Ion-induced stacking of photosensitizer molecules can remarkably affect the luminescence detection of singlet oxygen in *Candida albicans* cells

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Abstract. Singlet oxygen (\(1\text{O}_2\)) is an important reactive intermediate in photodynamic reactions, particularly in antimicrobial PDT (aPDT). The detection of \(1\text{O}_2\) luminescence is frequently used to elucidate the role of \(1\text{O}_2\) in various environments, particularly in microorganisms and human cells. When incubating the fungus, Candida albicans, with porphyrins XF73 (5,15-bis-[4-(3-Trimethylammonio-propyloxy)-phenyl]-porphyrin) or TMPyP (5,10,15,20-Tetrakis[1-methyl-4-pyridinio]-porphyrin tetra(p-toluenesulfonate)), the \(1\text{O}_2\) luminescence signals were excellent for TMPyP. In case of XF73, the signals showed strange rise and decay times. Thus, \(1\text{O}_2\) generation of XF73 was investigated and compared with TMPyP. Absorption spectroscopy of XF73 showed a change in absorption cross section when there was a change in the concentration from \(1 \times 10^{-5}\) M to \(1 \times 10^{-3}\) M indicating an aggregation process. The addition of phosphate buffered saline (PBS) substantially changed \(1\text{O}_2\) luminescence in XF73 solution. Detailed experiments provided evidence that the PBS constituents NaCl and KCl caused the change of \(1\text{O}_2\) luminescence. The results also indicate that Cl\(^-\) ions may cause aggregation of XF73 molecules, which in turn enhances self-quenching of \(1\text{O}_2\) via photosensitizer molecules. These results show that some ions, e.g., those present in cells in vitro or added by PBS, can considerably affect the detection and the interpretation of time-resolved luminescence signals of \(1\text{O}_2\), particularly in in vitro and in vivo. These effects should be considered for any other photosensitizer used in photodynamic processes. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction in any form or medium requires full attribution to the original publication, including its DOI. [DOI: 10.1117/1.BJO.18.4.045002]

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1 Introduction

The fast development of multiresistant patterns against antibiotics of many species of bacteria has led to novel antibacterial strategies like the antibacterial photodynamic therapy (aPDT). A lot of work has been done to develop molecular structures and their derivatives that are able to generate reactive oxygen species (ROS), which are the active agents for killing microorganisms. The search for photosensitizers (PSs) for aPDT has caused the synthesis of various porphyrin molecules, which have been investigated regarding their photophysics and antimicrobial activity. Naturally occurring porphyrins can be found endogenously, e.g., the protoporphyrin IX that is in the prosthetic group of the hemoglobin or the chlorophylls based on the chlorine structure. Some endogenous porphyrins in bacteria are used to treat acne, where Propionibacterium acnes is a causative of the inflammatory processes. The porphyrin TMPyP has been frequently used for cell staining in order to investigate generation and decay of \(1\text{O}_2\). Different PSs are considered to localize in different compartments or regions in the eukaryotic or prokaryotic cell due to their number of positive charges and structure of the side chain. In order to determine the subcellular localization of PS and hence the site of \(1\text{O}_2\) generation, fluorescence microscopy is applied by exciting the respective PSs. Since the resolution of light microscopy is limited, this procedure should fail with small bacteria and fungus cells with a diameter of about 1 \(\mu\)m. The direct measurement of \(1\text{O}_2\) luminescence at 1270 nm might be an alternative candidate to elucidate the cellular action of \(1\text{O}_2\) because the rise and decay time of \(1\text{O}_2\) luminescence depend critically on its adjacency. In addition, singlet oxygen luminescence can provide information about the photodynamic process in bacteria during irradiation.

XF73 is a newly synthesized porphyrin molecule that already showed a high potential in antimicrobial PDT against gram-negative and gram-positive bacteria. However, principal data are lacking regarding its use in \(1\text{O}_2\) detection in vitro. Thus, it is the goal of the present study to investigate the photophysical properties of XF73 and its potential to monitor photodynamic action in microorganisms. Exemplarily \(1\text{O}_2\) luminescence detection was analyzed in vitro in Candida albicans cells. The well-known TMPyP was used for reference experiments.

2 Material and Methods

2.1 Chemicals

The cationic diporphyrin-based 5,15-bis-[4-(3-Trimethylammonio-propyloxy)-phenyl]-porphyrin (also referred to herein as XF73) with a molar mass of \(M = 765.81\) g/mol, including the counter ion, was synthesized by Xiangdong Feng (Solvias Company,
Basel, Switzerland) and kindly provided by Destiny Pharma Ltd. (Brighton, United Kingdom).

The 5,10,15,20-Tetrakis(1-methyl-4-pyridinio)-porphyrin tetrakis(toluenesulfonate) (also referred to herein as TMPyP) with a molar mass of \( M = 1363.63 \) g/mol, purity 97%, Na\(_2\)N\(_3\), sodium azide, Mannitol, NaCl, KCl, Na\(_2\)HPO\(_4\), KH\(_2\)PO\(_4\), and D\(_2\)O have been purchased by Sigma Aldrich (Taufkirchen, Germany), and were used as received. The photosensitizers (PSs) were dissolved in bi-distilled water at a stock concentration of 1 mM and stored at 4°C until use. Figure 1 shows the chemical structure of XF73 and TMPyP.

Phosphate-buffered saline (PBS; PAA Laboratories GmbH, Pasching, Austria) at pH 7.4 has been used for aggregation experiments and contains NaCl (0.14 M), KCl (2.7 \( \times \) 10\(^{-3} \) M), Na\(_2\)HPO\(_4\) (1.0 \( \times \) 10\(^{-2} \) M), and KH\(_2\)PO\(_4\) (1.8 \( \times \) 10\(^{-3} \) M). For the NMR spectroscopy, a parent solution of the PSs dissolved in D\(_2\)O was made and a PBS solution for dilution containing D\(_2\)O has been prepared by adding NaCl, KCl, Na\(_2\)HPO\(_4\), and KH\(_2\)PO\(_4\) with the accordant concentrations.

2.2 Absorption Spectrum

Absorption spectra were recorded at room temperature with a spectrophotometer (DU640, Beckman Instruments GmbH, Munich, Germany) in a concentration range of 1 \( \times \) 10\(^{-6} \) M to 2 \( \times \) 10\(^{-3} \) M. The percentage transmission has been measured and the absorption cross-section \( \sigma (cm^2) \) was calculated according to Eq. (1):

\[
\sigma = -\frac{\ln(T/100)}{c \cdot l \cdot N_A},
\]

where \( c \) the concentration of PS, \( l \) the length of light path through the solution, \( T \) the transmission in percentage, and \( N_A \) the Avogadro constant.

2.3 Photostability

The PSs were irradiated with an incoherent broadband lamp (UV236; emission \( \lambda = 380 \) to 480 nm) provided by Waldmann Medizintechnik (Villingen-Schwenningen, Germany). The maximal light intensity was 15.2 mW cm\(^{-2}\) at the level of the irradiated samples. The samples were irradiated for either 15 min (13.7 J cm\(^{-2}\)) or 60 min (54.8 J cm\(^{-2}\)). The emitted spectrum of the light source was recorded with a spectrometer (270 M, Jobin Yvon, Longjumeau, France) with 300 grid lines/mm and a spectral resolution of approximately 0.4 nm [Fig. 1(b)]. The detection range was 350 to 650 nm. The recorded spectral data were corrected regarding the spectral sensitivity of the spectrometer. The emission spectrum of the Waldmann UV lamp was normalized to its maximum between 400 and 450 nm.

2.4 Cell Experiments

The \( \text{C. albicans} \) strain ATCC-MYA-273 was used for the experiments. The planktonic cells of \( \text{C. albicans} \) were diluted to a number of 10\(^6\). For the incubation of \( \text{C. albicans} \), the PSs stock solution has been diluted with H\(_2\)O. The cells were incubated with a PS concentration of 10\(^{-4} \) M in the dark for 15 min in H\(_2\)O plus 50% PBS in falcons at slow rotation. The cells were rinsed twice with PBS to remove the not included or nonadherent PSs and afterward dissolved in pure H\(_2\)O. For the singlet oxygen luminescence experiments, the planktonic cells were excited with a frequency doubled Nd:YAG-Laser (PhotonEnergy, Ottensoo, Germany).

2.5 Fluorescence Spectrophotometer

The localization of XF73 in \( \text{C. albicans} \) was examined by fluorescence microscopy (Zeiss Vario-AxioTech, Goettingen, Germany) with an appropriate dual-band filter set for excitation and emission (Omega Optical, Brattleboro, Vermont) and a 63x magnification. Planktonic \( \text{C. albicans} \) were incubated 2 h with 10\(^{-4} \) M XF73 in PBS and were rinsed twice with PBS.

2.6 Singlet Oxygen Luminescence and Quantum Yield of \( ^1\text{O}_2 \) Formation (\( \Phi_{\text{A}} \))

Solutions with PSs were filled in a cuvette (QS-101, Hellma Optik, Jena, Germany) and solutions of the planktonic cell suspension were investigated in acrylic cuvettes (SARSTEDT, Nümbrecht, Germany), both during magnetic stirring. The PSs were excited with a frequency doubled Nd:YAG-laser (PhotonEnergy, Ottensoo, Germany) with a wavelength \( \lambda = 532 \) nm, power output \( P = 50 \) mW, frequency of \( f = 2 \) kHz, and therefore, energy per pulse of \( E = 2.5 \times 10^{-5} \) J. Every sample was irradiated with 40,000 pulses. The C. albicans planktonic cells were excited with a frequency doubled Nd:YAG-laser (PhotonEnergy, Ottensoo, Germany) with a wavelength \( \lambda = 532 \) nm, power output \( P = 60 \) mW, frequency of \( f = 5 \) kHz, and therefore, energy per pulse of \( E = 1.2 \times 10^{-5} \) J. Every sample was irradiated with 100,000 pulses.

Direct detection as described in previous papers was done by time resolved measurements at 1270 nm (30 nm full width half maximum filter) in near-backward direction with...
respect to the exciting beam using an infrared-sensitive photomultiplier (R5509-42, Hamamatsu Photonics Deutschland GmbH, Herrsching, Germany) with an additional 950 nm cut-off filter. The luminescence intensity is given by

$$I(t) = \frac{C}{t_{R}^{-1} - t_{D}^{-1}} \left[ \exp\left(-\frac{t}{t_{R}}\right) - \exp\left(-\frac{t}{t_{D}}\right) \right]$$

where $C = [T_{1}]_{\lambda_{max}} \Delta \mu_{H_{2}O}$ was used to fit the singlet oxygen luminescence signal, describing the deactivation of the excited triplet state $T_{1}$ of the photosensitizer by oxygen in its ground state $(\Delta \mu_{H_{2}O} \Delta \mu_{T_{1}}$ and $t_{D}$ are the rise and decay times, which is the excited triplet state decay time $\tau_{T_{1}}$ of the photosensitizer and the decay time of singlet oxygen $\tau_{\Delta}$. The attribution of $\tau_{T_{1}}$ and $\tau_{\Delta}$ depends on the oxygen concentration in the system; at high oxygen concentrations, usually the decay time $t_{D}$ of the signal describes the decay time of singlet oxygen $\tau_{\Delta}$. In order to determine the rise and decay times, the Levenberg-Marquardt-algorithm of Mathematica (Wolfram Research, Champaign) was used. The luminescence signal was spectrally resolved using interference filters in front of the photomultiplier tube at wavelengths ranging from 1150 to 1400 nm or a monochromator (Horiba, Yobin Yvon Inc., USA) from 1200 to 1350 nm at 10 nm regular steps (XF73 in pure H$_{2}$O). The values show the integrated luminescence signals detected at a certain wavelength and are normalized to the maximal value. A Lorentz-shaped curve has been fitted through the measurement points, with the maximum at $\lambda = 1270$ nm, referring to the maximal value in H$_{2}$O.

For the determination of $\Phi_{\Delta}$ of XF73 in H$_{2}$O, it is compared with the $\Phi_{\Delta}$ of TMPyP, which is reported in literature being 0.74 and 0.77 ± 0.06 in aqueous solution. Therefore, five probes of each PS of different concentrations (between 30% and 70% absorption at a wavelength of $\lambda = 532$ nm) are irradiated and the emitted $^1$O$_2$-photons are integrated and the emitted $^1$O$_2$-photons are integrated with the integral over the luminescence curve, given with the fit routine mentioned.

### 3 Results and Discussion

As a first experiment, cells of *C. albicans* were incubated with XF73 or TMPyP for 15 min using a concentration of 100 µM. The cells were washed twice, suspended in H$_{2}$O solution, and subsequently excited with the laser at 532 nm. TMPyP in the cells produced a clear $^1$O$_2$ luminescence signal with a rise time of $t_{R} = (1.77 ± 0.2)$ µs and a decay time of $t_{D} = (6.74 ± 0.7)$ µs [Fig. 2(a)]. In contrast to that, XF73 in *C. albicans* produced completely different $^1$O$_2$ luminescence signals showing no or a very short rise time, whereas the signal decayed in a multieoxponentially manner. When starting the fit at 2 µs, the decay time was $t_{D} = (5.33 ± 0.5)$ µs [Fig. 2(b)].

On one hand, XF73 molecules were possibly localized at subcellular sites, where high quencher concentrations or low oxygen concentration affected the rise and decay of $^1$O$_2$ luminescence. On the other hand, the photophysical properties of XF73 could have been altered after the uptake of *C. albicans* cells. It is known for many porphyrin species that PS molecules can show stacking to J- (edge-to-edge) and H-aggregates (face-to-face) under certain conditions. Aggregation of porphyrin derivatives is influenced by concentration of inorganic salts, the polarity of the solvents, or the side chains of the porphyrins whereas the results are still controversially discussed. Aggregation of PSs like TMPyP should not occur for concentrations of less than 10$^{-4}$ M. An overview of the discussions related to the aggregation of TMPyP is given by Vergeldt et al., who described adsorption onto surfaces or aggregation effects due to the impurity of the solvent.

Stacking of porphyrin molecules could occur at high photosensitizer concentrations or could be mediated by inorganic salts, which were particularly added with PBS to cells. Photosensitizer stacking may change the rate and rate constants for XF73 molecules and thereby affect the generation and decay of $^1$O$_2$, which could be detected by time resolved detection of its luminescence.

### 3.1 Absorption Spectroscopy in Aqueous PS Solution

Changes in the π-electron-system of porphyrin molecules can lead to the change of absorption cross-section $\sigma$ and hence may affect $^1$O$_2$ generation. TMPyP showed a constant absorption cross-section in the range from 10$^{-6}$ to 10$^{-3}$ M (data not shown). In contrast to TMPyP, the absorption spectrum of XF73 in pure H$_{2}$O clearly depended on XF73 concentration. The absorption cross-section decreased with increasing XF73 concentration from 10$^{-5}$ to 2·10$^{-3}$ M and the absorption maximum (Soret band) shifted to shorter wavelengths (∼7 nm) [Fig. 2(b)]. Both effects indicate aggregation of XF73 molecules.
3.2 Absorption Spectroscopy in Aqueous XF73 Solution with PBS or PBS Constituents

The PBS and cytosol of living cells contain various ions like $K^+$, $Na^+$, $Cl^-$, $HCO_3^-$, $Mg^{2+}$, $Ca^{2+}$, and $HPO_4^{2-}$. As a first approximation to cellular environment, XF73 was dissolved in PBS solution. As XF73 was not easily soluble in PBS, the maximum concentration of PBS was 50% in $H_2O$. Absorption spectra of XF73 ($2 \times 10^{-5}$ M) were recorded in pure $H_2O$, in 50% $H_2O$ plus 50% PBS, and in 100% $H_2O$ adding single constituents of PBS such as KCl, NaCl, NaH$_2$PO$_4$, or KH$_2$PO$_4$, 0.1 M each [Fig. 3(b)].

In the presence of Na$_2$HPO$_4$ or KH$_2$PO$_4$, the absorption cross-section showed no wavelength shift or new absorption maxima within given experimental accuracy ($\pm 2$ nm) when compared with pure $H_2O$. The maximum value of absorption cross-section at $(402 \pm 2)$ nm decreased from $\sigma_{max} = 0.71 \times 10^{-15}$ cm$^2$ (pure $H_2O$) to $\sigma = 0.41 \times 10^{-15}$ cm$^2$ or $\sigma = 0.48 \times 10^{-15}$ cm$^2$ when Na$_2$HPO$_4$ or KH$_2$PO$_4$ was added, respectively.

When adding PBS, $\sigma_{max}$ decreased from $0.71 \times 10^{-15}$ cm$^2$ to $0.25 \times 10^{-15}$ cm$^2$ and shifted to longer wavelengths (red shift) of $24 \pm 2$ nm.

When adding NaCl or KCl to XF73 solution, $\sigma_{max}$ decreased to $0.25 \times 10^{-15}$ cm$^2$ for each. In addition, $\sigma_{max}$ shifted to the red by about $25 \pm 3$ nm. At the same time, the absorption spectrum showed new absorption maxima within the spectral range of the Soret band. Addition of $Cl^-$ leads to a fundamental change of the absorption spectrum including a red shift. It is suggested that $Cl^-$ affects the tetrapyrrol ring system and enhances the aggregation, which was already reported for other porphyrin structures.

A visible precipitation of the solute started when using >10% PBS + $H_2O$. This effect was shown to be reversible by diluting the solution with pure $H_2O$. As a consequence of this dilution, the absorption spectrum of XF73 in PBS changed back to the absorption spectrum in pure $H_2O$ (data not shown). The precipitation does not affect the absorption measurements because the probes are directly used after being diluted and the precipitation effect needs several hours to develop. No light scattering effect in solutions was detectable by checking the absorption spectrum at shorter wavelengths.

3.3 Photostability

Also, the photostability and hence the change of absorption spectrum during irradiation may affect $^{1}O_2$ luminescence. Therefore, the photostability of XF73 in solution containing PBS was investigated when illuminating the samples up to 54.8 J cm$^{-2}$.

No changes in the absorption spectrum of TMPyP were noticed within irradiation time of up to 60 min (data not shown). The XF73 in $H_2O$ and in 50% PBS + $H_2O$ showed a decrease in absorption that was mainly detected in the spectral range of the Soret band (Fig. 4). Obviously, the presence of PBS,
i.e., its ions, can additionally reduce radiation absorption of XF73. These effects may also affect the use of XF73 when applied for photodynamic inactivation of microorganisms.

In case of $^1\text{O}_2$ experiments (see below), XF73 solutions were irradiated with 1 J of laser energy (532 nm). It is expected that $\sigma$ values do not significantly change under these experimental conditions.

### 3.4 $^1\text{O}_2$ Luminescence Experiments without PBS

Incubation of bacteria or human cells with XF73 and subsequent irradiation yielded effective cell killing by means of $^1\text{O}_2$ generation, which was confirmed by adding $^1\text{O}_2$ quencher NaN$_3$ that significantly reduced the cell toxicity. Since detailed studies on $^1\text{O}_2$ generation of the novel porphyrin molecule XF73 were

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**Fig. 5** (a)–(c) $^1\text{O}_2$ luminescence signals of [XF73] = 5 × 10$^{-5}$ M with different PBS concentrations in H$_2$O with an oxygen concentration of [O$_2$] = 2.7 × 10$^{-4}$ M. (d) Spectroscopically resolved $^1\text{O}_2$ luminescence signal, generated by XF73 in H$_2$O with an oxygen concentration of [O$_2$] = 2.7 × 10$^{-4}$ M. A Lorentz-shaped curve has been fitted through the measurement points. (e) $^1\text{O}_2$ luminescence generated by XF73 in H$_2$O + 20%PBS at 1270 nm with 2 × 10$^{-3}$ M NaCl in solution. (f) Spectroscopically resolved $^1\text{O}_2$ luminescence signal, generated by XF73 in 30% PBS + H$_2$O with an oxygen concentration of [O$_2$] = 2.7 × 10$^{-4}$ M. A Lorentz-shaped curve has been fitted through the measurement points.
missing, we investigated XF73 in pure aqueous solution according to previous studies on other photosensitizers.

After dissolving [XF73] = 5 × 10^{-5} M in air saturated ([^{1}O_{2}] = 2.7 × 10^{-1} M), pure H_{2}O, the rise and decay part of the time resolved signals could be assigned to the decay time \( \tau_{A} \) of \(^{1}O_{2}\) and the decay time \( \tau_{T1} \) of PS, respectively. Experiments yielded \( \tau_{T1} = 1.6 \pm 0.2 \) \( \mu \)s and decay time \( \tau_{A} = 3.5 \pm 0.3 \) \( \mu \)s [Fig. 4(a)]. The decay time is in good correlation with the lifetime of \(^{1}O_{2}\) in pure water [Felgenträger et al.: Ion-induced stacking of photosensitizer molecules can remarkably affect the luminescence detection.]. The spectrally resolved \(^{1}O_{2}\) luminescence revealed a peak at 1270 nm, which clearly confirmed the generation of \(^{1}O_{2}\) [Fig. 5(b)]. The \(^{1}O_{2}\) quantum yield \( \Phi_{A} \) of XF73 was determined in air saturated, pure H_{2}O, using TMPyP as reference. The \( \Phi_{A} \) values of TMPyP are 0.74 and 0.77 \pm 0.04 [Felgenträger et al.: Ion-induced stacking of photosensitizer molecules can remarkably affect the luminescence detection.]. Using the previously reported technique, XF73 showed a value of \( \Phi_{A} = 0.57 \pm 0.06 \).

When changing the concentration of \( O_{2} \) in the solution at a constant concentration of [XF73] = 5 × 10^{-5} M, the meaning of the rates \( K_{A} \) and \( K_{T1} \) at \([^{1}O_{2}] = 1.1 \times 10^{-4} \) M changed according to the decay paths of \(^{1}O_{2}\) and \( T_{1} \) [Fig. 6]. This change occurs at a crossing point of \( t_{1}^{-1} \) and \( t_{2}^{-1} \), which was about \([^{1}O_{2}] = (0.11 \pm 0.02) \times 10^{-3} \) M for XF73. By extrapolating \( t_{2}^{-1}, K_{T1} ([^{1}O_{2} = 0] \text{ M}) = 0.03 \mu s^{-1} \) was determined yielding a lifetime of the triplet \( T_{1} \)-state of \((33 \pm 5) \mu s \) in aqueous solution without oxygen quenching. The quenching rate constant \( k_{q} \) for quenching of the excited triplet state of XF73 by oxygen is therefore \( k_{q} = 2.3 \times 10^{9} \text{ s}^{-1} \text{ M}^{-1} \) resulting from the Stern-Volmer-plot in Fig. 6A, where the oxygen concentration was varied and the triplet decay of XF73 was determined.

As a next step, XF73 concentration was varied from [XF73] = 10^{-6} to 5 × 10^{-3} M at \([^{1}O_{2}] = 5.6 \times 10^{-5} \) M [Fig. 6B]. The value of \( t_{2}^{-1} \) increased with increasing concentration that indicated a clear self-quenching effect of the excited triplet-\( T_{1} \)-state for [XF73] up to about 2 × 10^{-4} M. Above this concentration, the quenching effect decreased and reached a plateau at \( t_{2}^{-1} = 0.205 \mu s^{-1} \), which is equivalent to a decay time of the triplet-\( T_{1} \)-state of \( t_{1} = 4.9 \mu s \) [Fig. 6B]. According to the absorption spectroscopy data, a stacking of XF73 molecules occurred, which is easily detectable for XF73 concentration higher than 1 × 10^{-4} M [Fig. 6C]. Obviously, the stacking process had already formed the dimers or oligomers of XF73 molecules at this concentration. Besides a different absorption cross-section, these aggregates also show different deactivation of triplet \( T_{1} \)-state as compared with XF73 monomers [Fig. 6B].

### 3.5 \(^{1}O_{2}\) Luminescence Experiments with PBS

In light of the results above, \(^{1}O_{2}\) luminescence signals should be affected by molecule stacking, in particular when the photosensitizer in located in C. albicans cells [Fig. 2B]. Therefore, we investigated the PBS effect on time-resolved \(^{1}O_{2}\) luminescence generated by XF73 in air saturated solution at a concentration of 5 × 10^{-5} M, for which stacking due to PS concentration should be still minimal [Fig. 6A]. The results clearly show that \(^{1}O_{2}\) luminescence substantially changed with increasing PBS concentration [Fig. 6A–6C]. From 0% to 50% PBS in H_{2}O, the rising part of \(^{1}O_{2}\) luminescence signal disappeared, whereas the decay part shortened. Now, the luminescence signals at high PBS concentrations [Fig. 6C] were similar to those recorded for XF73 in C. albicans cells [Fig. 6B] yielding again a multiexponential decay.

When adding \(^{1}O_{2}\) quencher NaN_{3} to the 20% PBS solution up to a high concentration of 2 × 10^{-3} M NaN_{3}, the \(^{1}O_{2}\) luminescence signal almost disappeared. The residual signal should not originate from \(^{1}O_{2}\) luminescence [see Fig. 6C]. The same residual signal was detected in solutions without NaN_{3} and without oxygen (data not shown).

\(^{1}O_{2}\) luminescence was also spectrally resolved for PBS 0% and 50% in H_{2}O [Fig. 6D and 6E]. A Lorentz-shaped curve has been fitted through the measurement points and the values were normalized to the maximal value. Without PBS, the fit shows a clear maximum at 1270 nm that confirms the generated \(^{1}O_{2}\) [Felgenträger et al.: Ion-induced stacking of photosensitizer molecules can remarkably affect the luminescence detection.]. At 50% PBS, the maximum at 1270 nm almost disappeared, the baseline moved for wavelengths <1270 nm, and the signal-to-noise ratio decreased, which indicates a substantial decrease of \(^{1}O_{2}\) generation.

Comparable to absorption spectroscopy, the changes of time- and spectral resolved \(^{1}O_{2}\) luminescence signals, induced by PBS, could be simply reversed by diluting the used solutions with H_{2}O and hence reducing the PBS concentration. A high degree of dilution of PBS concentration yielded time- and spectrally resolved \(^{1}O_{2}\) luminescence signals comparable with Fig. 6A and 6D.

Scattering of photons within solution might also cause a \(^{1}O_{2}\) luminescence signal equal to the one in Fig. 6C, and might be
originating from precipitation due to the stacking of the porphyrins. To exclude any scattering effects, the scattering agent SiO2 was added to aqueous solutions containing 5 x 10⁻⁵ M XF73 or TMPyP. No effect on the shape of the ¹O₂ luminescence signal and no change of the rise and decay times were detected for both photosensitizers. Additionally there was no scattering effect visible in the absorption spectrum of XF73 in H₂O + 50% PBS.

4 Conclusions

The detection of singlet oxygen by its luminescence is a great tool to show the action of singlet oxygen even in cells or bacteria. In this context it is important to have a detection procedure that provides reliable data from inside such cells, in particular when knowing that cellular constituents can substantially affect singlet oxygen luminescence. The interaction of porphyrins with C. albicans is controversially discussed that ranges from no uptake to tight binding or even internalization. Many porphyrins are lipophilic and hence should accumulate in cellular membranes but the high water-solubility of XF73 suggests localization in the cytoplasm as well. Fluorescence microscopy showed the overall attachment of XF73 to the cell after washing; however, the low spatial resolution of optical microscopy impedes the evaluation of the subcellular photosensitizer localization (Fig. 7). Thus, it would be of importance to gain additional insight by evaluating the ¹O₂ luminescence data.

However, XF73 showed substantial stacking of molecules that affected light absorption as well as the generation and decay of ¹O₂. Stacking already occurred in pure H₂O along with the increase of the PS concentration. The stacking is additionally forced by the ionic pressure of Cl⁻. Such ions are either present in cells or are usually added in cell experiments in vitro via PBS to protect the cells from osmosis. Therefore, it is impossible to exclude such ions when investigating photosensitzers in cell experiments.

Depending on the uptake mechanisms and the chemical structure, a PS localizes in cellular membranes or in the cytoplasm close to any cellular structures. Cytoplasm shows a similar concentration of Cl⁻ like PBS; therefore, it is very likely that aggregation of XF73 occurs in cells such as C. albicans. The time-resolved detection of the ¹O₂ luminescence in a solution of planktonic C. albicans cells incubated with XF73 and surrounded by pure H₂O has been done [Fig. 2(b)]. In fact, the luminescence signal is similar to the signal of XF73 generating ¹O₂ in 30% PBS [Fig. 2(c)] showing a multiexponential decay. This signal indicates a surrounding of XF73 within C. albicans cells whose ionic concentration is similar to that of >30% PBS. Usually, the rise and decay times of luminescence provides information about the localization of ¹O₂ and hence of the photosensitizer applied due to the short diffusion length of ¹O₂ in cells. As the molecule XF73 is strongly influenced by the salts of the phosphate buffer PBS, such interpretations could be misleading at the moment. This problem may also occur for any other PS that undergoes stacking in the presence of ions such as Cl⁻.

Despite the results with XF73, the ¹O₂ luminescence detection in cells is a great tool to elucidate photodynamic processes. The porphyrin TMPyP showed neither stacking in the investigated range of concentration nor interference with the salts of PBS. After attached to or taken up by C. albicans, the generated ¹O₂ could be easily detected by its luminescence with clear rise and decay components. The decay time of the ¹O₂ luminescence in Fig. 2(a) of ⁴T₀ = (6.74 ± 0.5) μs, which is clearly longer than in pure water (3.5 μs) and can be most likely attributed to the decay time of the ¹T₁-state of TMPyP. If so, a triplet state decay time of 6.74 μs suggests an oxygen concentration of its surrounding of [O₂] = 8 x 10⁻³ M, which is 30% compared with the oxygen concentration of [O₂]sat = 2.7 x 10⁻⁴ M of air saturated water.

Nevertheless, the striking phototoxic effect of XF73 in bacteria was demonstrated. In vitro experiments showed a substantial reduction of bacteria (~8 log₁₀ steps), which were incubated very small XF73 concentrations (10⁻⁵ M) for 5 min, and subsequently irradiated with 13.7 J cm⁻². The action of ¹O₂ was proven with the addition of the ¹O₂ quencher NaN₃; however, the photodynamic effect could not be completely inhibited by the quencher. In addition, the rather small XF73 concentration in the range of 0.01 to 10 μM in those bacteria experiments could have minimized the stacking effect and therefore maximized phototoxicity by an effective singlet oxygen generation.

Aggregation effects influence also the fluorescence of a dye, which has recently been described by López-Chicón et al. with an investigation of Hypericin in different species of Candida. The grade of aggregation depends on the surrounding and the fluorescence is low or not existent at a high PS aggregation, which occurs in H₂O-environment. Upon incubation of different species of Candida with Hypericin, one can draw a conclusion about the localization of the PS by monitoring the radiative decay, here the fluorescence that depends on the aggregation status.

Recently, with an optimized experimental setup singlet oxygen generation in C. albicans cells was detected by irradiating directly the Soret-band of the porphyrin TMPyP at 420 nm. With irradiation of the absorption maximum, it is possible to detect singlet oxygen generation and decay at already very low photosensitizer concentrations in the range of few μM offering a concentration range where aggregation effects are expected to be low and thus the singlet oxygen generation is effective.
studies on the change of the singlet oxygen luminescence in different species of microorganisms should lead to better insights about the change of the decay times to the localization.

References


Feldt et al.: Ion-induced stacking of photosensitizer molecules can remarkably affect the luminescence detection...