Tetrahedron Letters 53 (2012) 4080–4083

Contents lists available at SciVerse ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Selective signaling of peracetic acid over hydrogen peroxide by desulfurization of an anthracene-thioamide

Suyoung Eor, Myung Gil Choi, Nayun Kim, Taihao Sun, Suk-Kyu Chang *

Department of Chemistry, Chung-Ang University, Seoul 156-756, Republic of Korea

ARTICLE INFO

Article history:
Received 18 March 2012
Revised 16 May 2012
Accepted 23 May 2012
Available online 29 May 2012

Keywords:
Peracetic acid
Fluorogenic signaling
Desulfurization
Anthracene-thioamide
Hydrogen peroxide

ABSTRACT

Selective signaling of peracetic acid by desulfurization of a thioamide was investigated. A thioamide derivative of anthracene **1** was efficiently desulfurized by peracetic acid to the corresponding amide **2**, which resulted in a pronounced turn-on type fluorescent signaling. Signaling was not affected by the presence of another important oxidant hydrogen peroxide thereby providing selective signaling of the peracetic acid from its frequent contaminant hydrogen peroxide. Anthracene-thioamide **1** also provided selectivity for peracetic acid over commonly encountered metal ions and anions. The chemical transformation was confirmed by ^{1}H NMR, ^{13}C NMR, and fluorescence measurements.

There is great interest in the development of smart molecular systems for the selective signaling of chemically and biologically important chemical species.[1] Recently, signaling of oxidants has attracted considerable research interest in the biological and environmental chemistry fields.[2] A number of probes have been developed for signaling or visualization of biologically important oxidants, such as hydrogen peroxide,[3] peroxynitrite,[4] and hypochlorous acid.[5] However, signaling of peracids, which have found more practical involvement in many aspects of synthetic chemistry, daily living, and industrial applications such as disinfection, food processing, and water treatment, is not so well studied.

Peracetic acid (PAA) is the peroxide of acetic acid. PAA is a strong oxidizing agent produced by reacting acetic acid and hydrogen peroxide in aqueous solution.[6] It is used widely as a green oxidant in synthetic organic chemistry and as a safe disinfectant. The disinfection power of PAA is known to be more efficient than chlorine or chlorine dioxide, and it could be used as a safer disinfectant in the food and beverage industry.[7] For disinfection purposes, typical concentrations of PAA range between 6.6×10^{-4} and 1.3×10^{-2} M.[8]

Accurate determination of PAA is required to assess PAA levels in oxidant or disinfectant solutions. A number of analytical methods have been developed to assay PAA, including titrimetry,[9] gas chromatography,[10] liquid chromatography,[11] electrochemistry,[12] and spectrophotometry.[13] Among these analytical methods, optical analysis is the most attractive due to its convenience and sensitivity. Difficulty in PAA analysis is the presence of varying amounts of hydrogen peroxide, which is a result of the synthesis of PAA from acetic acid as well as from decomposition of PAA via the reverse reaction. Therefore, the discrimination of PAA from hydrogen peroxide is a very important property in the analysis of PAA. Simultaneous determination of PAA, hydrogen peroxide, and acetic acid has been carried out using far-UV absorption bands in the 180–220 nm region.[14] On the other hand, the discrimination of PAA from hydrogen peroxide has been investigated by potentiometry,[15] reagentless biosensor,[16] and time resolved UV–vis spectrometry.[17]

We recently reported a convenient signaling system for the synthetically useful oxidant 3-chloroperbenzoic acid (mCPBA) that relied on the oxidative desulfurization of thiocoumarin.[18] In this Letter, a new simple PAA selective probe based on a thioamide derivative of anthracene was investigated. Anthracene based thioamide **1** showed pronounced fluorescence turn-on type signaling behavior toward PAA via desulfurization of the thioamide group in the presence of common metal ions and anions as well as hydrogen peroxide.

Compound **1** was prepared from 9-anthracenecarboxylic acid by acid chloride formation with oxalyl chloride, amidation with diethylamine (86%), and subsequent treatment with Lawesson's reagent (toluene, 64%) (Scheme 1). The anthracene fluorophore was chosen as the signaling moiety due to its relative stability to oxidation from the targeted oxidants. A diethylthioamide was utilized as a signal-switching moiety, due to the relative inertness of aromatic tertiary thioamides to metal ion-induced desulfurization.[19]

* Corresponding author. Tel.: +82 2 820 5199; fax: +82 2 825 4736.
E-mail address: skchang@cau.ac.kr (S.-K. Chang).

0040-4039/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tetlet.2012.05.101

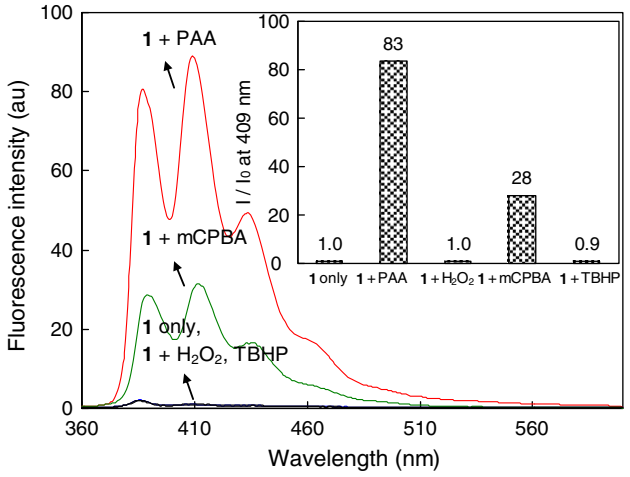


Figure 1. Fluorescence spectra of **1** in the presence of PAA, mCPBA, TBHP, and H_2O_2 in a mixture of CH_3CN and acetate buffer solution (pH 4.8, 10 mM), (10:90, v/v). λ_{ex} = 340 nm; [**1**] = 5.0×10^{-6} M; [Oxidant] = 5.0×10^{-4} M. Inset represents the fluorescence intensity ratio I/I_o of **1** at 409 nm for each oxidant.

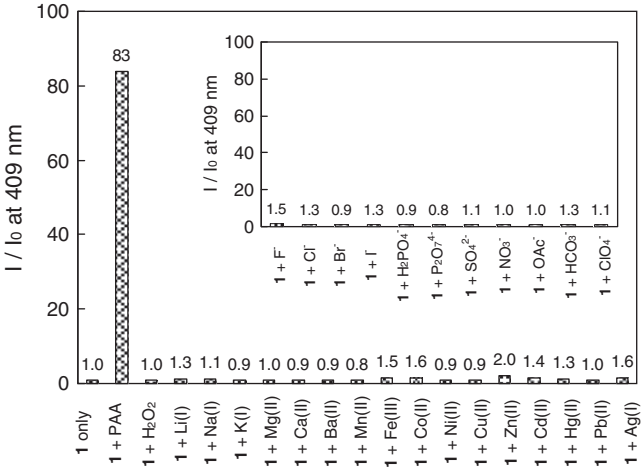
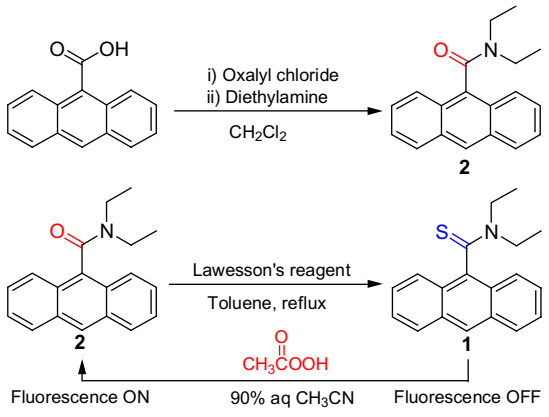


Figure 2. Changes in fluorescence intensity ratio I/I_o at 409 nm of **1** in the presence of PAA, H_2O_2, metal ions, and anions in a mixture of CH_3CN and acetate buffer solution (pH 4.8, 10 mM), (10:90, v/v). λ_{ex} = 340 nm; [**1**] = 5.0×10^{-6} M; [PAA] = 1.0×10^{-4} M; $[M^{n+}] = [A^{n-}] = [H_2O_2]$ 5.0×10^{-4} M.



Scheme 1. Preparation of anthracene-thioamide **1** and its peracetic acid signaling.

Initially, the response of **1** toward important peroxide and peracid oxidants was surveyed. In 90% aqueous acetonitrile, thioamide **1** showed very weak fluorescence emission due to the quenching nature of its thiocarbonyl function.[20] On the other hand, thioamide **1** revealed a large fluorescence enhancement with PAA; the fluorescence intensity ratio in the presence and absence of oxidant I/I_o at 409 nm was 83 (Fig. 1). Another widely used peracid, mCPBA, induced a 28-fold fluorescence enhancement. Other industrially important oxidants, such as hypochlorite (I/I_o = 60) and Oxone (I/I_o = 4.4) also induced significant responses (Fig. S1).[21] At the moment, we have no clear explanation for these differences in the reactivity of **1** toward surveyed oxidants. The response of **1** toward mCPBA, hypochlorite, and Oxone is not a drawback in the selective signaling of PAA, since PAA is usually used as a single component oxidant in many applications. In addition, thioamide **1** had almost no response to hydrogen peroxide, a major contaminant in PAA as well as *tert*-butyl hydroperoxide (TBHP) and di-*tert*-butyl peroxide (DTBP). Based on these results, the selective signaling of probe **1** for PAA over hydrogen peroxide was further tested. The signaling behavior of probe **1** was measured in the presence of varying amounts of hydrogen peroxide from 100 equiv to 7000 equiv with respect to **1** (Fig. S2) and was relatively stable toward hydrogen peroxide up to 2000 equiv.

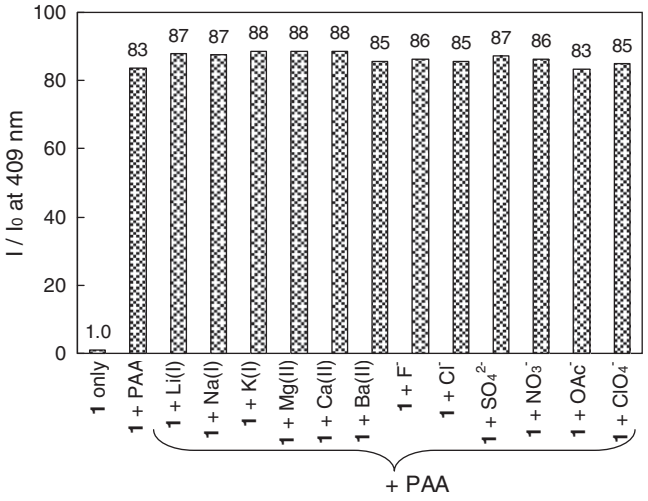


Figure 3. Competitive fluorescent signaling of PAA by **1** in the presence of metal ions and anions as background in a mixture of CH_3CN and acetate buffer solution (pH 4.8, 10 mM), (10:90, v/v). λ_{ex} = 340 nm; [**1**] = 5.0×10^{-6} M; [PAA] = 2.5×10^{-4} M; $[M^{n+}] = [A^{n-}] = 5.0 \times 10^{-4}$ M.

Selective signaling of PAA over other commonly encountered metal ions and anions might be an important characteristic for the practical use of **1** as a PAA probe. Thioamide **1** exhibited almost no response toward surveyed alkali (Li^+, Na^+, K^+), alkaline earth (Mg^{2+}, Ca^{2+}, Ba^{2+}), and transition metal ions (Mn^{2+}, Fe^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}, Pb^{2+}, Ag^+) (Fig. 2). The fluorescence intensity ratio in the presence and absence of metal ions I/I_o at 409 nm varied in a limited range between 0.8 for Mn^{2+} and 2.0 for Zn^{2+} ions. Possible responses of thioamide toward notable thiophilic metal ions of Cd^{2+}, Hg^{2+}, and Ag^+ were not observed as was similarly reported for the diethylthioamide derivative of pyrene.[19] The response of **1** toward common anions was also tested. As can be seen in Figure 2, frequently encountered anions induced negligible fluorescence signaling of **1**; the I/I_o at 409 nm varied within a narrow range between 0.8 (for $P_2O_7^{4-}$) and 1.5 (for F^-).

For practical applications, signaling of PAA under competitive conditions in the presence of commonly encountered coexisting metal ions and anions as background is necessary. To check the possibility of interference, fluorescence signaling of PAA by **1** in the presence of 20 equiv of coexisting ions with respect to PAA was measured (Fig. 3). With metal ions as background, no

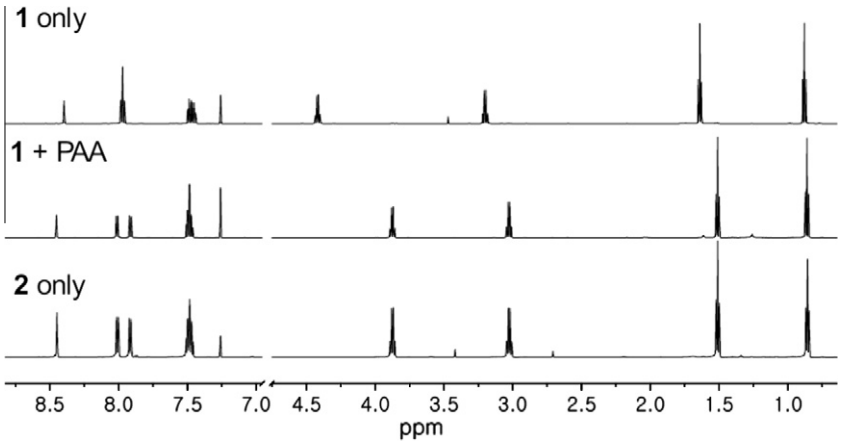


Figure 4. Partial ^{1}H NMR spectra of **1**, **1** upon reaction with PAA, and **2** in $CDCl_3$. [**1**] = [**2**] = 3.0×10^{-2} M. Middle spectrum (**1** + PAA) was obtained from the purified reaction product of **1** with PAA (10 equiv) in 90% aqueous acetonitrile.

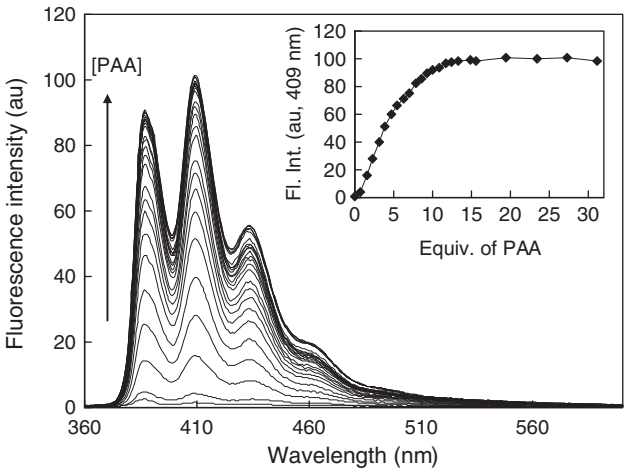


Figure 5. Fluorescence titration of **1** with PAA. [**1**] = 5.0×10^{-6} M in a mixture of CH_3CN and acetate buffer solution (pH 4.8, 10 mM), (10:90, v/v). λ_{ex} = 340 nm.

significant interference in the signaling of PAA was found with the exception of Hg^{2+} and Fe^{3+} ions. Hg^{2+} ions significantly interfered with the signaling of PAA because of a direct reaction with the analyte PAA.[22] Ferric ions also considerably interfered with signaling, possibly due to the known incompatibility of PAA with Fe^{3+} ions.[23] With anions, except for bromide and iodide, almost no interference with the fluorescent signaling of probe **1** with PAA was found. Interference from bromide and iodide ions is due to the well-known redox reaction of the oxidant PAA itself with these reactive ions.[24]

Transformation of **1** into **2** by PAA was confirmed by NMR measurements. The ^{1}H NMR spectrum of the purified reaction product of **1** after treatment with 10 equiv of PAA was almost identical to that of **2**. The ethyl proton resonances of **1** at 4.42 and 3.20 ppm disappeared, and new resonances at 3.87 and 3.02 ppm for the ethyl protons of **2** were observed (Fig. 4). In the ^{13}C NMR spectrum, particularly, the resonance of the thiocarbonyl carbon of **1** at 197.7 ppm disappeared, and a carbonyl carbon peak for **2** at 169.6 ppm was observed (Fig. S3). It has been reported that the thiocarbonyl group is oxidized by PAA to give a sulfine, followed by subsequent hydrolysis to give the carbonyl group.[25] Fluorescence measurements also supported the chemical transformation as the fluorescence spectrum of **1** in the presence of 20 equiv of PAA was almost identical to that of **2**. A time course plot for **1** in the presence of PAA showed that signaling was complete within 15 min after sample preparation (Fig. S4). The time plot also showed that the probe **1** was stable under the signaling conditions and did not exhibit any signaling with hydrogen peroxide and *tert*-butyl hydroperoxide (TBHP).

Finally, quantitative signaling of PAA by thioamide **1** was investigated. A concentration dependent response of **1** to PAA was observed with up to 10 equiv of PAA under the same experimental conditions (Fig. 5). The reaction of **1** with PAA appears not to proceed in a 1:1 stoichiometry, possibly due to the fact that PAA frequently contains varying amounts of hydrogen peroxide. That is a result of the synthesis of PAA from acetic acid as well as from decomposition of PAA via the reverse reaction. From this concentration dependent signaling profile, the detection limit of **1** for the determination of PAA in 90% aqueous acetonitrile was estimated to be 5.7 μM.[26]

In summary, a simple thioamide-based chemosignaling system for the widely used oxidant peracetic acid was developed. A thioamide derivative of anthracene **1** showed selective fluorescent turn-on type signaling behavior toward peracetic acid over common metal ions and anions. The developed probe **1** also exhibited significant discrimination for peracetic acid over hydrogen peroxide, a common contaminant of commercial peracetic acid. The probe **1** could be useful for the fluorescent determination of practical peracetic acid samples such as disinfectant in daily life and industrial applications, which typically contain varying amounts of hydrogen peroxide.

Acknowledgments

This work was supported by a fund from Korea Research Foundation of Korean government (2012-0002403).

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2012.05.101. These data include MOL files and InChiKeys of the most important compounds described in this article.

References and notes

1. (a) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515; (b) Jun, M. E.; Roy, B.; Ahn, K. H. *Chem. Commun.* **2011**, *47*, 7583.
2. Kohen, R.; Nyska, A. *Toxicol. Pathol.* **2002**, *30*, 620.
3. Lippert, A. R.; Van de Bittner, G. C.; Chang, C. J. *Acc. Chem. Res.* **2011**, *44*, 793.
4. Peng, T.; Yang, D. *Org. Lett.* **2010**, *12*, 4932.

5. Yang, Y. K.; Cho, H. J.; Lee, J.; Shin, I.; Tae, J. *Org. Lett.* **2009**, *11*, 859.
6. Zhao, X.; Zhang, T.; Zhou, Y.; Liu, D. *J. Mol. Catal. A* **2007**, *27*, 246.
7. Alvaro, J. E.; Moreno, S.; Dianez, F.; Santos, M.; Carrasco, G.; Urrestarazu, M. *J. Food Eng.* **2009**, *95*, 11.
8. Plnkernell, U.; Karst, U.; Cammann, K. *Anal. Chem.* **1994**, *66*, 2599.
9. Greenspan, F. P.; MacKellar, D. G. *Anal. Chem.* **1948**, *20*, 1061.
10. Di Furia, F.; Prato, M.; Scorrano, G.; Stivanello, M. *Analyst* **1988**, *113*, 793.
11. Pinkernell, U.; Effkemann, S.; Karst, U. *Anal. Chem.* **1997**, *69*, 3623.
12. Hua, M. Y.; Chen, H. C.; Tsai, R. Y.; Lin, Y. C. *Electrochim. Acta* **2011**, *56*, 4618.
13. (a) Pinkernell, U.; Lüke, H. J.; Karst, U. *Analyst* **1997**, *122*, 567; (b) Janotta, M.; Vogt, F.; Voraberger, H. S.; Waldhauser, W.; Lackner, J. M.; Stotter, C.; Beutl, M.; Mizaikoff, B. *Anal. Chem.* **2004**, *76*, 384.
14. Higashi, N.; Yokota, H.; Hiraki, S.; Ozaki, Y. *Anal. Chem.* **2005**, *77*, 2272.
15. Awad, M. I.; Oritani, T.; Ohsaka, T. *Anal. Chem.* **2003**, *73*, 2688.
16. Sanz, V.; de Marcos, S.; Galbán, J. *Anal. Chim. Acta* **2007**, *583*, 332.
17. Pettas, I. A.; Karayannis, M. I. *Anal. Chim. Acta* **2004**, *522*, 275.
18. Cha, S.; Hwang, J.; Choi, M. G.; Chang, S.-K. *Tetrahedron Lett.* **2010**, *51*, 6663.
19. Eor, S.; Hwang, J.; Choi, M. G.; Chang, S.-K. *Org. Lett.* **2011**, *13*, 370.
20. Maciejewski, A.; Steer, R. P. *Chem. Rev.* **1993**, *93*, 67.
21. By using similar desulfurization of thiocarbonyl functions, we have previously reported thiocoumarin and pyrene-thioamide based signaling probe for the practical oxidants of mCPBA[18] and Oxone, [19] respectively. We tried to clarify the relationship between the structural effects of the thiocarbonyl compounds on the reactivity toward the oxidants. However, the thio-compounds showed somewhat broad signaling behavior toward these oxidants depending on the measuring conditions as shown in Figure S1. In fact, we optimized the signaling conditions of **1** for a targeted oxidant by systematically varying the solvents and pH of the solution.
22. Kojima, K.; Fujita, M. *Toxicology* **1973**, *1*, 43.
23. Mücke, H. *Pharmazie* **1977**, *32*, 613.
24. (a) Fortnum, D. H.; Battaglia, C. J.; Cohen, S. R.; Edwards, J. O. *J. Am. Chem. Soc.* **1960**, *82*, 778; (b) Davies, D. M.; Deary, M. E. *Analyst* **1988**, *113*, 1477.
25. Corsaro, A.; Pistarà, V. *Tetrahedron* **1998**, *54*, 15027.
26. Shortreed, M.; Kopelman, R.; Kuhn, M.; Hoyland, B. *Anal. Chem.* **1996**, *68*, 1414.