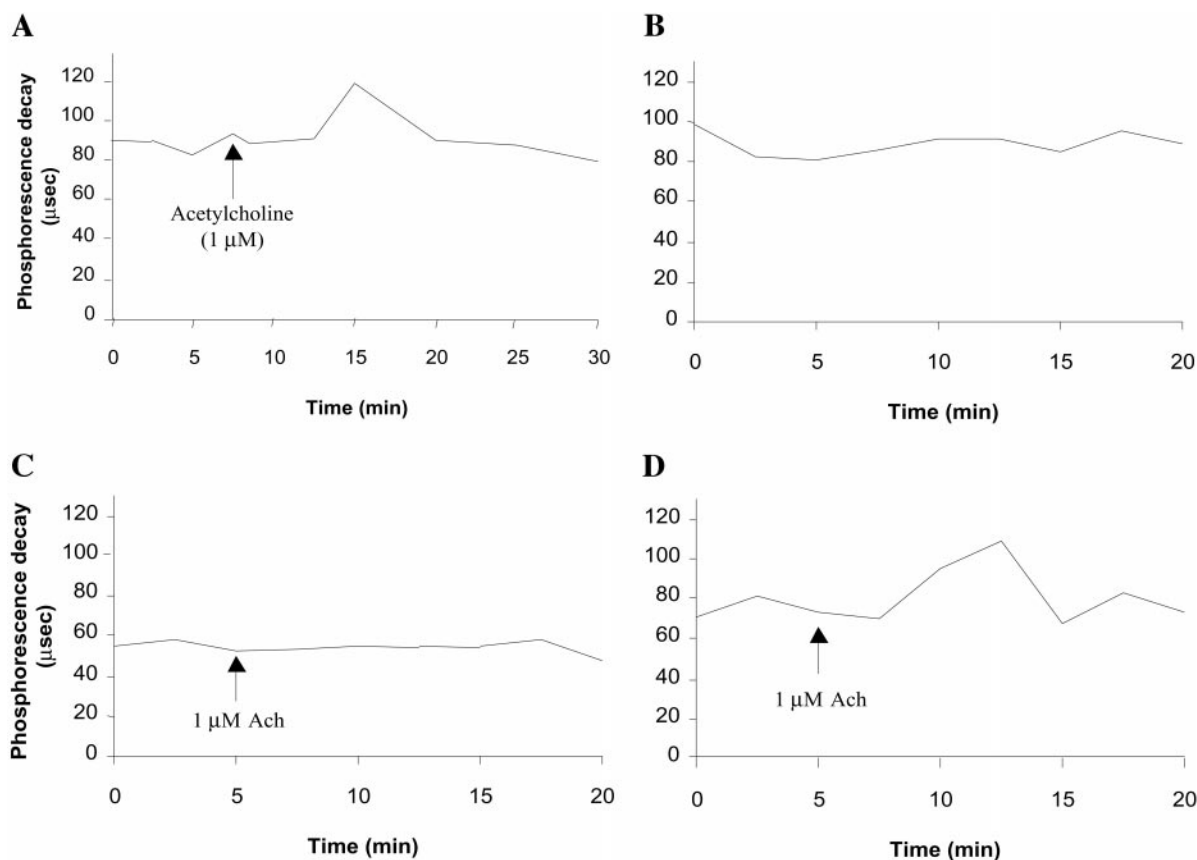


FIG. 5. Acetylcholine (Ach, 1 μM) induces a transient lengthening of phosphorescence decay (τ) on 100 μM PdTCPPNa₄-loaded HUVEC (A). Control tracing (B). Effect on 100 μM PdTCPPNa₄-loaded HUVEC, of 1 μM Ach immediately after incubation with 10 μM L-NAME (C) and 2 h after the end of L-NAME incubation (D). A representative tracing is shown in each case (A, $n = 3$; B, C, D, $n = 2$).

Experimental Results

Intracellular PO_2 variations during modification of extracellular oxygen tension. Argon bubbling (50 min) of a suspended HUVEC loaded with PdTCPPNa₄ was used to deplete the extracellular medium of solubilized O_2 , and phosphorescence intensity was recorded. PdTCPPNa₄ phosphorescence intensity increased by 7-fold, plateauing after 25 min (Fig. 3). This indicates that PdTCPPNa₄ strongly responds to the intracellular PO_2 decrease induced by extracellular decrease in oxygen tension.

Mitochondrial respiration and PO_2 variations. Under these conditions, the measurement of phosphorescence decay (τ) avoids the problem of working with the very weak signal of PdTCPPNa₄. As shown in Fig. 4, the addition of 100 μM DNP or 100 μM KCN does not modify the initial value of the phosphorescence decay (τ) over 30 min in PdTCPPNa₄-loaded HUVEC, suggesting that mitochondrial respiration does not significantly influence PO_2 .

Nonrespiratory oxygen consumption by eNOS and variations of PO_2 . Addition of 0.1, 1, and 10 μM acetylcholine to HUVEC induce transient and dose-dependent increases in τ (Fig. 5A and Figs. 6A–6C), generally occurring after 2–5 min (up to 10 min in a few experiments), whereas no increase in τ is observed in the corresponding control experiments (Fig. 5B). These results suggest a significant reduction of the intracellular PO_2 under acetylcholine stimulation. The average percentages of increase in amplitude of the phosphorescence decay peaks, compared to baseline, are in the range of 4.2% (0.1 μM Ach), 23% (1 μM Ach), and 81.6% (10 μM Ach) (Fig. 6D). A statistical analysis using a one-way ANOVA showed that the average percentages of increase in the amplitude of the phosphorescence decay peaks are significantly dependent upon the acetylcholine dose ($P < 0.05$).

Figure 5C shows that there is no increase in τ in response to 1 μM acetylcholine immediately after incubation with L-NAME. This tracing is comparable to the control (Fig. 5B). Nevertheless, 2 h after the end of L-NAME incubation, after eNOS activity resumed, the

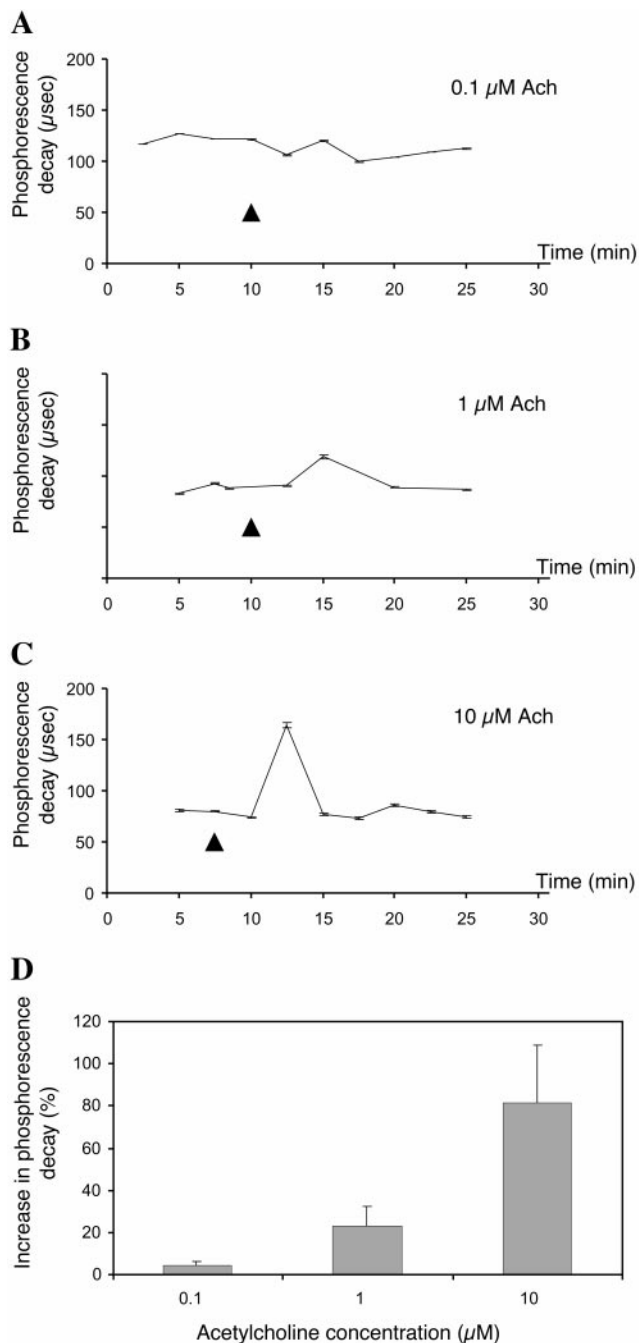


FIG. 6. Dose effect of acetylcholine (Ach) on the phosphorescence decay (τ) of 100 μM PdTCPPNa₄-loaded HUVEC. The amplitude of the phosphorescence decay peak induced by Ach addition increases with Ach concentration: 0.1 μM (A), 1 μM (B), and 10 μM (C). A representative tracing is shown in each case (A, $n = 5$; B and C, $n = 4$). The arrows indicate the time of Ach addition (A, B, and C). The average percentages of increase in amplitude of the phosphorescence decay peaks induced by Ach, compared to baseline, were calculated for each Ach dose using the results from all experiments and are represented in D.

acetylcholine-induced τ elevation—therefore PO_2 decrease—is restored (Fig. 5D). The fact that no detectable modification of luminescence, following Ach addi-

tion on L-NAME-treated HUVEC, indicates a causal relationship between O_2 consumption related to eNOS activation and the transient increase in τ . Moreover, the literature mentioned that a few porphyrins are sensitive to NO (20) or can be used as NO probe (21). Consequently, 10 and 100 nmol NO (final concentrations: 3 and 30 μM , respectively) have successively been added to a PdTCPPNa₄ solution (10 μM) in PSS, in order to verify that NO does not modify the value of τ corresponding to our probe (Fig. 2C). Therefore, these results depict actual PO_2 modifications rather than NO level detection.

DISCUSSION

The present *in vitro* study validate a novel technique for measuring intracellular PO_2 variations in acellular solutions as well as in living cells. Although, values of basal phosphorescent decay in acellular solutions (Fig. 2) and in living cells (Figs. 4 and 5) are different because the local environment surrounding the probe in the cell is likely to affect its response to PO_2 variations. PdTCPPNa₄ loaded into human umbilical venous endothelial cells (HUVEC) exhibits spectral properties similar to the well characterized phosphorescent oxygen probe Pd meso-tetra (4-carboxyphenyl) porphyrin (12). Moreover PdTCPPNa₄ could be used for the measurement of intracellular oxygen tension (PO_2) variations in living HUVEC, as shown by the intracellular response to extracellular PO_2 decrease induced by argon bubbling (Fig. 3). The original loading protocol used in this study, in contrast with microinjection techniques which allows measurements in a few cells at a given time (11), enables the study of intracellular PO_2 in a population of millions of cells. Furthermore, microscopy studies do not show any morphological cell damage due to PdTCPPNa₄ loaded in HUVEC, even under focused light (Fig. 1B). In addition, the fact that low intracellular concentrations of PdTCPPNa₄ were used is likely to keep the effect of any reactive O_2 species produced, due to energy transfer from the porphyrin probe in its excited state to molecular oxygen, at a very low level.

Extracellular oxygen transport toward the inside of the cell occurs by diffusion according to the gradient of concentration and tends to maintain a constant PO_2 . Using data from the literature (3, 4), theoretical maximum oxygen flow entering the cell by diffusion can be estimated in the range of $3 \times 10^{-15} \text{ mol O}_2 \cdot \text{sec}^{-1} \cdot \text{cell}^{-1}$ and oxygen uptake measured by oxygraphy in HUVEC (37°C) has been found at a basal level, about 75 times lower: $4 \times 10^{-17} \text{ mol O}_2 \cdot \text{s}^{-1} \cdot \text{cell}^{-1}$ (8). Therefore, physiological modulations of mitochondrial respiration, which usually vary by a factor 2–4 times (8), should have no impact on intracellular PO_2 , because O_2 diffusion flow allows a O_2 influx 20- to 50-fold higher. Thus, it is not surprising that, in these conditions, modula-

tion of mitochondrial respiration using 100 μM KCN or 100 μM DNP, which respectively inhibits and stimulates respiratory function by 2-fold, does not measurably modify PO_2 (Fig. 4).

Besides, oxygen consumption independent from respiration and resulting from activation of endothelial nitric oxide synthase (eNOS) has been evaluated. The use of a NO sensitive microelectrode previously allowed to calculate NO concentration, at a distance of 50 μm from the surface of rat aorta endothelial cell, in the range of $6.2 \times 10^{-16} \text{ mol NO} \cdot \text{s}^{-1} \cdot \text{cell}^{-1}$ (22). Therefore, since NO synthesis has a stoichiometry of 1/1 with regard to consumed O_2 , the basal production of NO by eNOS in rat aorta single endothelial cell requires the consumption of about $6.2 \times 10^{-16} \text{ mol O}_2 \cdot \text{s}^{-1} \cdot \text{cell}^{-1}$. Moreover, eNOS has been shown to be activated by endothelial cell stimulation with acetylcholine (Ach), leading to activation of NO release (23). In the endothelium from rabbit aorta, Ach increases NO extracellular level—therefore production—by ≈ 10 times (23) and probably more if intracellular NO degradation is taken into account. Therefore, the corresponding quantity of O_2 transiently consumed by Ach-stimulated eNOS can be evaluated in the range of 10 times the basal consumption, i.e., $6.2 \times 10^{-15} \text{ mol O}_2 \cdot \text{s}^{-1} \cdot \text{cell}^{-1}$. This value is about 2-fold higher than the maximum rate of O_2 diffusion through the cell membrane. Consequently, eNOS activation is a physiological mechanism which can induce a much stronger decrease in intracellular PO_2 than modulation of respiration. Our experiments corroborate this calculation, since 0.1–10 μM acetylcholine induce transient and dose-dependent increases in PdTCPNa₄-loaded cell phosphorescence decay, indicating a corresponding PO_2 reduction (Fig. 5A and Fig. 6). On the contrary, no change in porphyrin phosphorescence was observed when cell respiration was increased or decreased by the use of DNP or KCN (Fig. 4). Also, as expected, no PO_2 variation is detected in response to acetylcholine when eNOS is blocked by L-NAME (Figs. 5C and 5D).

The present results suggest that other oxygen-related mechanisms of the cell physiology can now be further investigated using cell loading with PdTCPNa₄.

ACKNOWLEDGMENT

The authors thank the Région Rhône-Alpes (France) for its financial support concerning the present work (Grant: Nanotechnology).

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