acetone and **2** as substrates to yield 0.35 g (90%) of an off-white solid: ^{1}H NMR (60 MHz, $CDCl_3$) 8.1-7.9 (m, 1 H), 7.7-7.4 (m, 4 H), 6.2 (s, 2 H), 2.1 (s, 3 H); mp 56-58 °C.

Preparation of α-Benzoyl-γ-butyrolactone. This reaction was conducted on a 3.0-mmol scale with γ-butyrolacetone as the limiting species. Removal of the solvent afforded 0.52 g (92%) of a pale yellow oil: ^{1}H NMR (60 MHz, $CDCl_3$) δ 8.3-8.1 (m, 1 H), 7.7-7.4 (m, 4 H), 4.4 (t, 2 H), 3.6 (t, 1 H), 2.5 (m, 2 H).

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Chemical Sources of Singlet Oxygen. 3.[1] Peroxidation of Water-Soluble Singlet Oxygen Carriers with the Hydrogen Peroxide-Molybdate System

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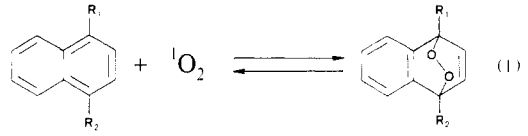
Naphthalenic endoperoxides **2** provide highly useful chemical sources of singlet oxygen ($^1O_2$, $^1\Delta_g$) for mechanistic studies as they split off known quantities of pure $^1O_2$ when warmed at moderate temperature (30-50 °C).[3] In particular, water-soluble derivatives have been used in aqueous media as singlet oxygen carriers[4-6] (eq 1) to assess the role of this species in inorganic reactions[5] and in photodynamic effect.[6]



1 2

a : $R_1 = (CH_2)_2COONa$, $R_2 = CH_3$

b : $R_1 = (CH_2)_2COOH$, $R_2 = CH_3$

c : $R_1 = R_2 = (CH_2)_2COONa$

d : $R_1 = R_2 = (CH_2)_2COOH$

However, endoperoxides **2** are secondary sources of $^1O_2$ as they must be prepared from a primary source. Up to now, only prolonged photooxidation at low temperature was able to generate the high flux of $^1O_2$ necessary to peroxidize the poorly reactive substrates **1**.[3d,4a,5] In the present paper, we show that the newly discovered chemical source of $^1O_2$, H_2O_2/MoO_4^{2-}, is a simpler alternative to the usual photochemical method to peroxidize water-soluble substrates like **1**.

Results and Discussion

Molybdate ions catalyze disproportionation of hydrogen peroxide in basic solution, providing $^1O_2$ in quantitative yield through the intermediacy of a diperoxomolybdate, MoO_6^{2-} (eq 2 and 3).[1]

$$2H_2O_2 + MoO_4^{2-} \rightleftarrows 2H_2O + MoO_6^{2-} \quad (2)$$

$$MoO_6^{2-} \rightarrow MoO_4^{2-} + {}^1O_2 \quad (3)$$

When a substrate A is present, singlet oxygen produced by reaction 3 at a rate v_f, is either quenched by water or A with rate constants k_d (eq 4) and k_q (eq 5) or reacts with A at a rate constant k_r (eq 6). The endoperoxide AO_2 thus obtained can undergo thermolysis at a rate constant k_t, giving back A and oxygen, a part of which is in a singlet state (eq 7).

$$^1O_2 + \text{water} \xrightarrow{k_d} {}^3O_2 \quad (4)$$

$$^1O_2 + A \xrightarrow{k_q} {}^3O_2 + A \quad (5)$$

$$^1O_2 + A \xrightarrow{k_r} AO_2 \quad (6)$$

$$AO_2 \xrightarrow{k_t} A + O_2 \quad (7)$$

Stationary concentration of singlet oxygen, $[^1O_2]_{st}$, may be calculated by neglecting $^1O_2$ coming from the slow dissociation of AO_2 (eq 7) compared with the one evolved by the disproportionation of hydrogen peroxide (eq 2 and 3).

$$[^1O_2]_{st} = v_f/\{k_d + (k_q + k_r)\}[A] \quad (8)$$

Reaction 1 shifts to the right as long as the peroxidation rate of A is higher than the decomposition of AO_2:

$$k_r[A][^1O_2]_{st} \geq k_t[AO_2] \quad (9)$$

substituting (8) into (9) we obtain

$$v_f \geq \frac{[AO_2]}{[A]}\frac{k_t}{k_r}\{k_d + (k_q + k_r)[A]\} \quad (10)$$

Since under our conditions, the main pathway for $^1O_2$ decay is the quenching by water ($k_d \gg (k_r + k_q)[A]$),[7] (10) reduces to

$$v_f \geq \frac{[AO_2]}{[A]}\frac{k_t k_d}{k_r} \quad (11)$$

If the reaction is performed at 20 °C under optimized conditions of pH (9.5-11.5) and H_2O_2 concentration ($[H_2O_2]/[MoO_4^{2-}] = 2$-3), the rate of $^1O_2$ generation by reaction 3 is $v_f = (1.8 \times 10^{-3})[MoO_4^{2-}]$.[1] At the same

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(7) In water $k_d = 2.4 \times 10^5$ s^{-1} (Rodgers, M. A. J. *J. Am. Chem. Soc.* **1983**, *105*, 6201-6205), $k_q + k_r = 6.9 \times 10^6$ M^{-1} s^{-1} for **1a** and 2.8×10^6 M^{-1} s^{-1} for **1c** (Aubry, J. M.; Bensasson, R. V.; Rougée, M.; Cazin, B.; Rigaudy, J., unpublished), and the concentration of A at the end of the reaction is 1.5×10^{-3} M for **1a** and 1.8×10^{-2} M for **1c** with 95% peroxidation.

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temperature, the rate constants for thermolysis of **2a** and **2c** are identical, $k_t = 4.8 \times 10^{-5}$ s^{-1},[2] and the quenching ratios k_d/k_r for naphthalenic compounds **1a** and **1c** are respectively 0.07 M and 0.16 M.[2] It appears from (11) that a 95% peroxidation of the substrates can be achieved only if the molybdate concentration is higher than 3.5×10^{-2} for **1a** and 8.1×10^{-2} M for **1c**.

Thus, for preparative purposes, all the parameters must be optimized to achieve the high flux of $^1O_2$ expected from kinetic calculations. The major one is the rate of H_2O_2 addition. When it is too high, a part of the yellow active complex MoO_6^{2-} is converted into the red brown tetraperoxomolybdate MoO_8^{2-},[8] which is less efficient than MoO_6^{2-} in the generation of $^1O_2$ (eq 12); moreover, the acidity of H_2O_2 will decrease the pH and another part of MoO_6^{2-} will be protonated, giving the inactive acid $HMoO_6^-$ (eq 13).[1]

$$MoO_6^{2-} + 2H_2O_2 \rightleftarrows MoO_8^{2-} + 2H_2O \quad (12)$$

$$MoO_6^{2-} + H_2O_2 \rightleftarrows HMoO_6^- + HO_2^- \quad (13)$$

In practice, hydrogen peroxide is added by fractions so that the concentration of H_2O_2 introduced is twice that of molybdate ions. Thereupon, the solution turns red, and the reaction is allowed to proceed until the reappearance of a yellow gold color, then another fraction of H_2O_2 is added. The acidity is monitored throughout the process to check that pH remains between 9.5 and 11.5. This condition is achieved spontaneously when MoO_6^{2-} is the predominating complex; however, carbonate buffer is added to the solution to limit pH changes induced by the little excess of H_2O_2 and by the carboxylate functions of substrates.

The reacting medium is analyzed by high performance liquid chromatography (HPLC), showing no secondary products, unlike the photochemical method.[5] The areas of the peaks corresponding to the residual substrates **1a** and **1c** and to the endoperoxides **2a** and **2c** are measured and afford peroxidation yields by comparison with standard solutions. These yields rise to 98% for **1a** and **1c** at the end of the reaction before workup; they could be slightly higher if more concentrated molybdate was used. The endoperoxides are recovered by precipitation of the acids **2b** and **2d** after acidification with phosphoric acid. Then, their dried solutions in ether or THF are neutralized with an almost stoichiometric amount of sodium methylate, leading to the precipitation of sodium carboxylates **2a** and **2c**. A part of the endoperoxides dissociates during workup and isolated salts **2a** and **2c** contain only 92% and 94% of endoperoxide, respectively. The purity of the endoperoxides can be determined accurately by HPLC or UV spectroscopy comparing aqueous solutions of **2** kept at 0 °C with the same solutions warmed at 50 °C for 1 h; the peaks of the endoperoxides **2** completely disappear in favor of those of the naphthalenic compounds **1** while the characteristic absorbances of **1** at 288 nm increase.

Experimental Section

Material and Methods. High performance liquid chromatographic analyses (HPLC) were carried out with a Gilson pump Model 303 using a 25-cm column packed with Sperisorb 5 ODS. A mixture of $H_2O/CH_3OH/H_3PO_4$ was used as an eluent (90/210/1 for **1a**, 105/195/1 for **1c**) and UV detection was performed with a variable wavelength monitor (Gilson Holochrome H/MD). Nuclear magnetic resonance ^1H (NMR) spectra were recorded with a Bruker WP80 instrument at 80 MHz, the solvent was D_2O, and the chemical shifts are reported in parts per million (δ) relative to the sodium salt of 3-(trimethylsilyl)-3,3,2,2-tetradeuteriopropionic acid = TSPA-d_4 (δ = 0.00) as an internal standard.

3-(4-Methyl-1-naphthyl)propionic acid (**1b**) and 3,3′-(naphthalene-1,4-diyl)dipropionic acid (**1d**) were prepared according to known procedures.[9] Authentic samples of the corresponding endoperoxides **2a** and **2c** were obtained by photooxygenation.[5] Sodium molybdate (rectapur), 30% hydrogen peroxide (normapur), sodium hydroxide (rectapur), sodium hydrogenocarbonate (normapur), and sodium carbonate (normapur) were purchased from Prolabo.

Endoperoxide of Sodium 3-(4-Methyl-1-naphthyl)-propionate (2a). The acid **1b** (2 g, 9.3 mmol, 31 mM) was dissolved in 300 mL of an aqueous solution of sodium hydroxide (0.37 g, 9.3 mmol), sodium hydrogen carbonate (0.4 g, 4.8 mmol), sodium carbonate (1 g, 9.4 mmol), and sodium molybdate dihydrate (10 g, 41.3 mmol, 138 mM). The reactor was immersed in a thermostated bath and was equipped with a glass electrode, a thermometer, and a magnetic rod. Throughout the reaction, the temperature was maintained at 20 ± 0.5 °C and the pH between 9.5 and 11. Hydrogen peroxide, 30% (10 mL, 100 mmol), was added and the red brown mixture was stirred for 15 min until the color faded to gold yellow. Four other fractions of 10 mL of hydrogen peroxide were allowed to react in the same way and the reaction was monitored by HPLC. Thus after 75 min, 50 mL (500 mmol) of hydrogen peroxide had reacted and 98% of **1b** was peroxidized. The mixture was cooled to 0 °C with an ice bath and was acidified under stirring at pH ~2.5 with cold phosphoric acid (2 M) (70 mL, 140 mmol). The white precipitate was collected on a sintered glass funnel, washed three times with iced water, and drained under suction. Drying was completed 2 h in vacuum (0.1 Torr, 0 °C), yielding **2b** (1.91 g, 83%) as a white powder. Its ^1H NMR spectrum was correct,[4a] and it was analyzed by HPLC and UV spectroscopy, comparing an ethanolic solution kept at 0 °C with the same solution warmed 1 h at 50 °C; it contained 95% of endoperoxide **2b**, 5% of the starting material **1b**, and no secondary product.

The dry acid **2b** was dissolved in 200 mL of cold ether (0 °C) and neutralized with 2 M sodium methylate in methanol (3.8 mL, 7.6 mmol). The precipitate was collected on a sintered glass funnel, washed with cold ether, and dried for 1 h in vacuum (0.1 Torr, 0 °C), yielding **2a** (1.75 g, 70%) as a white powder. HPLC and UV analysis of an aqueous solution of **2a** showed 93% of endoperoxide **2a**, 7% of starting material **1a** and no secondary product: ^1H NMR (D_2O) δ 1.9 (s, 3 H, CH_3), 2.4–2.7 (m, 4 H, CH_2CH_2), 6.8 (d, 2 H, CH=CH), 7.3–7.7 (m, 4 H, Ar).

Endoperoxide of Disodium 3,3′-(Naphthalene-1,4-diyl)-dipropionate (2c). The acid **1d** (2 g, 7.3 mmol, 0.37 M) was dissolved in 20 mL of an aqueous solution of sodium hydroxide (0.59 g, 14.7 mmol), sodium hydrogen carbonate (0.2 g, 2.4 mmol), sodium carbonate (0.5 g, 4.7 mmol), and sodium molybdate dihydrate (2.5 g, 10.3 mmol, 0.51 M). The solution was immersed in a thermostated bath maintained at 20 ± 0.5 °C. Six fractions of 2 mL (20 mmol) of hydrogen peroxide were added following the procedure described for **2a**. Thus after 90 min, 12 mL (120 mmol) of hydrogen peroxide had reacted and 98% of **1d** was peroxidized. The mixture was cooled to 0 °C with an ice bath and was acidified under stirring at pH ~2.5 with cold phosphoric acid (2 M) (25 mL, 50 mmol). The white precipitate was collected on a sintered glass funnel and washed three times with iced water. The moist acid was dissolved in 300 mL of cold THF (0 °C) and dried with 15 g of $MgSO_4$. After filtration, 7 mL (14 mmol) of 2 M sodium methylate in methanol was added, and the precipitate was collected by centrifugation, washed with cold ether, and dried 30 min in vacuum (0.1 Torr, 0 °C), yielding **2c** (2.34 g, 92%) as a white powder.

HPLC and UV analysis showed 94% of endoperoxide **2c**, 6% of the starting material **1c**, and no secondary product: ^1H NMR

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(D_2O) δ 2.35-2.65 (m, 8 H, CH_2CH_2), 6.95 (s, 2 H, CH=CH), 7.3-7.6 (m, 4 H, Ar).

Registry No. **1a**, 90549-82-9; **1b**, 76673-34-2; **1c**, 97860-58-7; **1d**, 118071-16-2; **2a**, 118111-04-9; **2b**, 76673-35-3; **2c**, 97860-59-8; O_2, 7782-44-7.

Facile and Convenient Syntheses of Quinones from Phenols

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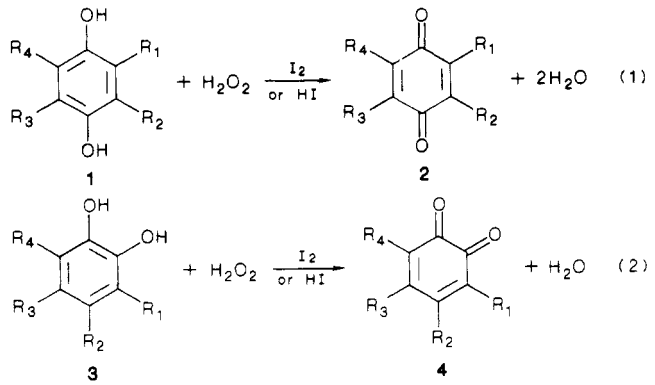
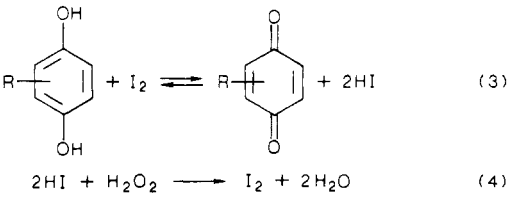
The oxidation of monohydroxy and dihydroxy aromatics is the most general method to obtain quinones. The oxidation of 1,2- or 1,4-dihydroxybenzenes to the corresponding quinones has been achieved by a variety of oxidants. The use of silver oxide or silver carbonate is generally the method of choice,[1] but it is not practical for large-scale preparations, due to the expensive oxidants.

Recently, a new method of oxidation of 1,4-hydroquinones to 1,4-benzoquinones by diphenyl diselenide catalyzed hydrogen peroxide has been reported.[2] That prompts up to report a patented,[3] new facile, general procedure of oxidation of dihydroxybenzenes, which is more convenient and less expensive than the methods so far known. The procedure involves the oxidation of the dihydroxybenzenes by H_2O_2 in methanolic or aqueous solution, depending on the solubility of the dihydroxybenzene, at room temperature in the presence of catalytic amounts of I_2 or HI (eq 1 and 2). While the reaction is

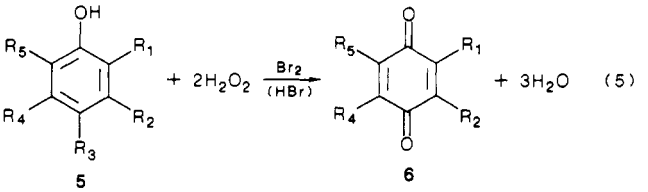


also catalyzed by Br_2, it is less selective because of the competitive electrophilic addition of bromine to the activated aromatic ring, and with complete conversions of the dihydroxybenzenes the yields are generally significantly lower (Table I) compared with I_2 catalysis. Chlorine is not suitable.

The actual oxidant appears to be I_2 (eq 3) and hydrogen peroxide serves to regenerate iodine from HI (eq 4). In the absence of iodine the starting dihydroxybenzene is recovered unchanged. However, the use of a stoichiometric amount of iodine leads only to low conversions (~10%) of the dihydroxybenzene to the quinone. On the other hand, the quinone is significantly reduced to hydroquinone by HI, clearly indicating that reaction of eq 3 is reversible and the equilibrium is shifted at left. Our procedure is particularly effective because the fast oxidation of HI by H_2O_2 (eq 4) keeps very low the stationary concentration of HI, shifting the equilibrium of eq 3 at right. Thus hydrogen peroxide makes catalytic in I_2 the process and at the same time makes very efficient the overall reaction by fast oxidation of HI.



The oxidation of monohydric phenols is another general method to obtain *p*-quinones.[1] High yields can be obtained by suitable choice of the oxidant[1] or anodic oxidation.[10] However, severe limitations exist for a large-scale application of the known procedures, also with the most selective and mild oxidants (thallium nitrate,[11] Jones reagent,[12] Fremy's salt,[4] etc.), owing to their toxicity and the high cost. More convenient oxidants, such as molecular oxygen[13] and hydrogen peroxide,[14] have therefore attracted considerable attention; they were generally used in the presence of expensive metal-complex catalysts with moderate to good selectivity and were mainly applied to simple substrates. We now report a new highly selective synthesis of *p*-quinones from 2,6-disubstituted phenols suitable for large-scale work.[3] It involves the oxidation of the phenol by hydrogen peroxide in the presence of molecular bromine or hydrogen bromide as catalyst (eq 5). Also in this case the actual oxidant appears to be bromine (eq 6), and H_2O_2



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