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High-efficiency microphotooxidation using milliwatt LED sources

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ABSTRACT

Inexpensive milliwatt light emitting diode (LED) sources allow energy- and atom-efficient microphotochemical reactions. Thus, sources constructed from three 120 mW 5 mm diameter 627 nm LED's enable μmol–mmol scale methylene blue-sensitized singlet oxygen photooxidations of various arenes and cyclopentadienones using a 3–5 M excess of oxygen in 82–98% yields.

1. Introduction

Arene endoperoxides, the first of which was described in 1926 by Dufraisse,[1] usually are prepared by photosensitized [4+2] cycloaddition of arenes with singlet oxygen.[2,3] Depending on the arene, the corresponding endoperoxide may thermally revert; for this reason arene endoperoxides have been demonstrated to act as singlet oxygen storage batteries.[2a,4] Interested in preparing a series of ^{17}O labeled arene endoperoxides[5] for spectroscopic studies of this phenomenon, we sought a general, label-efficient, high-yielding, small-scale photochemical method for endoperoxide synthesis.

Operationally, two factors stand out as potential roadblocks to photooxidations of arenes to produce thermally labile, ^{17}O labeled arene endoperoxides. First, even on a small scale, expense of ^{17}O labeled oxygen preempts the normal, 'open system' practice of bubbling oxygen through solutions of substrate in the presence of a sensitizer.[6] Even were this not the case, open systems passing relatively large volumes of dry gas through volatile solvents can experience significant solvent loss: This is particularly undesirable when reaction rates are being examined. For these reasons, use of a closed system was considered essential. Secondly, some common light sources employed for photooxidation generate significant heat from which thermally unstable photoadducts must be protected. Use of such sources requires inconvenient infrared filters, ventilating devices, and dewars with illumination windows; in any case, these sources are capable of warming any closed system and, therefore, pose an additional safety risk. Thus, for the intended application a low thermal output visible light source was considered important. We report here that static atmospheres of oxygen at modest pressures result in efficient production of endoperoxides using commercial milliwatt light emitting diode (LED) sources.

2. Results and discussion

To assay optimum conditions for NMR-scale ^{17}O labeled arene endoperoxide synthesis, 30–60 μmol of 9,10-dimethylanthracene (**1a**) was chosen as a representative substrate (Fig. 1). The extent of 9,10-dimethylanthracene-9,10-endoperoxide[7] (**2a**) formation was easily determined by integration of its methyl signals (δ 2.19) relative to that of the starting arene (δ 3.15) in the crude reaction product.[8]

In initial experiments to design a closed, recirculating system, a gas buret was used to deliver a known volume of excess oxygen to a small gas manifold, attached via capillary and return tubes to a 10 mL round bottomed flask containing the substrate dissolved in 5 mL of a 25 μM solution of methylene blue in dichloromethane.

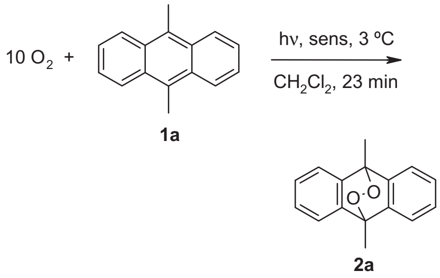

Figure 1.

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The oxygen was recirculated in the manifold using a miniature DC diaphragm pump to bubble it through the reaction solution using the capillary tube.

A simplification of this recirculating closed atmosphere concept was achieved using a straightforward static atmosphere of oxygen over a previously degassed reaction solution. A 10 mL hypovial equipped with stirring bar was charged with 30–60 μmol of 9,10-dimethylanthracene, then crimped shut using a silicone septum stopper and aluminum seal. An inverted 14/20 septum stopper was placed over the top of the sealed hypovial to insure that it was gas-tight, and the entire vial was wrapped in aluminum foil to exclude light. After charging with 5 mL of a 25 μM solution of methylene blue in dichloromethane, the vial was subjected to two −78 °C freeze-aspirator pump-N_2 purge-thaw cycles; in a last cycle, it was injected with 5–15 mL of oxygen, corresponding to a ca. 10-fold molar excess, and resulting in a 1–2.8 atm pressure inside the vial. Rapid stirring of the vial was sufficient to saturate the solution with oxygen, and no endoperoxide formation was observed as long as the vial remained foil-wrapped.

With a satisfactory closed system available, attention turned to identifying the best sources of visible light for photooxidation. In order to consider monochromatic as well as polychromatic sources, a baseline assay of common commercially available or easily prepared sensitizers used in dichloromethane was performed (Table 1). Using a traditional 250 W tungsten–halogen light source projected through a 10 cm, 3 °C recirculating water wall and a source-to-reaction vessel distance of 30 cm, 23 min irradiations indicated that methylene blue[9] was the most effective sensitizer choice; tetraphenylporphyrin (TPP)[10] and the bis-triethylammonium[11] or bis(cetyltributylphosphonium)[12] salts of rose bengal, while performing about the same, were less effective. Phase transfer conditions using aqueous methylene blue or rose bengal and cetyltributylphosphonium bromide[12] were least effective. Based on this assay further investigations were confined to source optimization for endoperoxide formation using methylene blue, rose bengal bis(triethylammonium) salt, and tetraphenylporphyrin.

Struck by the gross energy inefficiency of incandescent light sources, which not only generate more heat than light but, for use in the work at hand, require additional active cooling to remove that heat from the reaction environment, more energy-efficient light sources were considered. Aware of the recent introduction of a high-power multiwatt light emitting diode (LED) photoreactor[13] and the use of LED arrays in photodynamic therapy[14] and photodynamic therapy sensitizer development,[15] in NOx photocatalytic oxidation,[16] in oxygen sensing devices,[17] and in annular flow, microfluidic and batch photoreactor design,[18] we hypothesized that inexpensive, energy-efficient, low working temperature, narrow band (full width at half maximum (FWHM) typically ⩽30 nm) milliwatt LED's would be superior light sources for small-scale photooxidations of arenes. To test this hypothesis, LED light sources to irradiate 10 mL hypovials were constructed from three 5 mm narrow viewing angle LED's of the same peak emission wavelength inserted into 1.5 × 11 cm piece of glass tubing so that the LED's lenses were flush with the end of the tubing. Power was provided with a standard 12 VDC power supply (Fig. 2; photographs are available in the Supplementary data). Depending on peak emission wavelength used, total power consumption of these sources ranges from 240 to 375 mW; over 30 min irradiation with the LED source touching the side of the hypovial, heating of the vial contents was observed to be minimal.

Table 1
Conversion of **1a**–**2a** versus sensitizer

Sensitizer	Conversion %
27 μM methylene blue	51
190 μM methylene blue—phase transfer	9
33 μM rose bengal bis(triethylammonium) salt	35
51 μM rose bengal—phase transfer	24
31 μM rose bengal bis(cetyltributylphosphonium) salt	34
18 μM tetraphenylporphyrin	33

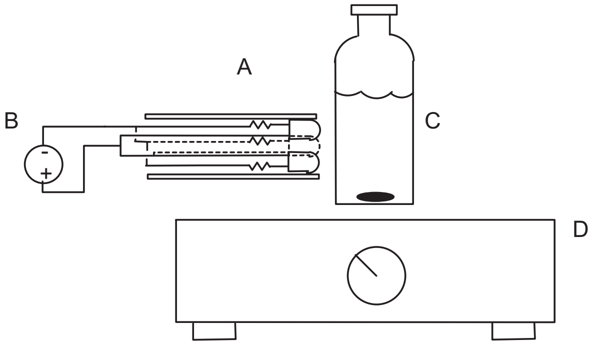

Figure 2. (A) 3 LED source in 1.5 cm glass tube; (B) 12 VDC power supply; (C) sealed hypovial with stirring bar and O_2 atmosphere; (D) magnetic stirrer.

Table 2
Conversion of **1a**–**2a** using various sensitizers versus LED peak emission wavelength

LED wavelength (nm)	Conversion % (sens MB[e])	Conversion % (sens TPP[f])	Conversion % (sens $Et_3NH)_2RB$[g])
405[a]	98		
420[b]	36	24	10
470[b]	12	26	54
505[c]	6	32	37
525[b]	11	77	75
588[d]	24	13	5
605[b]	32	8	1
627[b]	98	59	1
660[a]	48	16	0
250 W W/X	51	33	35

[a] 3 × 80 mW 5 mm LED lamps.
[b] 3 × 120 mW 5 mm LED lamps.
[c] 3 × 100 mW LED lamps.
[d] 3 × 125 mW LED lamps.
[e] MB, methylene blue.
[f] TPP, tetraphenylporphyrin.
[g] $(Et_3NH)_2RB$, bis(triethylammonium) salt of rose bengal.

Using methylene blue as the sensitizer, photooxidation of **1a** was investigated as a function of LED source peak emission wavelength (Table 2). Two LED sources—those with peak emission wavelengths at 627 (red) and 405 (violet) nm—provided ⩾98% conversion to endoperoxide. The increased energy efficiency of the photooxidation was notable: Lower source energy input, coupled with low source working temperature obviating the need for IR filtering result in these LED sources providing more than an 8000-fold increase in efficiency of watts used per unit conversion.

The rapidity and ease of formation of **2a** using the 627 nm source for 23 min is explained by the nearly complete overlap of the 627 nm (FWHM = 20 nm) LED emission spectrum and the absorption spectrum of methylene blue (λ_{max} 656 nm, FWHM = 37 nm) in dichloromethane: Essentially all of the incident light is absorbed by the photosensitizer, allowing maximal singlet oxygen production (Fig. 3a). At the 405 nm source wavelength, methylene blue is transparent, but **1a** is not: with a significant absorption band at 400 nm (FWHM = 12 nm), overlap of the 405 nm (FWHM = 14 nm) LED emission spectrum allows the arene itself to act as a sensitizer.[19] Thus, ⩾98% conversion to endoperoxide also was observed after irradiation for 23 min in the absence of methylene blue. In either case, the technique provides rapid access to **2a** with conversions equal to or better than other known methods.[6–8,20]