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Published on Web 01/09/2009

# Iodomesitylene-Catalyzed Oxidative Cleavage of Carbon−Carbon Double and Triple Bonds Using *m*-Chloroperbenzoic Acid as a Terminal Oxidant

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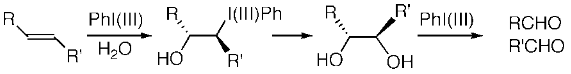
Transition metal-catalyzed oxidative cleavage of carbon−carbon multiple bonds has emerged as a powerful tool in organic synthesis.[1] High-valent oxometals, mostly of Ru, Os, Mn, Mo, W, and Re, were used catalytically as reactive oxygen transfer agents to the multiple bonds.[2] We report herein for the first time the organocatalytic version of the oxidative cleavage reactions. Our method involves use of iodomesitylene as an effective organocatalyst, which generates an active aryl(hydroxy)-$\lambda^3$-iodane **5** in situ, and *m*-chloroperbenzoic acid (*m*-CPBA) as a terminal oxidant under metal-free conditions.[3]

Recently, we developed an aryl-$\lambda^3$-iodane-based method for C−C double bond cleavage, yielding carbonyl compounds, in which a combination of stoichiometric iodosylbenzene and $HBF_4$ in the presence of water generates an activated iodosylbenzene monomer as an ozone equivalent and serves as a safety alternative to ozonolysis, because of the environmentally friendly nature of aryl-$\lambda^3$-iodanes.[4,5] The method involves syn vicinal dihydroxylation of olefins through an initial electrophilic anti addition of aryl-$\lambda^3$-iodanes, followed by a nucleophilic displacement of the hyper-leaving $\lambda^3$-iodanyl group by water with inversion of configuration (Scheme 1).[6,7] Subsequent oxidative glycol fission by $\lambda^3$-iodanes, probably via the intervention of cyclic dialkoxy-$\lambda^3$-iodanes, affords carbonyl compounds.

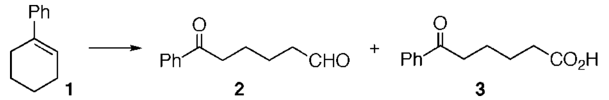
***Scheme 1***



Exposure of phenylcyclohexene **1** to iodobenzene (1 mol %), *m*-CPBA (3.1 equiv), and aqueous $HBF_4$ (2.2 equiv) in $CH_2Cl_2$-hexafluoroisopropanol (HFIP)-$H_2O$ (9:3:1) at room temperature resulted in a facile cleavage of the double bond to afford $\epsilon$-keto acid **3** in a high yield, being isolated as a methyl ester (75%) after treatment with $TMSCHN_2$ (Table 1, entry 7). Adipic acid monophenyl ester (**4**) (5%) was obtained as a byproduct, probably produced via Baeyer−Villiger oxidation of **3** with *m*-CPBA. Increase in the catalyst loading to 5 mol % inhibited the byproduct formation, with an increased yield of **3** (93%) (entry 6). The reaction provided no evidence for the double bond cleavage without the organocatalyst (entry 1). Separate experiments indicate that most of the keto acid **3** obtained is formed via oxidation of the initially formed keto aldehyde **2** by *m*-CPBA under the acidic conditions (Supporting Information, Scheme S1).

After extensive studies on the reactions, we finally found that iodomesitylene serves as the most efficient organocatalyst and the 1 mol % catalyst afforded an 96% yield of the acid **3** with only trace amount of the byproduct **4** (entry 12). Introduction of methyl groups on iodobenzene catalyst seems to enhance the rates of oxidation to reactive aryl-$\lambda^3$-iodanes, which, in turn, suppresses the unfavorable Baeyer−Villiger oxidation of **3** by *m*-CPBA (compare entries 7, 9, 11, and 12). It is noted that pentamethyl- and *p*-methoxyiodobenzenes gave significant amounts of tarry matter, while sterically demanding 2,4,6-tri-*tert*-butyliodobenzene showed high catalytic efficiency for the oxidative cleavage.

***Table 1.*** Iodoarene-Catalyzed Oxidative Cleavage of Olefin **1**[a]



| entry | ArI | (equiv) | *m*-CPBA (equiv) | time (h) | yield (%)[b] **2** | yield (%)[b] **3** |
|---|---|---|---|---|---|---|
| 1 | − |  | 2.2 | 2.5 | − | − |
| 2 | PhI | (2.2) | 2.2 | 2 | 72 | 5 |
| 3 | PhI | (0.3) | 2.2 | 2.5 | 57 | 29 |
| 4 | PhI | (0.1) | 2.2 | 2.5 | 36 | 36 |
| 5 | PhI | (0.1) | 3.1 | 5 | − | 91 (88) |
| 6 | PhI | (0.05) | 3.1 | 7 | − | 93 (85) |
| 7 | PhI | (0.01) | 3.1 | 24 | − | 86 (75)[c] |
| 8 | 4-$MeOC_6H_4I$ | (0.01) | 3.1 | 24 | − | 18 (23)[c] |
| 9 | 4-$MeC_6H_4I$ | (0.01) | 3.1 | 24 | − | 91 (85)[c] |
| 10 | 4-$ClC_6H_4I$ | (0.01) | 3.1 | 30 | − | 83 (81)[c] |
| 11 | 3,5-$Me_2C_6H_3I$ | (0.01) | 3.1 | 22 | − | 94 (83)[c] |
| 12 | 2,4,6-$Me_3C_6H_2I$ | (0.01) | 3.1 | 14 | − | 96 (88)[c] |
| 13 | 2,3,4,5,6-$Me_5C_6I$ | (0.01) | 3.1 | 48 | − | 35 (36)[c] |
| 14 | 2,4,6-*t*$Bu_3C_6H_2I$ | (0.01) | 3.1 | 24 | − | 93 (89)[c] |

[a] Conditions: **1**/ArI/*m*-CPBA/48% aq $HBF_4$ (2.2 equiv)/$CH_2Cl_2$−HFIP−$H_2O$ 9:3:1/room temperature/$N_2$. [b] $^1H$ NMR yields. Parentheses are isolated yields after methylation with $TMSCHN_2$. [c] Yields of **4**: 5−6% (entries 7−10, 13, and 14), 3% (entry 11), and <1% (entry 12).

Table 2 demonstrates that cyclopentenes and cyclohexenes with alkyl or aryl substituents on the double bond are catalytically cleaved smoothly in good to high yields with iodomesitylene (1 mol %)/$CH_2Cl_2$−HFIP−$H_2O$/room temperature (method A), while unsubstituted five- to seven-membered cycloalkenes afforded only moderate yields of diesters. Oxidative scission of 1-decene is sluggish under the conditions, affording a low yield of methyl nonanoate (19%) even after 48 h and formation of a large amount of decane-1,2-diol (54%) was detected (Table 2, entry 13). Changing the solvent to MeCN-$H_2O$ (9:1), heating at 50 °C, and use of 10 mol % of iodomesitylene (method B) improved the efficiency of the reaction and afforded the ester in 67% yield. Method B resulted in an efficient cleavage of *E*- and *Z*-disubstituted as well as trisubstituted olefins (entries 14−17). Reactive tetrasubstituted olefin 2,3-dimethyl-2-butene afforded 69% yield of acetone using 1 mol % of iodomesitylene (method A). Our cleavage reaction tolerates various kinds of functionalities such as carboxylic acid, hydroxy group, amide, and sulfonamide. 11-Tetradecenyl acetate undergoes both deprotection of the acetoxy group and the double bond cleavage at once (entry 21).

It is noted that both aliphatic and aromatic alkynes were smoothly cleaved to carboxylic acids under our organocatalytic conditions (method B), without no evidence for formation of α-dicarbonyl

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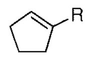
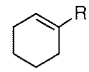
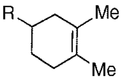
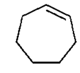
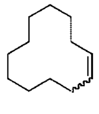
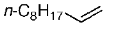
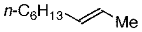
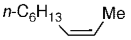
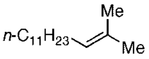
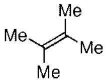
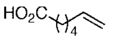
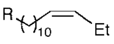
10.1021/ja808829t CCC: $40.75

***Table 2.*** Iodomesitylene-Catalyzed Oxidative Cleavage of Olefins

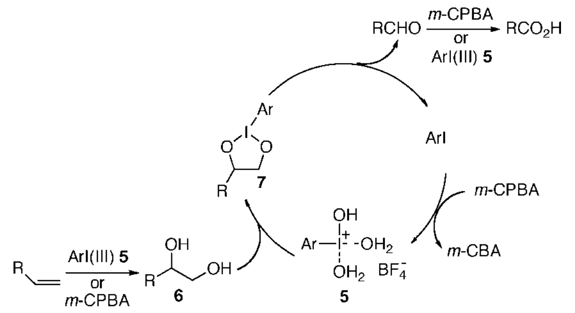
| entry | olefin | | method[a] | equiv[b] | time h | yield (%)[c] |
|---|---|---|---|---|---|---|
| 1 |  | R = H | A | 4.1 | 168 | 40 (40) |
| 2 | | Me | A | 3.1 | 9 | 67 (59) |
| 3 |  | R = H | A[d] | 4.1 | 42 | 49 |
| 4 | | Me | A | 3.1 | 49 | 84(79) |
| 5 | | *n*-Bu | A | 3.1 | 19 | 70(66) |
| 6 | | *p*-$MeC_6H_4$ | A | 3.1 | 14 | 76(73) |
| 7 | | *p*-$ClC_6H_4$ | A | 3.1 | 14 | 86(85) |
| 8 | | *p*-$CF_3C_6H_4$ | A | 3.1 | 25 | 79(61) |
| 9 |  | R = H | A | 2.2 | 12 | 88 (60) |
| 10 | | $SO_2Ph$ | A | 2.2 | 36 | 89 (93) |
| 11 |  | | A[d] | 4.1 | 48 | (48) |
| 12[e] |  | | B | 4.1 | 10 | 77 (65) |
| 13 |  | | A | 4.1 | 48 | 19 |
| | | | B | 4.1 | 10 | 84 (67)[f] |
| 14 |  | | B | 4.1 | 10 | 75 (74)[f] |
| 15 |  | | B | 4.1 | 12 | 87 (71)[f] |
| 16[g] |  | | B | 4.1 | 13 | 82 (70)[f] |
| 17 |  | | B | 3.1 | 10 | 90 (57) |
| 18 |  | | A | 2.2 | 21 | 87 (69)[f] |
| 19 |  | | B | 4.1 | 10 | 57 (42) |
| 20 |  | R = OH | B | 4.1 | 10 | 78 (67) |
| 21 | | OAc | B | 4.1 | 10 | 73 (67)[h] |
| 22 | | $NHCOCF_3$ | B | 4.1 | 10 | 78 (68) |
| 23 | | NHTs | B | 4.1 | 10 | 98 (95) |
| 24 | $R(CH_2)_8—\equiv$ | R = H | B | 4.1 | 10 | 93 (81)[f] |
| 25 | | $CH_2OH$ | B | 4.1 | 10 | 72 (60) |
| 26 | | $CH_2Cl$ | B | 4.1 | 10 | 91 (82) |
| 27 | | $CO_2Me$ | B | 4.1 | 10 | 84 (88) |
| 28 | $Ar—\equiv$ | Ar = Ph | B | 4.1 | 10 | 66 (62)[f] |
| 29 | | *p*-$CF_3C_6H_4$ | B | 4.1 | 10 | 58 (58)[f] |
| 30 | *n*-$C_7H_{15}—\equiv—$*n*-$C_7H_{15}$ | | B | 4.1 | 10 | 68 (43)[f] |

[a] Method A: iodomesitylene (1 mol %)/*m*-CPBA/48% aq $HBF_4$ (2.2 equiv)/$CH_2Cl_2$−HFIP−$H_2O$ 9:3:1/room temperature/$N_2$. Method B: iodomesitylene (10 mol %)/*m*-CPBA/48% aq $HBF_4$ (2.2 equiv)/MeCN−$H_2O$ 9:1/50 °C/$N_2$. [b] *m*-CPBA. [c] $^1H$ NMR yields. Parentheses are isolated yields of diketones or methyl esters obtained after methylation with $TMSCHN_2$. For structures of products, see Scheme S2. [d] Iodomesitylene (10 mol %). [e] *E*:*Z* = 3:7. [f] GC yields. [g] *E*:*Z* = 72:28. [h] Methyl 11-hydroxyundecanoate was obtained.

compounds and α-hydroxy ketones (entries 24−30);[8] thus, 1-decyne afforded high yields of nonanoic acid and formic acid (entry 24 and Figure S1).

Scheme 2 depicts a catalytic cycle for the olefin cleavage, which involves in situ generation of tetracoordinated squareplanar hydroxy-$\lambda^3$-iodane **5** as a reactive species.[4,9] The iodane **5** undergoes oxidative cleavage of 1,2-diol **6** derived from an olefin, probably via the intermediacy of cyclic dialkoxy-$\lambda^3$-iodane **7**.[10] In fact, CSI-MS spectrum of a mixture of hydroxy-$\lambda^3$-iodane [$PhI(OH)BF_4 \cdot$18-crown-6] **8** and *trans*-1,2-cyclohexanediol in dichloromethane detected a peak assignable to the corresponding cyclic dialkoxy-$\lambda^3$-iodane·18-crown-6 complex (Figure S2). Time course for the catalytic cleavage of 1-decene under the conditions of method B (Figure S3) revealed a rapid disappearance of the olefin within 10 min, with the formation of a large amount of decane-1,2-diol. The subsequent gradual decrease of the diol was accompanied by the formation of nonanoic acid. Interestingly, the organocatalyst was found to be rapidly oxidized to the iodane **5** by *m*-CPBA. These results indicate that a slow step in the catalytic cycle for the cleavage of 1-decene is probably an oxidative scission of the 1,2-diol derived from the olefin. Furthermore, kinetic measurements for the cleavage of *trans*-1,2-cyclohexanediol with the hydroxyiodane **8** suggested a rapid pre-equilibrium formation of a cyclic dialkoxy-$\lambda^3$-iodane such as **7**, followed by its rate-limiting decomposition to dialdehyde (Figure S4).

***Scheme 2***



Ar = 2,4,6-$Me_3C_6H_2$

In summary, we have developed an efficient method for organocatalytic oxidative cleavage of carbon−carbon multiple bonds as an environmentally friendly, safe alternative to ozonolysis.

**Supporting Information Available:** Experimental details, Schemes S1 and S2, and Figures S1−S4. This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) In a separate experiment (PhI/*m*-CPBA (1 equiv)/$HBF_4$ (1 equiv)/$D_2O$/room temperature/3 h), exclusive formation of **5** (R = Ph) was observed.

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JA808829T