

# Novel porphyrins and a chlorin as efficient singlet oxygen photosensitizers for photooxidation of naphthols or phenols to quinones

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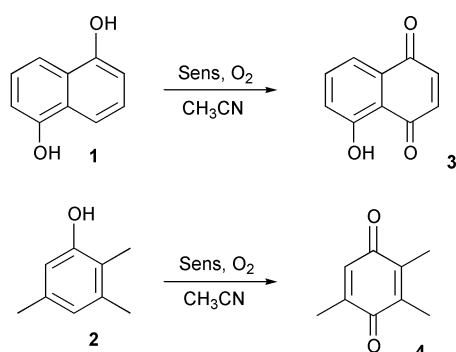
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Four porphyrins and one chlorin having aromatic groups at the *meso* position have been synthesized and tested as potential sensitizers for the photooxidation of phenols. The yields of conversion of 1,5-dihydroxynaphthalene and 2,3,5-trimethylphenol to their corresponding quinones have been determined following photolysis in air-saturated acetonitrile–dichloromethane solutions in the presence of these compounds, and are higher than those obtained using other photosensitizers. The reactions are shown to proceed *via* formation of singlet oxygen ( $^1\Delta_g$ ), followed by its addition to the phenol. A mechanism is presented. Rates of reaction of singlet oxygen with the substrates were determined by studying the decay of the  $^1O_2^*$  emission. Singlet oxygen quantum yields and formation efficiencies for the photosensitizers have been determined by laser flash photolysis and photoacoustic calorimetry. In addition, for two of the porphyrins, these were also measured using time-resolved luminescence. In all cases, highly efficient singlet oxygen formation is observed. The stabilities of the sensitizers to prolonged photolysis were studied. The compound 5,10,15,20-tetrakis(2,6-dichlorophenyl)porphyrin was found to be a particularly efficient photosensitizer for oxidation of phenols. It is suggested that this is due both to its high singlet oxygen yield and to its good photostability.

## Introduction

Quinone derivatives are naturally occurring compounds which play important roles in the pharmaceutical<sup>1–3</sup> and dye industries.<sup>4</sup> There is a strong interest in the development of efficient routes for preparing these compounds. The oxidations of 1,5-dihydroxynaphthalene **1** or 2,3,5-trimethylphenol **2** to the corresponding quinones **3** and **4** (Scheme 1) are of particular



**Scheme 1** Sensitized photooxidation reactions for 1,5-dihydroxynaphthalene and 2,3,5-trimethylphenol.

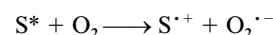
interest, since they are intermediates for the syntheses of plumbagin and vitamin E, respectively, and they can be used as starting materials for preparing antitumor and antiviral agents.<sup>5</sup>

Normal synthetic routes to quinones involve either enzymatic<sup>4</sup> or chemical oxidation of phenols and naphthols. Particular interest has focused on the use of inorganic oxidants, such as Fremy's salt,<sup>6</sup> K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>,<sup>7</sup> RuCl<sub>3</sub>,<sup>8</sup> and, more recently, H<sub>2</sub>O<sub>2</sub>–heteropolyacid,<sup>9</sup> or potassium monopersulfate.<sup>10</sup>

Complementary to the chemical oxidation processes, photooxidation methods also show great promise, since they possess the environmental advantages resulting from minimum usage of toxic chemicals. The use of singlet molecular oxygen in

photosensitized oxygenations would seem to be a particularly useful synthetic method<sup>10–14</sup> and a number of examples have been reported of the use of classic dyes, such as Methylene Blue and Rose Bengal, as photosensitizers in these reactions.<sup>1,15</sup> For example, the photooxidation of 1,5-dihydroxynaphthalene **1** to the corresponding quinone in 85% yield has been achieved using Methylene Blue as photosensitizer.<sup>1</sup> In addition, Rose Bengal has been shown to be an efficient photosensitizer for the photooxidation of other dihydroxynaphthalenes.<sup>16</sup> In this case, the photosensitizer was bound to a poly(styrene) backbone to facilitate separation from products. However, with both Rose Bengal<sup>17</sup> and Methylene Blue, photodegradation of the photosensitizer is observed upon extensive irradiation. For practical synthetic applications it is important to develop efficient, stable singlet oxygen photosensitizers.

The attractive spectroscopic and photophysical properties of porphyrins make them good candidates for applications in areas as diverse as photodynamic therapy (PDT),<sup>17–20</sup> molecular electronics,<sup>21,22</sup> and catalysis.<sup>23,24</sup> Both the free base porphyrins and their metal complexes are of interest. For many of these applications the photosensitizing ability of the porphyrins with molecular oxygen is important. This may produce either superoxide radical anion or singlet oxygen in the type I:



or type II processes:



With the free base porphyrins the type II processes are normally thought to be dominant.<sup>25</sup> By suitable choice of porphyrin, high yields of singlet oxygen may be obtained.

Recently we have described<sup>20</sup> the advantageous effects of bulky substituents in the *meso* positions of the porphyrin skeleton on the quantum yield of the singlet oxygen formation. Use of the corresponding chlorins, obtained on reduction of the porphyrins, is also observed to increase the singlet

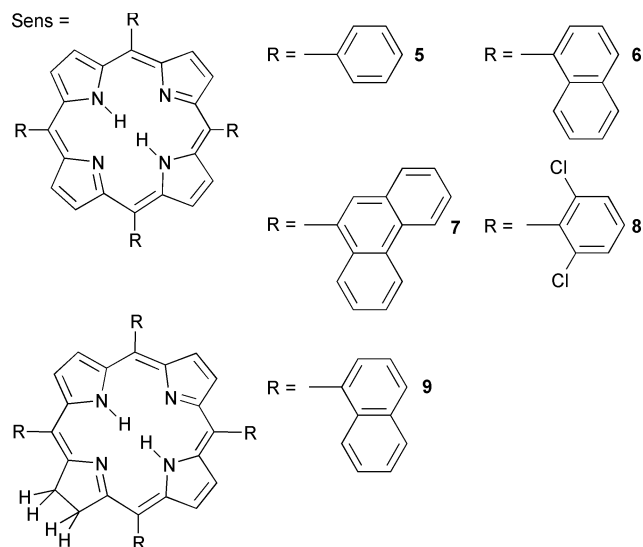


Fig. 1 Structures of the porphyrins and chlorin used in this study.

oxygen generation efficiency. It is, therefore, important to test these novel compounds as possible photosensitizers for photo-oxidation reactions.

The photooxidation of 1,5-dihydroxynaphthalene and 2,3,5-trimethylphenol to the corresponding quinones is reported, using the *meso*-arylporphyrins and the *meso*-naphthylchlorin shown in Fig. 1 as photosensitizers. To understand the effect of the photosensitizers on the kinetics and the mechanism of the reaction we have also studied the main photophysical properties, including singlet oxygen formation efficiency and quantum yield, of the porphyrins 5–8 and chlorin 9, in addition to their stability in the reaction medium. Particular emphasis is given to the use of time-resolved photoacoustic calorimetry (PAC) and flash photolysis to study the energy transfer from the photosensitizers to oxygen.<sup>20</sup> In addition, time-resolved emission spectroscopy has been used to follow the reactions of singlet oxygen with the substrates 1 and 2.

## Experimental

All solvents were purified before use according to literature procedures.<sup>26</sup> Methylene Blue, 9-carboxyphenanthraldehyde, 1,5-dihydroxynaphthalene and 2,3,5-trimethylphenol were used as purchased from Aldrich. The synthesis of the tetrapyrrolic photosensitizers is described in this paper.

### Instrumentation

<sup>1</sup>H NMR spectra were recorded on a 300 MHz Bruker-AMX spectrometer. *J* values are given in Hz. Mass spectra were obtained on a VG autospec apparatus. Elemental analysis was carried out using a Fisons Instruments EA1108-CHNS-0 apparatus. Absorption and luminescence spectra were measured on Shimadzu UV-2100 and SPEX Fluoromax 322-2 spectrophotometers, respectively. Gas chromatography was carried out using an OV1 (25 m × 0.3 mm, id) capillary column on a Hewlett-Packard 5890A with a Hewlett-Packard 3396A integrator. GC analysis was run at 70 °C (3 min)/10 °C min<sup>-1</sup>/220 °C (10 min); detector temperature 250 °C, injector temperature 220 °C.

### Methods

**Fluorescence measurements.** Fluorescence measurements were made in 1 cm quartz cuvettes on toluene solutions, carefully deaerated by saturating with N<sub>2</sub>. Fluorescence excitation spectra were obtained for all the porphyrins and the chlorin studied, and agreed well with the corresponding absorption spectra, confirming the high purity of the samples. For emission measurements, solutions were excited at the maximum of

the corresponding Soret band. Fluorescence quantum yields ( $\Phi_F$ ) were measured as described previously.<sup>20</sup>

**Singlet oxygen luminescence measurements.** Time-resolved singlet oxygen luminescence was measured at the Free Radical Research Facility of the Paterson Institute for Cancer Research, Manchester, England. A J. K. Lasers systems Nd/YAG laser was used for excitation, and emission was monitored using a germanium diode. Details of the system and data analysis methods are given elsewhere.<sup>27,28</sup>

**Flash photolysis measurement.** Flash photolysis was performed with an Applied Photophysics LKS.60 Laser Flash Photolysis Spectrometer using a Spectra-Physics Quanta-Ray GCR-130 Nd/YAG laser and a Hewlett-Packard Infinum oscilloscope. Solutions were prepared with absorbance between 0.2 and 0.4 at the Soret band, and were saturated with air for the measurement of triplet lifetime in the presence of the quencher. The lifetime decay was collected in the maximum of the singlet–triplet difference spectrum (460 nm) for all the compounds.

**Photoacoustic measurements.** Full details of the PAC apparatus have recently been described.<sup>20,29</sup> To minimize the background and maximize the sensitivity of the measurements a front-face cell with a dielectric mirror was used.<sup>30</sup> The solvent, sample and reference solutions were allowed to flow through a 0.11 mm thick cell at a rate of 1 ml min<sup>-1</sup> (SSI chromatographic pump) where they were irradiated with an unfocused PTI dye laser (model PL2300), pumped by a pulsed N<sub>2</sub> laser working at a frequency of 2 Hz. Compounds 5–7 were irradiated at 421 nm and the compound 9 at 517 nm. A small fraction of the laser beam was reflected to a photodiode (Tektronix DSA 601, 1 GS s<sup>-1</sup>). The photoacoustic waves were detected with a 2.25 MHz Panametrics transducer (model 5676) and the signals stored by the transient recorder, from where they were transferred to a PC for data analysis. In a typical PAC experiment 100 waves of the sample, reference and pure solvent are recorded and averaged using the same experimental conditions. Four sets of averaged sample, reference and solvent waves were used for the data analysis at a given laser intensity, and four different laser intensities were employed in each set of experiments. Introducing neutral density filters with transmission between 25 and 100% varied the laser intensity. For oxygen photosensitization studies, the sample solutions were saturated with air, while for all other measurements solutions were deaerated by continuously bubbling N<sub>2</sub>. All the measurements were made in toluene solution with Mn(III) 5,10,15,20-tetraphenylporphyrinate acetate as standard.

### Synthesis of photosensitizers

The porphyrins used in this study were all prepared according to the method we have previously described for the synthesis of 5,10,15,20-tetraarylporphyrins.<sup>31</sup>

**General procedure.** The appropriate aryl aldehyde ( $0.4 \times 10^{-3}$  mol) is dissolved in a mixture of acetic acid (140 ml, 2.45 mol) and nitrobenzene (70 ml, 0.68 mol), and the temperature is raised to 120 °C. Pyrrole (2.8 ml,  $0.4 \times 10^{-3}$  mol) is then added. The reaction is followed by monitoring the UV–visible absorption spectra until the Soret band intensity reaches a maximum. At this point the solution is cooled to room temperature to give porphyrin crystals, which are filtered off and washed with methanol. The compound is recrystallized from dichloromethane–methanol. The synthesis and characterization of compounds 5, 6, 8 and 9 have previously been reported.<sup>32</sup>

**Synthesis of 5,10,15,20-tetra(9-phenanthryl)porphyrin (7).** From 2.8 ml of pyrrole and 82.4 mg of 9-carboxyphen-

anthraldehyde the required porphyrin was obtained. (Yield, 26.4 mg, 26%) (Found: C, 89.84; H, 4.67; N, 5.53. Calc. for  $C_{76}H_{46}N_4$ : C, 89.87; H, 4.62; N, 5.52%);  $^1H$  NMR  $\delta_H$  (300 MHz;  $CDCl_3$ ) -2.11 (2H, br s, NH), 7.10–7.20 (8H, m, phenanthryl), 7.60–7.66 (4H, m, phenanthryl), 7.76–7.78 (4H, m, phenanthryl), 7.84–7.88 (4H, m, phenanthryl), 8.03–8.05 (4H, m, phenanthryl), 8.51–8.56 (4H, m, phenanthryl), 8.58–8.61 (8H, m, phenanthryl), 8.94–8.98 (8H, s,  $H_\beta$ ); mass spectrum (FAB)  $m/z$  = 1015 (molecular ion).

### Photosynthetic oxidation experiments

**General procedure.** Photooxidation experiments were carried out using a laboratory-built photoreactor consisting of a water-refrigerated 250 ml vessel, equipped with an entrance for air and external water-cooling. The photoreactor used visible light (unfiltered output from four 100 W tungsten lamps) for irradiation.

The substrate in acetonitrile (190 ml) was mixed with a solution of the appropriate photosensitizer (porphyrins **5–8** or chlorin **9** (0.006 mmol)) in  $CHCl_3$  (10 ml). The solutions were irradiated using visible light with a stream of air continuously flowing into the system. The evolution of the reaction was monitored by UV–vis spectroscopy at 450 nm (compound **3**) and by GC (compound **4**). The reaction mixtures were evaporated. The residue was either chromatographed on a silica gel column using  $CHCl_3$  as eluent and recrystallized from petroleum ether (Juglona) or sublimed (2,3,5-trimethylbenzoquinone) to give the pure products.

**5-Hydroxy-1,4-naphthoquinone (3).** (103 mg, 89%) (Found: C, 68.98; H, 3.56. Calc. for  $C_{10}H_6O_3$ : C, 68.96; H, 3.45%);  $\nu_{max}$  (KBr)/ $cm^{-1}$  3500–3250 (hydroxy), 1664 and 1643 (aromatic ketone), 1601 (aromatic double bond);  $\delta_H$  (300 MHz;  $CDCl_3$ ) 7.28 (1H, d,  $J$  2.49, H-naph.), 7.30 (1H, d,  $J$  2.52, H-naph.), 7.64 (3H, m, H-naph.), 11.9 (1H, s, OH); mass spectrum (FAB)  $m/z$  = 174 (molecular ion).

**2,3,5-Trimethylbenzoquinone (4).** (91.5 mg, 83%) (Found: C, 68.25; H, 6.40. Calc. for  $C_9H_{10}O_2$ : C, 71.98; H, 6.70%);  $\nu_{max}$  (KBr)/ $cm^{-1}$  1635 (aromatic ketone) and 1286 (methyl);  $\delta_H$  (300 MHz;  $CDCl_3$ ) 2.01 (3H, s,  $CH_3$ ), 2.03 (3H, s,  $CH_3$ ), 2.04 (3H, d,  $J$  1.47,  $CH_3$ ), 6.56 (1H, d,  $J$  1.41, H);  $m/z$  = 150 ( $M^+$ , 100%), 122 ( $M^+ - 28$ ), 96 ( $M^+ - 104$ ).

### Photostability study of the photosensitizers

To study the photostability of the photosensitizers, 0.03 ml samples were taken in 200 ml 95% (v/v) acetonitrile–chloroform and photolyzed with visible light in a flowing air stream. 2 ml aliquots of the reaction medium were taken and the absorbance at the Soret band was measured by UV–visible absorption spectroscopy.

## Results and discussion

### Photooxidation of substrates

Solutions of 1,5-dihydroxynaphthalene **1** and 2,3,5-trimethylphenol **2** (3 and 6 mM respectively) in 95% (v/v) acetonitrile–chloroform containing 0.006 mmol of porphyrins **5–8** or chlorin **9** were irradiated with visible light with a stream of air continuously flowing into the system.

For substrate **1** the formation of 5-hydroxynaphthoquinone **3** was monitored by its UV–visible absorption at 450 nm and the total yield of product after 2 hours determined. Values are given in Table 1. For comparison, to check our photoreactor and technique, Methylene Blue was also used as sensitizer under identical conditions and yields of 78% after 2 hours and 82% after 7 hours determined, in complete agreement with the results of Duchstein.<sup>1</sup>

**Table 1** Yields of products on photooxidation of substrates **1** or **2** with porphyrin or chlorin photosensitizers in air-saturated acetonitrile–dichloromethane solution

Sensitizer	Yield of <b>3</b> <sup>a</sup> (%)	Yield of <b>4</b> <sup>b</sup> (%)	Residual porphyrin <sup>c</sup> (%)
—	28	<2	—
<b>5</b>	95	46	85
<b>6</b>	84	28	60
<b>7</b>	90	6	44
<b>8</b>	94	93	96
<b>9</b>	93	81	84

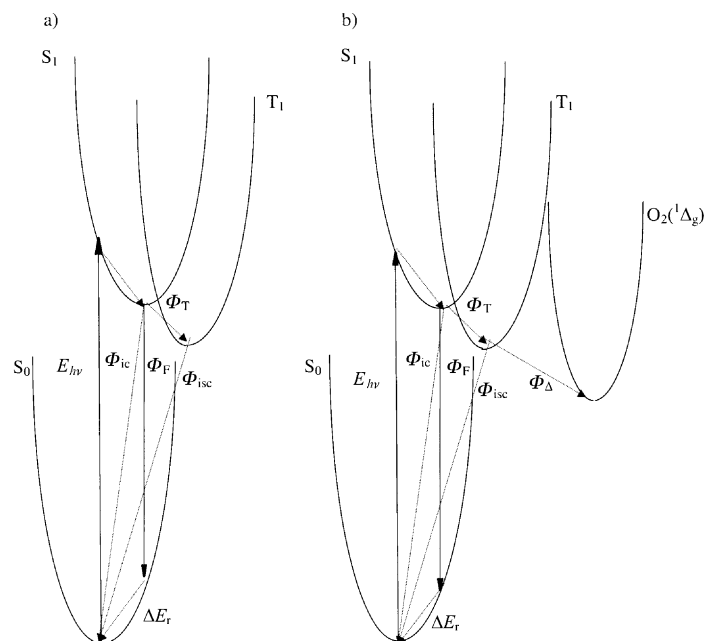
<sup>a</sup> 2 h photolysis of **1**. <sup>b</sup> 24 h photolysis of **2**. <sup>c</sup> 24 h photolysis in absence of substrates.

1,5-Dihydroxynaphthalene, **1**, is an easily oxidized substrate, and photooxidation yields of 28% were observed, even in the absence of photosensitizer (Table 1). With this system we did not observe any significant influence of the structure of the photosensitizer on the rates and reaction yields, and yields of over 84% of the corresponding quinone were observed with all the photosensitizers used after short reaction times. However, the photooxidation of 2,3,5-trimethylphenol, **2**, is more difficult, and in the absence of the sensitizer less than 2% of quinone was observed. Since the UV–visible absorption spectrum of the quinone overlaps that of the photosensitizers, the reaction in this case was monitored by GC (using pure 2,3,5-trimethylbenzoquinone obtained from the oxidation of 2,3,5-trimethylhydroquinone with  $K_2Cr_2O_7$ <sup>7</sup> as standard). The yields after 24 hours are presented in Table 1. The photooxidation of substrate **2** is very sensitive to the structure of the photosensitizer, with yields varying from 6% with photosensitizer **7** to 93% with **8**. Since our primary interest in this study is obtaining a good preparative route for photooxidation of phenols to quinones, no attempt was made to determine quantum yields, and polychromatic light was used in all irradiations. Some of the differences may thus result from different amounts of light absorbed by the various photosensitizers. However, another important factor in prolonged irradiations in both these studies and earlier experiments using Methylene Blue or Rose Bengal as photosensitizers<sup>16</sup> is the photostability of the photosensitizers. We have, therefore, tested their photostabilities under the same conditions as those used for the photooxidations. Solutions of each of the photosensitizers in 95% (v/v) acetonitrile–chloroform were irradiated under a continuous flow of air, and the total residual amount of porphyrin or chlorin measured after 24 hours. Data are also presented in Table 1. From here it is clear that the most stable photosensitizer is **8**, the porphyrin with two chlorine atoms in *ortho* positions, in agreement with the work of Quast.<sup>23</sup> This is also the sensitizer which gives the best yields of quinone. The phenanthryl derivative **7** and the naphthyl porphyrin **6** show relatively low photostability, which limits their applications as photosensitizers for prolonged photolyses. It is possible that these are degraded by reaction of singlet oxygen with the aromatic rings.

### Photophysical properties of sensitizers

In addition to the effects of photosensitizer stability on these reactions, the overall effect of the structure of the photosensitizers in the mechanism of these reactions will also depend on their photophysical properties. We have determined triplet lifetimes in the presence of air, singlet oxygen quantum yields and singlet oxygen formation efficiencies for all the photosensitizers, in addition to their fluorescence quantum yields and the energies of their lowest excited singlet states.

To confirm that these photosensitizers do produce singlet oxygen, the compounds **6** and **9** were taken as particular cases and time-resolved emission measurements used to study



**Fig. 2** Modified Jablonski diagrams showing decay of the photosensitizers in a) degassed and b) air-saturated solutions, and the pathways for dissipation of absorbed laser energy.

singlet oxygen phosphorescence at 1270 nm and to determine relative quantum yields. Optically matched aerated solutions in benzene of the porphyrin **6**, the chlorin **9**, and the standard (5,10,15,20-tetraphenylporphyrin, **5**) were excited with frequency tripled (355 nm) pulses from an Nd/YAG laser. In all cases, emission was observed at 1270 nm, confirming the formation of singlet oxygen, *i.e.* showing that photosensitization involves predominantly the type II process. The decay of singlet oxygen luminescence was monitored at 1270 nm, and the intensity extrapolated to time zero. The singlet oxygen lifetimes measured for 5,10,15,20-tetraphenylporphyrin, TPP (**5**) and 5,10,15,20-tetranaphthylchlorin (TNC) (**31** ± 1 μs) were identical to literature values for O<sub>2</sub>(<sup>1</sup>Δ<sub>g</sub>) in benzene,<sup>32</sup> indicating that it did not react significantly with the photosensitizers. Relative singlet oxygen quantum yields (Φ<sub>Δ</sub>) were obtained by comparison with a standard. We have used TPP in air-saturated benzene as standard, and have taken the value Φ<sub>Δ</sub> = 0.67.<sup>20</sup> This is slightly higher than the value Φ<sub>Δ</sub> = 0.62 given by Schmitt and Afshari,<sup>33</sup> but is more convenient for comparison with the photoacoustic calorimetry (PAC) data. From the time-resolved luminescence measurements, values of Φ<sub>Δ</sub> = 0.67 (**6**) and 0.69 (**9**) were obtained for air-saturated solutions. Estimated errors are ±10%.

Photoacoustic calorimetry (PAC) provides an excellent method for the absolute determination of singlet oxygen quantum yields.<sup>20</sup> However, for this it is necessary to have the energy of the lowest excited singlet (S<sub>1</sub>), and the fluorescence quantum yield. The S<sub>1</sub> energies were determined for all the photosensitizers from the intersection of the (0,0) band of the corrected fluorescence spectra and the lowest energy band of the absorption spectra. Time-resolved PAC gives the fraction of heat released in radiationless processes within the decay times associated with them. In Fig. 2, Jablonski-type diagrams are given for the sensitizer in degassed and air-saturated solutions; in addition the pathways for dissipation of the absorbed laser energy (E<sub>hv</sub>) by radiative and radiationless processes are shown. In the absence of phosphorescence, these processes can be expressed quantitatively by eqn. (1), where E<sub>F</sub> is the integrated

$$E_{hv} = E_F + E_{hv}(\varphi_1 + \varphi_2) \quad (1)$$

radiative energy emitted from the singlet state. The fraction of nonradiative energy released after the excitation with a pulse

laser can be separated into two fractions. The faster process (φ<sub>1</sub>) has a lifetime (τ<sub>1</sub>) less than 1 ns and includes the internal conversion from higher excited singlet states (Φ<sub>ic</sub>), the intersystem crossing to the triplet manifold (Φ<sub>T</sub>) and the relaxation of the spectroscopically formed ground state species (ΔE<sub>r</sub>).

In N<sub>2</sub>-saturated solutions the slower process (φ<sub>2</sub>) gives the fraction of energy released in a lifetime greater than 10 μs (τ<sub>2</sub> = 1/k<sub>T</sub>), corresponding to the intersystem crossing from the lowest triplet excited state to the ground state. In air-saturated solutions the slow process, φ<sub>2</sub>, will involve both intersystem crossing and energy transfer from the triplet state of the photosensitizer (T<sub>1</sub>) to molecular oxygen, leading to singlet oxygen (O<sub>2</sub>(<sup>1</sup>Δ<sub>g</sub>)). This is associated with a shorter lifetime (τ<sub>2</sub> = 1/(k<sub>T</sub> + k<sub>q</sub>[O<sub>2</sub>])), which can be measured by flash photolysis, where the quenching rate constant, k<sub>q</sub>, is controlled both by diffusion and by a spin-statistical factor.<sup>34–36</sup> Under our experimental conditions, in aerated solutions we have k<sub>q</sub>[O<sub>2</sub>] ≫ k<sub>T</sub>, and the lifetime is dominated by oxygen quenching, such that τ<sub>2</sub> = 1/(k<sub>q</sub>[O<sub>2</sub>]).

Using the methodology previously discussed,<sup>20</sup> the triplet quantum yield (Φ<sub>T</sub>), the singlet oxygen quantum yield (Φ<sub>Δ</sub>) and the efficiency of singlet oxygen formation (Φ<sub>Δ</sub> = Φ<sub>Δ</sub>/Φ<sub>T</sub>) were calculated for the photosensitizers **5**, **6** and **9**. In our earlier work the triplet state lifetimes in air-saturated solutions were obtained from PAC experiments. We have redetermined these from laser flash photolysis, and observe slight, but significant (±200 ns) differences. In the present calculations, we have used the more accurate τ<sub>2</sub> values obtained by laser flash photolysis, which are then introduced in the deconvolution of the photoacoustic waves. Compared with our previous report,<sup>20</sup> these slight differences do not significantly affect the overall singlet oxygen quantum yields for the photosensitizers **5** and **9**, but do reduce the Φ<sub>Δ</sub> value for sensitizer **6** from 0.97 to 0.86. This new value is more accurate, and leads to a more realistic singlet oxygen efficiency φ<sub>Δ</sub> = 1.0.

For the photosensitizers **7** and **8**, phosphorescence quantum yields were too low to detect with our apparatus and, hence, it was not possible to measure the lowest triplet state energy. However, we can estimate an upper limit to Φ<sub>T</sub> using the relation (2) and assuming that Φ<sub>ic</sub> = 0. A lower limit for Φ<sub>T</sub> is given by Φ<sub>Δ</sub>, which is given by eqns. (3) and (4).

$$1 = \Phi_{ic} + \Phi_T + \Phi_F \quad (2)$$

**Table 2** Photophysical properties and singlet oxygen yields of photosensitizers

	$\Phi_F$	$E_S/\text{kJ mol}^{-1}$	$\tau_T(\text{O}_2)/\text{ns}$	$\Phi_T$	$\Phi_\Delta$	$\varphi_\Delta$
<b>5</b>	$0.10 \pm 0.01$	$183.9 \pm 0.3$	$349 \pm 5$	$0.73 \pm 0.10$	$0.67 \pm 0.14$	$0.92 \pm 0.22$
<b>6</b>	$0.16 \pm 0.02$	$183.8 \pm 0.3$	$480 \pm 5$	$0.86 \pm 0.13$	$0.86 \pm 0.06$	$1.00 \pm 0.16$
<b>7</b>	$0.13 \pm 0.01$	$183.1 \pm 0.4$	$565 \pm 12$	$<0.87 \pm 0.10$	$0.72 \pm 0.07$	$>0.83 \pm 0.10$
<b>8</b>	$0.005 \pm 0.002$	$181.3 \pm 0.6$	$641 \pm 10$	$<0.995 \pm 0.005$	$0.98 \pm 0.04$	$>0.98 \pm 0.04$
<b>9</b>	$0.36 \pm 0.02$	$182.9 \pm 0.7$	$348 \pm 7$	$0.55 \pm 0.10$	$0.55 \pm 0.05$	$1.00 \pm 0.19$

$$E_T\Phi_T = (1 - \varphi_1)E_{hv} - \Phi_F E_S \quad (3)$$

$$\Phi_\Delta = (\Phi_T E_T - E_{hv}\varphi_2)/E_\Delta \quad (4)$$

$$\varphi_\Delta = \Phi_\Delta/\Phi_T \quad (5)$$

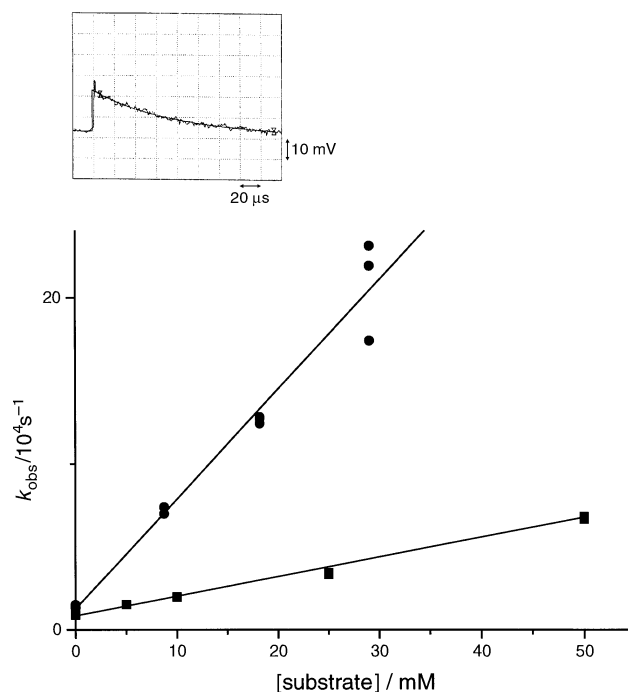
Thus we obtain  $0.87 \geq \Phi_T \geq 0.72$  for **7** and  $0.985 \geq \Phi_T \geq 0.98$  for **8**. We can also define the efficiency of singlet oxygen formation in characterizing the triplet state efficiency in energy transfer to molecular oxygen.

In Table 2 all the photophysical and photochemical properties that are relevant to the characterization of these singlet oxygen photosensitizers are collected. Although the experimental uncertainties are relatively large, the values obtained by PAC and time-resolved emission measurements for  $\Phi_\Delta$  for the photosensitizers **6** and **9** do appear to show small but significant differences. Previous reports have discussed differences in singlet oxygen quantum yield values determined by different methods.<sup>25,37</sup> With porphyrins in benzene solution, it is suggested that quantum yields determined by time-resolved emission measurements might be affected by the formation of a non-fluorescent encounter complex between singlet oxygen and the ground-state photosensitizer.<sup>25</sup> For comparative purposes we feel it best to choose results determined by one technique, and for this discussion we will rely on the PAC results.

The results clearly show that the 5,10,15,20-tetrakis-(2,6-dichlorophenyl)porphyrin derivative, **8**, shows the highest singlet oxygen quantum yield. This compound is also the most efficient photosensitizer for photooxidation of substrates **1** and **2**. Although the chlorin **9** shows a rather lower singlet oxygen yield, it appears to be an excellent photosensitizer for these reactions. However, it is important to remember that these photolyses are carried out with unfiltered light, and that this compound presents stronger long wavelength absorption than the corresponding porphyrins,<sup>20</sup> such that more light is absorbed in the synthetic photooxidation experiments.

### Kinetics of reaction of singlet oxygen

The kinetics of the reactions of singlet oxygen with 1,5-dihydroxynaphthalene, **1**, and with 2,3,5-trimethylphenol, **2**, were studied in acetonitrile–dichloromethane (50% v/v) solutions using laser flash photolysis. 2-Acetonaphthone or perinaphthone was used as a singlet oxygen photosensitizer to avoid problems associated with overlap of the long tail of the porphyrin or chlorin fluorescence with the singlet oxygen phosphorescence. Aerated solutions were excited at 355 nm, and the singlet oxygen produced monitored by its decay at 1270 nm. The luminescence decayed by good pseudo-first-order kinetics, independent of laser intensity. A typical decay trace is shown in the insert in Fig. 3. In the absence of **1** or **2** the singlet oxygen decayed with a lifetime of  $73.4 (\pm 5.0) \mu\text{s}$ . This is intermediate between the values reported for the lifetime of singlet oxygen in acetonitrile ( $58.3 \mu\text{s}$ ) and dichloromethane ( $82.9 \mu\text{s}$ ).<sup>38</sup> Further, for binary mixtures the contributions of the two solvents to singlet oxygen lifetimes are found to be additive.<sup>38–40</sup> Using literature data,<sup>38</sup> a lifetime of  $68.4 \mu\text{s}$  was estimated for  $\text{CH}_3\text{CN}-\text{CH}_2\text{Cl}_2$ , in good agreement with our experimental value.

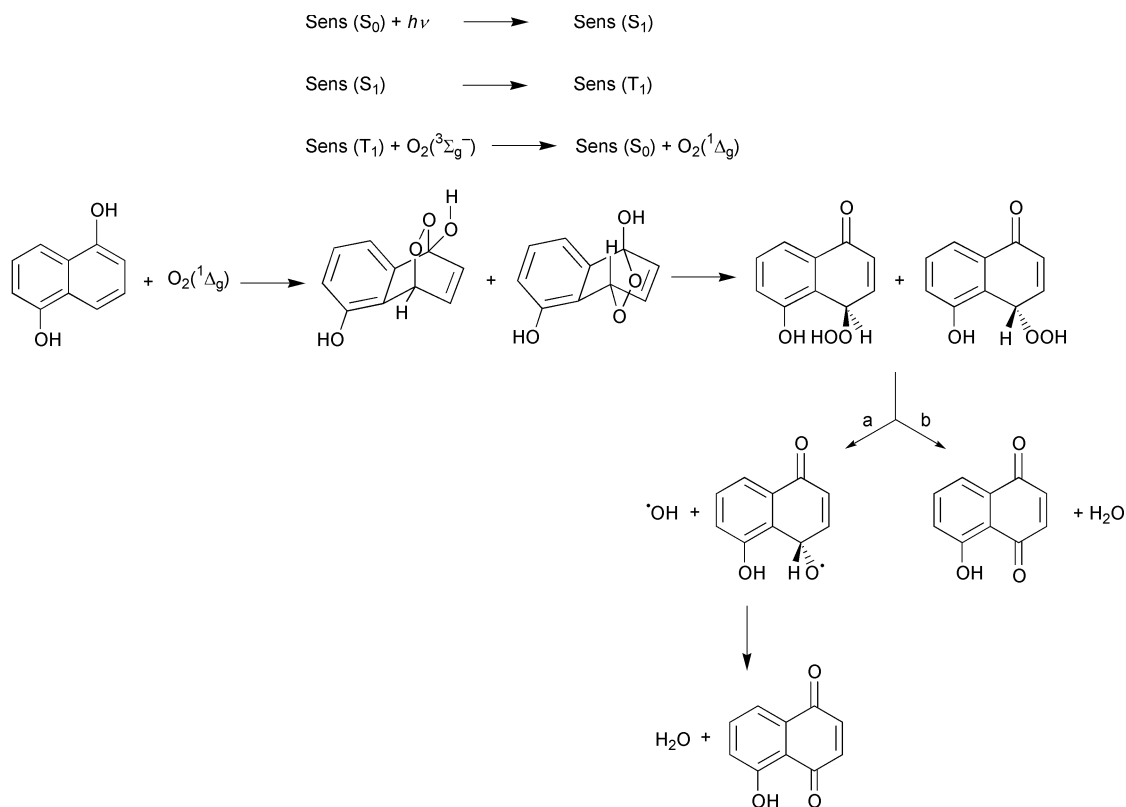


**Fig. 3** Plots of pseudo-first-order rate constants for decay of singlet oxygen luminescence as a function of substrate concentration for 1,5-dihydroxynaphthalene (circles) and 2,3,5-trimethylphenol (squares). The insert shows a typical kinetic trace with fit to a first-order decay, using 2-acetonaphthone as photosensitizer.

The reaction of singlet oxygen with the substrates was studied by following the luminescence decay at various naphthol or phenol concentrations (up to 50 mM). For both substrates, the pseudo-first-order rate constants showed good linear dependence on concentration (Fig. 3), confirming the overall rate law given in eqn. (6).

$$\text{Rate} = k_2[\text{substrate}][^1\text{O}_2^*] \quad (6)$$

From the slopes of the graphs, second-order rate constants of  $6.50 (\pm 0.39) \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$  (1,5-dihydroxynaphthalene) and  $1.16 (\pm 0.03) \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$  (2,3,5-trimethylphenol) were determined. These values can be compared with literature data on related compounds. In studies on singlet oxygen reactions with a series of dihydroxynaphthalenes,<sup>41,42</sup> a rate constant for reaction of singlet oxygen with **1** in methanol  $k_2 = 6.1 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$  was reported, in excellent agreement with our value in  $\text{CH}_3\text{CN}-\text{CH}_2\text{Cl}_2$ . Whilst we have been unable to find any data on compound **2**, similar rate constants for reaction of singlet oxygen with the sterically hindered 2,6-di-*tert*-butylphenol in alcohol solutions of  $1.01$ – $1.7 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$  have been reported.<sup>43</sup> Although these rate constants involve both chemical and physical processes,<sup>41</sup> the slower reaction of singlet oxygen with **2** than with the dihydroxynaphthalene probably reflects both electronic effects and steric hindrance towards singlet oxygen attack, and is in agreement with the observed lower reactivity of this substrate towards photosensitized oxidation.



Scheme 2 Mechanism for the photooxidation reactions, exemplified using the substrate **1**.

### Proposed mechanism

Since the classic work of Schenk on the synthesis of ( $\pm$ )-ascaridole<sup>44</sup> photosensitized oxygenation has proved to be an important route for synthesis of quinones. The mechanism for the synthesis of these quinones is thought to involve singlet oxygen<sup>15</sup> via 1,4-cycloaddition to the aromatic ring to form a stable *endo*-peroxide.<sup>11,23,41,45</sup> This may then be followed by hydrolysis of the intermediate 1,4-*endo*-peroxide to form the allylic hydroperoxide, possibly involving intramolecular acid catalysis. Evidence for the role of acid catalysis in this scheme comes from observation of a deuterium isotope effect.<sup>42</sup> The hydroperoxide is then oxidized to the quinone via either homolytic or heterolytic cleavage. The general mechanism is shown in Scheme 2.

The lower reactivity of the phenol **2** compared with 1,5-dihydroxynaphthalene (**1**) in these photooxidations probably reflects both electronic effects and steric hindrance towards singlet oxygen attack. Although the observed second-order rate constants for singlet oxygen reaction with the substrates involve both chemical and physical processes,<sup>41</sup> the qualitative correlation between the observed lower yields of quinone formation from **2** and the slower reaction of singlet oxygen with this substrate does suggest that the chemical quenching process may be dominant.

### Conclusion

The oxidation of air-saturated solutions of 1,5-dihydroxynaphthalene and of 2,3,5-trimethylphenol photosensitized by a set of porphyrins and a chlorin selected as photosensitizers has been studied. Previous studies of this reaction using larger quantities (*ca.* tenfold higher) of other types of photosensitizers gave relatively low yields of products compared with those obtained with the porphyrins,<sup>1</sup> and needed longer reaction times. In addition, many of the other photosensitizers used undergo degradation during the photolysis. The photosensitizers studied appear to be excellent candidates for synthetic applications in this area. The compound **8** seems to be

particularly valuable, as this combines the advantages of high singlet oxygen yield and photochemical stability.

As has previously been discussed,<sup>16</sup> for practical synthetic applications it would be useful to bind the photosensitizers to an inert solid support so that the photosensitizer can easily be removed by filtration from the reaction medium. Preliminary studies using either silica gel or organic polymers as supports suggest that this is possible,<sup>46</sup> although problems still remain to be resolved concerning low reactivity in these systems, and potential photodegradation of the solid supports.

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