Photooxygenation of chiral 1,3-cyclohexadienes: strong influence of substituents on the stereo- and mode selectivities

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Dedicated to Professor Waldemar Adam on the occasion of his 70th birthday

Abstract

Four different chiral 1,3-cyclohexadienes were synthesized and investigated in photooxygenations with singlet oxygen. A strong influence of substituents at the double bond was observed for the mode selectivity of the reactions. Phenyl and alkyl groups afford mixtures of ene and [4 + 2] products, whereas a trimethylsilyl group yields exclusively hydroperoxides, presumably due to a “large group effect”. Additionally, the same diastereoselectivity for both reaction modes gives evidence for common perepoxide intermediates. Finally, the photooxygenation of a methylenesulfonyl substituted 1,3-cyclohexadiene proceeds with very high diastereoselectivity, which can be explained by an intramolecular hydrogen bridge, shielding one face of the compound.

Keywords: Cyclohexadienes, singlet oxygen, mode selectivity, stereoselectivity, reaction mechanisms

Introduction

Singlet oxygen (1O2) represents a powerful and atom-economic oxidant, which has found numerous applications in organic synthesis.1 The most convenient method for the generation of 1O2 is the dye-sensitized photoreaction of molecular oxygen with visible light (photooxygenation). Alkenes react with 1O2 by an ene-reaction to allylic hydroperoxides, whereas 1,3-dienes undergo predominantly [4 + 2]-cycloadditions to provide endoperoxides.2 Singlet-oxygen ene reactions with high diastereoselectivities are based on the pioneering work of
Adam. On the other hand, the stereochemical course of \([4 + 2]\)-cycloadditions of \(1\) to cyclic 1,3-diienes was studied less intensively, although this reaction is known for many years. More recently, auxiliary controlled and even organocatalytic enantioselective photooxygenations were realized. Finally, singlet oxygen was applied for reversible light and air-driven lithography.

During our work on synthetic applications of singlet oxygen, we found excellent regio- and high diastereoselectivities in the photooxygenation of 1,4-cyclohexadienes 1, which are easily available by Birch reduction, to afford hydroperoxides 2 (Scheme 1). However, a direct comparison of ene-reaction versus \([4 + 2]\)-cycloaddition was not possible with such systems. Therefore, we became interested in the photooxygenation of chiral 1,3-cyclohexadienes, which allow the examination of stereo- and mode selectivities within the same molecule. Herein, we present our results on the addition of singlet oxygen to 1,3-cyclohexadienes, which exhibits strong substituent effects.

![Scheme 1](image-url)

### Results and Discussion

For the convenient synthesis of cyclohexadienes, we developed a new cobalt-catalyzed Diels-Alder methodology, starting from a boron-functionalized 1,3-diene 3 and various alkynes 4. Very recently, we succeeded in a one-pot combination of this reaction with an allylboration in the presence of aldehydes 5, which afforded the desired 1,3-cyclohexadienes 6 from three simple precursors in moderate to good yields (Scheme 2). Furthermore, the reactions exhibit a high degree of diastereoselectivity and even asymmetric induction was achieved by chiral ligands.
Scheme 2

For the photooxygenations, four differently substituted 1,3-cyclohexadienes 6a-d were chosen in racemic form, since only the diastereo- and mode selectivities were examined. Singlet oxygen was conveniently generated at –30 °C from molecular oxygen by irradiation with two sodium lamps in the presence of catalytic amounts of tetraphenylporphine (TPP) as sensitizer. Complete conversion was achieved after 10 min in deuterochloroform as solvent and the product ratios were directly determined from the \(^1\)H NMR spectra (500 MHz) of the crude reaction mixture. The photooxygenations afforded hydroperoxides 7 and endoperoxides 8 in various ratios and the labile products were directly isolated by column chromatography in high yields and in analytically pure form (Table 1).

Table 1. Photooxygenation of the 1,3-cyclohexadienes 6

| Entry | 1,3-Diene | R\(^1\) | R\(^2\) | 7 : 8\(^a\) | Yield (%)
<table>
<thead>
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<tbody>
<tr>
<td>1</td>
<td>6a</td>
<td>Cl</td>
<td>Ph</td>
<td>70:30</td>
<td>63 (64:36)</td>
</tr>
<tr>
<td>2</td>
<td>6b</td>
<td>CF(_3)</td>
<td>Ph</td>
<td>75:25</td>
<td>69 (65:35)</td>
</tr>
<tr>
<td>3</td>
<td>6c</td>
<td>NO(_2)</td>
<td>SiMe(_3)</td>
<td>&gt;95:5</td>
<td>80 (65:35)</td>
</tr>
<tr>
<td>4</td>
<td>6d</td>
<td>CF(_3)</td>
<td>CH(_2)SO(_2)Ph</td>
<td>30:70</td>
<td>21 (&gt;95:5)</td>
</tr>
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</table>

\(^a\) Product and diastereomeric ratios (dr) were determined by \(^1\)H NMR of the crude product (500 MHz). \(^b\) Yield of isolated products after silica gel chromatography.
The first reactions were performed with the phenyl substituted 1,3-cyclohexadiene 6a ($R^2 = \text{Ph}$) (entry 1), affording the hydroperoxides 7a as main products in 63\% yield. On the other hand, the endoperoxides 8a were isolated only as minor products in 21\% yield. Thus, the photooxygenation of diene 6a proceeds with moderate mode selectivity. This result can be rationalized by the “large-group-effect” of the phenyl group,\textsuperscript{1a} activating the adjacent methylene group for an ene-reaction. Even more interesting are the diastereoselectivities of the photooxygenation, since stereoisomers of hydroperoxide 7a and endoperoxide 8a were obtained in almost the same ratio ($dr$ 64:36 and 66:34) (entry 1). The relative configurations of the newly formed stereocenters were determined by NOE measurements (Figure 1).

![Figure 1](characteristic_NOE_contacts_in_the_main_hydroperoxide_7a_and_endoperoxide_8a.png)

**Figure 1.** Characteristic NOE contacts in the main hydroperoxide 7a and endoperoxide 8a.

Distinct NOE contacts between the methyl group and H-1 of the main hydroperoxide 7a and H-4 of the main endoperoxide 8a indicate the preferential attack of $^1\text{O}_2$ from the side of the benzylic alcohol. This result can be rationalized by a stabilizing hydrogen bridge between the OH group and the negatively charged oxygen in a perepoxide intermediate, which is in accordance with the photooxygenation of allylic\textsuperscript{3a} and homoallylic\textsuperscript{8b} alcohols. However, due to the flexibility of 1,3-cyclohexadienes,\textsuperscript{11} the diastereomeric ratio ($dr$) of the products are only 64:36 and 66:34 (Table 1, entry 1).

To further increase the stereoselectivities, we subsequently investigated the influence of para substituents at the aromatic ring of the benzylic alcohol (entry 2). Thus, an electron acceptor ($R^1 = \text{CF}_3$) should strengthen the postulated hydrogen bridge to singlet oxygen, resulting in a preferential attack *syn* to the OH group. However, almost the same stereo- and mode selectivity was observed in the photooxygenation (entry 2), which might be due to the remote position of the substituent.

On the other hand, a remarkable result is the almost identical diastereoselectivity ($dr$ 65:35) for all products 7a, 8a, 7b and 8b, irrespective of an ene-reaction or [4 + 2]-cycloaddition (Table 1, entries 1 and 2). This gives clear evidence for a common perepoxide intermediate in both reaction modes, which is interesting for the mechanism of $^1\text{O}_2$ reactions and is in accordance with our studies on the photooxygenation of 1,2-dihydronaphthalenes.\textsuperscript{12} Thus, in the first step the perepoxides 9a,b are formed by attack of the electrophilic $^1\text{O}_2$ to the phenyl substituted double bond (Scheme 3). This step controls the stereoselectivities of all further
pathways and explains the similar diastereomeric ratios for all products.

Scheme 3

The perepoxide intermediates 9 can directly react to the endoperoxides 8 by attack of the terminal oxygen atom to the adjacent double bond (pathway A). However, heterolysis to the zwitterions 10 might compete (pathway B), which is favored by the stabilizing propensity of the phenyl group (R² = Ph) on the positively charged carbon atom. Finally, tautomerization affords the hydroperoxides 7a,b. This mechanistic rational explains the mode selectivity in favor of the hydroperoxides (7:8 = 70:30, entry 1 and 75:25, entry 2, Table 1).

To shift the mode selectivity to the side of the hydroperoxides, we investigated the photooxygenation of the silyl substituted 1,3-cyclohexadiene 6c (R² = SiMe₃), since the "large group effect" of the silyl group strongly activates the geminal position. Indeed, now pathway B afforded only hydroperoxides 7c as sole oxidation products (Table 1, entry 3) and the formation of endoperoxides 8c (pathway A) could not compete, which is in accordance to our mechanistic rational. The diastereomeric ratio (dr) is again 65:35 in favor of a syn attack of ¹O₂ to the OH group.

Finally, alkyl substituents should stabilize the zwitterions 10 less effectively than phenyl groups. Therefore, we investigated the photooxygenation of 1,3-cyclohexadiene 6d (R² = CH₂SO₂Ph), which bears an additional acceptor. Indeed, the mode selectivity is now in favor of the endoperoxide (7d:8d = 30:70, Table 1, entry 4). Thus, different substituents strongly influence the product distribution from >95:5 (R² = SiMe₃) to 30:70 (R² = CH₂SO₂Ph).

A very interesting result is the high diastereoselectivity of the photooxygenation of the 1,3-cyclohexadiene 6d (entry 4) in contrast to all other substrates (entries 1-3). Thus, the
hydroperoxide 7d and endoperoxide 8d were isolated in high yields in diastereomerically pure form. Furthermore, \(^1\)O\(_2\) attacks the diene from exactly the opposite face (anti to the OH group), which was confirmed by NOESY and distinct NOE contacts between the benzylic proton and H-1 of the hydroperoxide 7d and H-4 of the endoperoxide 8d (Figure 2).

![Figure 2. Characteristic NOE contacts in the hydroperoxide 7d and endoperoxide 8d.](image)

Therefore, the high stereoselectivity cannot be due to the interaction of \(^1\)O\(_2\) with the benzylic alcohol during the photooxygenation. We explain this remarkable result by the conformation of the starting material 6d. The OH group and the phenyl sulfone can form an intramolecular hydrogen bridge, which was established by X-ray analysis (Figure 3).\(^{10}\)

![Figure 3. Crystal structure of 1,3-cyclohexadiene 6d\(^{10}\) and preferred attack of \(^1\)O\(_2\).](image)

This does not only block the alcohol for coordination with singlet oxygen, but also shields one face of the 1,3-cyclohexadiene 6d efficiently. Therefore, the photooxygenation can occur only from the less hindered side, irrespective of the reaction mode. Such severe steric interactions by hydrogen bonding were hitherto unknown in singlet oxygen reactions. Finally,
especially the endoperoxide 8d is not only of mechanistic but also of synthetic interest, since starting from the boron-functionalized 1,3-diene 3 and other simple precursors, four stereogenic centers are constructed in only few steps with high selectivity.

In summary, the photooxygenation of chiral 1,3-cyclohexadienes affords hydroperoxides and endoperoxides in high yields. Substituents at the double bond strongly influence the mode selectivity of the reactions. The same diastereoselectivity for ene-reaction and [4 + 2]-cycloaddition gives evidence for common peroxide intermediates. Finally, the photooxygenation of a methylensulfonyl substituted 1,3-cyclohexadiene proceeds with very high diastereoselectivity, which can be explained by an intramolecular hydrogen bridge, shielding one face of the compound. Future work will focus on synthetic applications of these new oxidation reactions, generating four stereogenic centers in only few steps from simple precursors.

**Experimental Section**

**General Procedures.** Commercially available compounds were used without further purification; solvents were dried according to standard procedures. Flash chromatography was performed using Merck Kieselgel 60 silica. TLC analysis was carried out on Alugram silica gel 60 F254 plates (Macherey-Nagel). Potassium iodide was used as developing reagent for the peroxide products. NMR spectra were measured on a Bruker AC 300 (300 MHz) and AC 500 (500 MHz) spectrometer using deuterochloroform (CDCl3) as internal standard. IR spectra were recorded on a Perkin Elmer 1600 FT-IR and elemental analysis were performed on a Vario El 3 instrument (Elementar).

**General procedure for the cobalt-catalyzed Diels-Alder / allylboration reaction sequence**

Anhydrous zinc iodide (60 mol%), zinc dust (60 mol%) and CoBr2(dppe) (10 mol%) were stirred under argon in 0.5 mL DCM until the green suspension turned brown (5-10 min). Then, the boron diene 1 (1.0 eq.) in DCM (c = 200 mg / mL) and the appropriate alkyne 2 (1.0 eq.) were added and the mixture was stirred at room temperature. After 30 min the aldehyde (1.0 eq.) was added and the reaction was stirred at room temperature for 15 h. The suspension was diluted with MTBE and washed with 1 M aqueous NaOH and saturated NaHSO3 solution. After drying with MgSO4 the solution was filtered over a short pad of silica gel and then the solvent was removed under vacuum. The residue was then purified by flash column chromatography (pentane/MTBE). For analytical data see reference 10.

**General photooxygenation procedure**

The 1,3-cyclohexadienes 1a-d and tetrphenylporphin (1 mg) were dissolved in CDCl3 (3 mL) in a glass tube. A slow stream of oxygen was bubbled through the solution and the tube was irradiated at – 30 °C with two sodium lamps (250 W). After 10 min tlc (hexane / ethyl acetate 2:1) showed complete conversion. The ratio of the isomers was directly determined from the NMR spectra (500 MHz) of the crude reaction mixture and the oxidation products were isolated by column chromatography.
Numbering of compounds and ring carbon atoms

Photooxygenation of 1,3-cyclohexadiene (6a). The photooxygenation of 1,3-cyclohexadiene 6a (132 mg, 0.42 mmol) afforded a crude product mixture (140 mg) of hydroperoxides 7a (dr = 64:36) and endoperoxides 8a (dr = 66:34) in a ratio of 70:30. Column chromatography (hexane / ethyl acetate 4 : 1) yielded 20 mg (14 %) of the main endoperoxide 8a (Rf = 0.61), 10 mg (7 %) of the minor endoperoxide 8a (Rf = 0.46), 30 mg (21%) of the minor hydroperoxide 7a (Rf = 0.36) and 60 mg (42%) of the main hydroperoxide 7a (Rf = 0.25) as colorless oils.

Main hydroperoxide 7a. $^1$H-NMR (300 MHz, CDCl$_3$) $\delta$ 1.15 (s, 3H, CH$_3$), 1.59, 2.08 (each bs, 1H, OH, OOH), 4.58 (bs, 1H, CHOH), 5.11 (dd, $J$ = 3.0, 1.2 Hz, 1H, H-1), 6.05 (d, $J$ = 1.2 Hz, 1H, 3-H), 6.08 (dt, $J$ = 9.9, 1.2 Hz, 1H, 5-H), 6.18 (dd, $J$ = 9.9, 3.0 Hz, 1H, 6-H), 7.20-7.50 (m, 9H, H-arom.); $^{13}$C-NMR (75 MHz, CDCl$_3$) $\delta$ 23.6 (q, CH$_3$), 44.5 (s, C-4), 76.3 (d, CHOH), 80.2 (d, C-1), 124.4 (q, CF$_3$), 126.2, 126.6, 127.7, 128.0, 128.5, 133.8, 134.6, 135.7 (each d, C-3, C-5, C-6, C-arom.), 124.9, 128.2, 139.3, 145.0 (each s, C-2, C-arom.); IR (KBr) 3420, 2982, 2940, 1740, 1445, 1395, 1221, 1172, 1022, 939 cm$^{-1}$; Anal. Calcd for C$_{20}$H$_{19}$ClO$_3$: C, 70.07; H, 5.59; Found: C, 70.32; H, 5.80.

Minor hydroperoxide 7a. $^1$H-NMR (300 MHz, CDCl$_3$) $\delta$ 1.07 (s, 3H, CH$_3$), 1.63, 3.34 (each bs, 1H, OH, OOH), 4.58 (bs, 1H, CHOH), 5.41 (d, $J$ = 3.8, 1.2 Hz, 1H, H-1), 5.97 (d, $J$ = 1.8 Hz, 1H, 3-H), 6.11 (dd, $J$ = 9.9, 1.2 Hz, 1H, 5-H), 6.22 (dd, $J$ = 9.9, 3.9 Hz, 1H, 6-H), 7.20-7.60 (m, 9H, H-arom.); $^{13}$C-NMR (75 MHz, CDCl$_3$) $\delta$ 24.5 (q, CH$_3$), 44.0 (s, C-4), 77.2 (d, CHOH), 79.7 (d, C-1), 125.2 (q, CF$_3$), 125.8, 126.0, 127.4, 127.7, 128.2, 133.8, 134.6, 135.8 (each d, C-3, C-5, C-6, C-arom.), 133.8, 135.6, 138.5 (each s, C-2, C-arom.); IR (KBr) 3420, 2982, 2940, 1740, 1445, 1395, 1221, 1127, 1022, 939 cm$^{-1}$.

Main endoperoxide 8a. $^1$H-NMR (300 MHz, CDCl$_3$) $\delta$ 0.82 (s, 3H, CH$_3$), 1.67 (d, $J$ = 13.2 Hz, 1H, 6-H), 2.75 (d, $J$ = 2.5 Hz, 1H, OH), 2.84 (d, $J$ = 13.2 Hz, 1H, 6'-H), 4.22 (dd, $J$ = 5.4, 1.8 Hz, 1H, 4-H), 5.18 (d, $J$ = 2.5 Hz, 1H, CHOH), 6.69 (dd, $J$ = 7.8, 5.4 Hz, 1H, 3-H), 6.71 (dd, $J$ = 7.8, 1.8 Hz, 1H, 2-H), 7.20-7.70 (m, 9H, H-arom.). $^{13}$C-NMR (75 MHz, CDCl$_3$) $\delta$ 20.0 (q, CH$_3$), 29.7 (t, C-6), 40.9 (s, C-5), 77.4 (d, CHOH), 78.4 (d, C-4), 79.1 (s, C-1), 124.9 (q, CF$_3$), 126.0, 126.7, 128.3, 128.7, 132.4, 134.6, 135.7 (each d, C-2, C-3, C-arom.), 128.1, 139.3, 145.0 (each s,
C-arom.); IR (KBr) 3420, 2982, 2940, 1740, 1445, 1395, 1221, 1127, 1022, 939 cm⁻¹; Anal. Calcd for C₂₀H₁₉ClO₃: C, 70.07; H, 5.59; Found: C, 70.33; H, 5.34.

**Minor endoperoxide 8a.** ¹H-NMR (300 MHz, CDCl₃) δ 1.36 (s, 3H, CH₃), 1.85 (bs, 1H, OH), 2.18 (d, J = 13.3 Hz, 1H, 6-H), 2.21 (d, J = 13.3 Hz, 1H, 6'-H), 3.88 (dd, J = 5.8, 1.3 Hz, 1H, 4-H), 4.44 (bs, 1H, CHOH), 6.78 (dd, J = 8.3, 1.3 Hz, 1H, 2-H), 6.93 (dd, J = 8.3, 5.8 Hz, 1H, 3-H), 7.20-7.60 (m, 9H, H-arom.); ¹³C-NMR (75 MHz, CDCl₃) δ 20.0 (q, CH₃), 29.7 (s, C-5), 77.4 (d, CHOH), 78.4 (d, C-4), 79.1 (s, C-1), 124.9 (q, CF₃), 126.0, 126.7, 128.3, 132.4, 134.6, 135.7 (each d, C-2, C-3, C-arom.), 128.1, 139.3, 145.0 (each s, C-arom.); IR (KBr) 3420, 2982, 2940, 1740, 1445, 1395, 1221, 1127, 1022, 939 cm⁻¹.

**Photooxygenation of 1,3-cyclohexadiene 6b.** The photooxygenation of 1,3-cyclohexadiene 6b (67 mg, 0.19 mmol) afforded a crude product mixture (75 mg) of hydroperoxides 7b (dr = 65:35) and endoperoxides 8b (dr = 65:35) in a ratio of 75:25. Column chromatography (hexane / ethyl acetate 4 : 1) yielded 20 mg (27 %) of the main endoperoxide 8b (Rf = 0.43), 32 mg (44%) of a mixture of both hydroperoxides 7b (Rf = 0.2-0.3) and 18 mg (25%) of the pure main hydroperoxide 7b (Rf = 0.16) as colorless oils.

**Main hydroperoxide 7b.** ¹H-NMR (300 MHz, CDCl₃) δ 1.17 (s, 3H, CH₃), 3.35, 3.60 (each bs, 1H, OH, OOH), 4.65 (bs, 1H, CHOH), 5.08 (ddd, J = 3.1, 2.0, 1.5 Hz, 1H, H-1), 6.03 (d, J = 1.5 Hz, 1H, 5-H), 6.09 (dd, J = 10.0, 2.0 Hz, 1H, 5-H), 6.19 (dd, J = 10.0, 3.1 Hz, 1H, 6-H), 7.20-7.60 (m, 9H, H-arom.); ¹³C-NMR (75 MHz, CDCl₃) δ 23.6 (q, CH₃), 44.5 (s, C-4), 76.3 (d, CHOH), 80.2 (d, C-1), 124.4 (q, CF₃), 126.2, 126.4, 127.7, 128.0, 128.5, 133.8, 134.6, 135.7 (each d, C-3, C-5, C-6, C-arom.), 124.9, 128.2, 139.3, 145.0 (each s, C-2, C-arom.); IR (KBr) 3423, 2855, 1620, 1460, 1326, 1313, 1295, 1156, 1124, 1067, 978, 609 cm⁻¹; Anal. Calcd for C₂₁H₁₉F₃O₃: C, 67.02; H, 5.09; Found: C, 66.82; H, 5.12.

**Minor hydroperoxide 7b.** ¹H-NMR (300 MHz, CDCl₃) δ 1.07 (s, 3H, CH₃), 3.41, 3.70 (each bs, 1H, OH, OOH), 4.49 (bs, 1H, CHOH), 5.39 (dd, J = 4.0, 1.9 Hz, 1H, H-1), 5.94 (d, J = 1.9 Hz, 1H, 3-H), 6.05 (d, J = 10.0 Hz, 1H, 5-H), 6.22 (dd, J = 10.0, 4.0 Hz, 1H, 6-H), 7.20-7.60 (m, 9H, H-arom.); ¹³C-NMR (75 MHz, CDCl₃) δ 24.5 (q, CH₃), 44.0 (s, C-4), 77.2 (d, CHOH), 79.7 (d, C-1), 125.2 (q, CF₃), 125.8, 126.0, 127.4, 127.7, 128.2, 133.8, 134.6, 135.8 (each d, C-3, C-5, C-6, C-arom.), 133.8, 135.6, 138.5 (each s, C-2, C-arom.); IR (KBr) 3431, 2971, 1620, 1419, 1327, 1166, 1124, 1067, 851, 760, 698, 609 cm⁻¹; Anal. Calcd for C₂₁H₁₉F₃O₃: C, 67.02; H, 5.09; Found: C, 66.82; H, 5.12.

**Endoperoxide 8b.** ¹H-NMR (300 MHz, CDCl₃) δ 0.82 (s, 3H, CH₃), 1.66 (d, J = 13.4 Hz, 1H, 6-H), 2.80 (d, J = 2.5 Hz, 1H, OH), 2.85 (d, J = 13.4 Hz, 1H, 6'-H), 4.21 (dd, J = 6.1, 1.5 Hz, 1H, 4-H), 5.25 (d, J = 2.5 Hz, 1H, CHOH), 6.69 (dd, J = 8.3, 6.1 Hz, 1H, 3-H), 6.71 (dd, J = 8.3, 1.5 Hz, 1H, 2-H), 7.20-7.70 (m, 9H, H-arom.); ¹³C-NMR (75 MHz, CDCl₃) δ 20.0 (q, CH₃), 29.7 (t, C-5), 77.4 (d, CHOH), 78.4 (d, C-4), 79.1 (s, C-1), 124.9 (q, CF₃), 126.0, 126.7, 128.3, 128.7, 132.4, 134.6, 135.7 (each d, C-2, C-3, C-arom.), 128.1, 139.3, 145.0 (each s, C-arom.); IR (KBr) 3494, 2928, 1618, 1449, 1326, 1163, 1113, 1016, 698 cm⁻¹; HRMS Calcd. C₂₁H₁₉F₃O₃Na: 399.1184; Found: 399.1184.
Photooxygenation of 1,3-cyclohexadiene 6c. The photooxygenation of 1,3-cyclohexadiene 6c (160 mg, 0.50 mmol) afforded a crude product mixture (150 mg) of hydroperoxides 7c (dr = 65:35) and no endoperoxide 8c could be detected. Column chromatography (hexane / ethyl acetate 6 : 1) yielded 20 mg (11%) of the pure minor hydroperoxide 7c (Rf = 0.57) and 120 mg (69%) of a mixture of both hydroperoxides 7c (Rf = 0.43) as a white solid (mp 67-68 °C).

Main hydroperoxide 7c. $^1$H-NMR (300 MHz, CDCl$_3$) δ 0.09 (s, 9H, SiMe$_3$), 1.17 (s, 3H, CH$_3$), 2.71, 3.60 (each bs, 1H, OH, OOH), 4.45 (bs, 1H, CHOH), 4.57 (dd, $J$ = 2.8, 2.1 Hz, 1H, H-1), 5.86 (t, $J$ = 2.1 Hz, 1H, 3-H), 6.13 (dd, $J$ = 10.1, 2.8 Hz, 1H, 6-H), 7.36 (d, $J$ = 8.7 Hz, 2H, H-arom.), 8.08 (d, $J$ = 8.7 Hz, 2H, H-arom.); 13C-NMR (75 MHz, CDCl$_3$) δ –1.5 (q, SiMe$_3$), 23.7 (q, CH$_3$), 43.5 (s, C-4), 77.5 (d, CHOH), 79.6 (d, C-1), 122.2, 128.6 (each d, C-arom.), 127.8, 133.5, 143.5 (each d, C-3, C-5, C-6), 137.2, 147.1, 147.7 (each s, C-2, C-arom.); IR (KBr) 3433, 2958, 2872, 1606, 1519, 1348, 1267, 1047, 840 cm$^{-1}$; Anal. Calcd for C$_{17}$H$_{23}$NSiO$_5$: C, 58.43; H, 6.63; N, 4.01; Found: C, 58.60; H, 6.91; N 4.05.

Minor hydroperoxide 7c. $^1$H-NMR (300 MHz, CDCl$_3$) δ 0.15 (s, 9H, SiMe$_3$), 1.01 (s, 3H, CH$_3$), 1.64, 3.35 (each bs, 1H, OH, OOH), 4.61 (d, $J$ = 2.8 Hz, 1H, CHOH), 4.95 (dd, $J$ = 3.6 Hz, 1H, H-1), 5.83 (d, $J$ = 1.4 Hz, 1H, 3-H), 6.05 (dd, $J$ = 10.1, 1.4 Hz, 1H, 5-H), 6.18 (dd, $J$ = 10.1, 3.6 Hz, 1H, 6-H), 7.46 (d, $J$ = 8.8 Hz, 2H, H-arom.), 8.20 (d, $J$ = 8.8 Hz, 2H, H-arom.); 13C-NMR (75 MHz, CDCl$_3$) δ –1.5 (q, SiMe$_3$), 24.4 (q, CH$_3$), 42.8 (s, C-4), 77.1 (d, CHOH), 78.9 (d, C-1), 123.3, 126.9, 130.5 (each d, C-3, C-5, C-6), 137.9, 143.6, 147.6 (each s, C-2, C-arom.); IR (KBr) 3445, 2943, 2864, 1612, 1519, 1344, 1258, 1044, 838 cm$^{-1}$; Anal. Calcd for C$_{17}$H$_{23}$NSiO$_5$: C, 58.43; H, 6.63; N, 4.01; Found: C, 58.86; H, 6.31; N 4.23.

Photooxygenation of 1,3-cyclohexadiene 6d. The photooxygenation of 1,3-cyclohexadiene 6d (266 mg, 0.63 mmol) afforded a crude product mixture (285 mg) of hydroperoxide 7d (dr > 95:5) and endoperoxides 8d (dr = 90:10) in a ratio of 30:70. Column chromatography (hexane / ethyl acetate 4 : 1) yielded 180 mg (63%) of the main endoperoxide 8d (Rf = 0.47) as white crystals (mp 64–65 °C) and 60 mg (21%) of the hydroperoxide 7d (Rf = 0.27) as white crystals (mp 45-46 °C). The minor endoperoxide 8d (< 10%) could not be isolated.

Hydroperoxide 7d. $^1$H-NMR (300 MHz, CDCl$_3$) δ 1.03 (s, 3H, CH$_3$), 1.64, 3.35 (each bs, 1H, OH, OOH), 2.03, 2.43 (each bs, 1H, CH$_2$S), 3.75 (d, $J$ = 13.9 Hz, 1H, CH$_2$´S), 4.17 (d, $J$ = 13.9 Hz, 1H, CH$_2$´S), 4.53 (bs, 1H, CHOH), 4.55 (d, $J$ = 3.0 Hz, 1H, H-1), 5.78 (d, $J$ = 1.5 Hz, 1H, 3-H), 5.89 (dd, $J$ = 10.1, 1.5 Hz, 1H, 5-H), 6.02 (dd, $J$ = 10.1, 3.0 Hz, 1H, 6-H), 7.46 (d, $J$ = 8.8 Hz, 2H, H-arom.), 8.20 (d, $J$ = 8.8 Hz, 2H, H-arom.); $^{13}$C-NMR (75 MHz, CDCl$_3$) δ –1.5 (q, SiMe$_3$), 24.4 (q, CH$_3$), 42.8 (s, C-4), 77.1 (d, CHOH), 78.9 (d, C-1), 122.7, 128.6 (each d, C-arom.), 123.3, 126.9, 130.5 (each d, C-3, C-5, C-6), 137.9, 143.6, 147.6 (each s, C-2, C-arom.); IR (KBr) 3412, 2929, 1448, 1327, 1162, 1128, 747, 526 cm$^{-1}$; Anal. Calcd for C$_{22}$H$_{21}$F$_3$SO$_5$: C, 58.14; H, 4.66; S, 7.05; Found: C, 58.14; H, 4.70; S 7.03.

Main endoperoxide 8d. $^1$H-NMR (300 MHz, CDCl$_3$) δ 1.20 (s, 3H, CH$_3$), 1.82 (d, $J$ = 13.5 Hz, 1H, 6-H), 2.15 (d, $J$ = 13.5 Hz, 1H, 6´-H), 2.69 (bs, 1H, OH), 3.39 (d, $J$ = 14.4 Hz, 1H, CH$_2$S), 3.46 (d, $J$ = 14.4 Hz, 1H, CH$_2$´S), 3.71 (dd, $J$ = 5.8, 0.9 Hz, 1H, 4-H), 4.36 (bs, 1H, CHOH), 6.80
(dd, $J = 8.5$, 5.8 Hz, 1H, 3-H), 7.03 (dd, $J = 8.5$, 0.9 Hz, 1H, 2-H), 7.40-7.90 (m, 9H, H-arom.); $^{13}$C-NMR (75 MHz, CDCl$_3$) $\delta$ 18.2 (q, CH$_3$), 40.1 (t, C-6), 41.2 (s, C-5), 59.5 (t, CH$_2$S), 75.8 (s, C-1), 77.4 (d, CHO), 78.1 (d, C-4), 125.2 (q, CF$_3$), 127.4, 128.0, 129.1, 129.4, 131.8, 132.7, 134.1 (each d, C-2, C-3, C-arom.), 140.3, 144.5 (each s, C-arom.); IR (KBr) 3514, 2976, 1448, 1327, 1156, 1128, 566 cm$^{-1}$; Anal. Calcd for C$_{22}$H$_{21}$F$_3$SO$_5$: C, 58.14; H, 4.66; S, 7.05; Found: C, 58.06; H, 4.65; S 7.17.

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References


