

in the β' -silyl variant.² We have now demonstrated the stereochemical significance of this effect.

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to the A. P. Sloan Foundation for a Fellowship (1985-1989). We thank Dr. Scott R. Wilson for the X-ray crystallographic analyses of **9** and **12**.

Supplementary Material Available: A listing of crystal and positional parameters, bond lengths and angles, and torsional angles for **9** and **12** (23 pages). Ordering information is given on any current masthead page.

A Novel Oxidation of Internal Alkynes with Hydrogen Peroxide Catalyzed by Peroxotungsten Compounds

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Summary: Internal alkynes underwent a novel oxidation with aqueous hydrogen peroxide catalyzed by peroxotungsten compounds under two-phase conditions using chloroform as the solvent, giving α,β -epoxy ketones and α,β -unsaturated ketones as principal products. The epoxidation of α,β -unsaturated ketones by this catalyst-oxidant system appeared to involve the electrophilic attack of the peroxy species to the double bond.

In general, alkynes are converted into either 1,2-dicarbonyl compounds or carboxylic acids by permanganate,¹ ruthenium tetroxide,² osmium tetroxide,³ thallium nitrate,⁴ and metal peroxide like (HMPA)MoO(O₂)₂ in the presence of Hg(OAc)₂,⁵ as well as peroxy acids.⁶ Although hydrogen peroxide oxidation of acetylenes has been applied in fewer examples than peroxy acids,⁷ it has recently been reported that alkynes are oxidized to keto aldehydes or 1,2-dicarbonyl compounds with hydrogen peroxide catalyzed by NaMO₄⁸ or (cetylpyridinium)₃PMO₁₂O₄₀ (M: Mo or W)⁹ in combination with Hg(OAc)₂, which is an essential component to complete the oxidation.

In a previous paper, we showed that treatment of 12-tungstophosphoric acid or 12-molybdophosphoric acid in 35% H₂O₂ with cetylpyridinium chloride (CPC) in water easily produced peroxotungstophosphate (PCWP) or peroxomolybdophosphate (PCMP), respectively, containing the cetylpyridinium moiety as the counter cation.^{10,11} The PCWP and PCMP thus prepared stoichiometrically oxidized not only a variety of substrates (i.e., olefins to

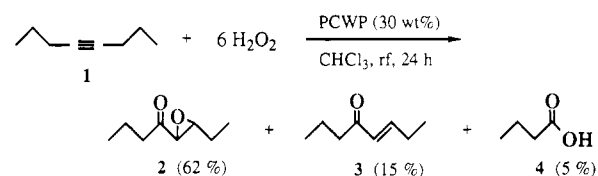
Table I. Oxidation of 4-Octyne (**1**) with 35% H₂O₂ Catalyzed by Several Peroxoheteropoly Compounds^a

run	catalyst	H ₂ O ₂	conv, %	yield, ^b %		
				2	3	4
1	PCWP	6	98	54	12	12
2 ^c	PCWP	6	98	32	—	73 (26) ^d
3	PCWP	3	92	47	13	7
4	PCWP	3 + 3 ^e	98	62	15	5
5	PHWP	6	80	25	30	5
6	5	6	76	26	27	4

^a **1** (3 mmol) was allowed to react with 35% H₂O₂ in the presence of catalyst (30 wt %) in CHCl₃ (7.5 mL) under refluxing for 24 h. ^b Determined by VPC analysis. Based on **1** used. Remainders were unidentified products. ^c *t*-BuOH was used as solvent. ^d Yield of propionic acid. ^e After 8 h, another portion of H₂O₂ was added.

epoxides, *sec*-alcohols to ketones, α,ω -diols to lactones, and 1,2-diols to carboxylic acids), but also catalyzed the oxidation of the same substrates with 35% H₂O₂.^{10,11}

We now find that the PCWP catalyzed a novel oxidation of internal alkynes with aqueous hydrogen peroxide to form α,β -epoxy ketones as the principal product (eq 1). This is the first catalytic transformation of internal alkynes into α,β -epoxy ketones.¹²



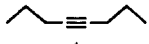
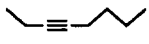
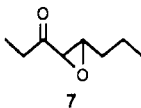
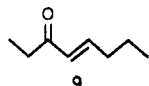

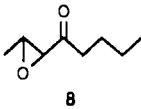
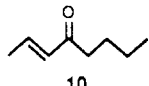
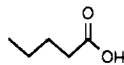
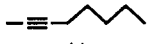
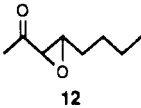
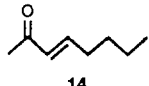
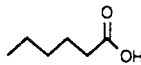
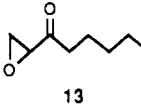
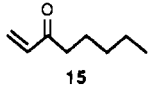
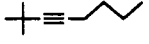
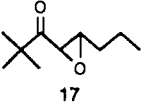
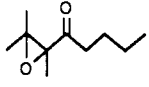

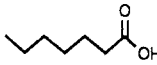
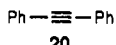


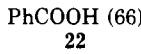
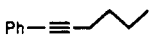
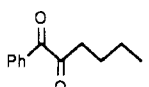


4-Octyne (**1**) was chosen as a model substrate and allowed to react with 35% H₂O₂ under the influence of several heteropoly compounds as catalysts (Table I).

The oxidation of **1** with 35% H₂O₂ (6 equiv) in the presence of a catalytic amount (30 wt %, 1.6 mol %) of PCWP under two-phase conditions using chloroform as the solvent produced 3,4-epoxy-5-octanone (**2**), 5-octen-4-one (**3**), and a small amount of cleaved product, butyric acid (**4**). The stereochemistry of **2** and **3** was determined by comparing their spectral data to those of authentic samples. Under homogeneous conditions using *tert*-butyl alcohol as the solvent, the yield of **2** decreased and a

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(12) It is reported that di-*tert*-butylacetylene is oxidized with MCPBA to form α,β -epoxy ketone through the 1,2-migration of methyl group.^{6b}

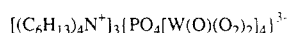
Table II. Oxidation of Alkynes with H₂O₂ by PCWP^a

run	alkyne	conv, %	product (yield, %) ^b			
1		98	2 (62) 3 (15) 4 (8)			
2		98	 (57)	 (2)	 (5)	
			 (11)	 (9)	 (8)	
3		98	 (40)	 (14)	 (13)	
			 (6)	 (7)		
4		34	 (13)	 (6)		
5		50			 (17)	
6		45		 (42)		
7 ^c		66		 (66)		
8		33		 (13)		
9		87	 (59)			

^a Alkyne (3 mmol), catalyst (30 wt %), H₂O₂ (18 mmol); CHCl₃ (7.5 mL), refluxing temperature, 24 h. ^b Based on alkynes used. Remainders were unidentified products. ^c *t*-BuOH was used as solvent.

considerable amount of cleaved products, 4 and propionic acid, were formed (run 2). When 6 equiv of hydrogen peroxide was used, 2 was obtained with satisfactory yield. The reaction with 3 equiv of hydrogen peroxide resulted in a lowering of the epoxy ketone 2 (run 3). The yield of 2 was improved by adding the 6 equiv of hydrogen peroxide in two portions (run 4).

An alternative peroxotungstophosphate, PHWP, prepared using tetrahexylammonium bromide in place of CPC, was also efficient for the oxidation of 1, though the selectivity was slightly different from that of PCWP. Recently, Venturello and co-workers reported that a novel tungsten peroxo complex, tetrahexylammonium tetrakis(diperoxotungsto)phosphate (5), is prepared by treatment of an aqueous hydrogen peroxide solution of tungstic acid and phosphoric acid with a benzene solution of tetrahexylammonium chloride (THAC), with the structure being defined by X-ray diffraction analysis.¹³



5

It is interesting to note that spectral data of the PHWP¹⁴ were in fair agreement with those of 5 prepared by the Venturello method.¹⁵ Further, the peroxo tungsten complex, which was prepared using CPC instead of THAC in the Venturello complex 5, was found to be identical with the PCWP obtained by our method.¹⁶ Thus, the PCWP, though differing in the counter cation, proved to be the same complex class as 5.

Peroxomolybdophosphate, PCMP, did not catalyze the present oxidation. The (cetylpyridinium)₃PW₁₂O₄₀-H₂O₂ system,¹⁰ which showed high activity for the epoxidation

(14) Analytical data of PHWP are as follows: IR (KBr) of PHWP [5]: 2954 [2953], 2858 [2858], 1485 [1463], 1378 [1377], 1090 [1093], 1057 [1056], 1034 [1034], 971 [975], 853 [853], 843 [842], 649 [648], 591 [590], 573 [573], 548 [548], 524 [524], 443 [442] cm⁻¹. The absorption bands of 843, 591 and 524 cm⁻¹ are assigned to O-O, (W-O-O)_{syn}, (W-O-O)_{as}, respectively.¹⁵

(15) Venturello, C.; D'Aloisio, R. *J. Org. Chem.* 1988, 53, 1553.

(16) In a previous paper, the active oxygen contained in PCWP¹⁰ and PCMP¹¹ was estimated to 1.1-1.5 and 2.3-2.5 mmol/g, respectively, by normal iodometry. However, it has been pointed out that this method does not give a satisfactory active oxygen value due to the interference of onium moiety.¹⁵ Thus, the active oxygen value of PCWP and PCMP was reexamined by using the improved iodometric method proposed by Venturello¹⁵ and corrected to 3.6-3.8 mmol/g for PCWP and 4.4-4.7 mmol/g for PCMP, respectively.

(13) Venturello, C.; D'Aloisio, R.; Bart, J. J.; Ricci, M. *J. Mol. Catal.* 1985, 32, 107.

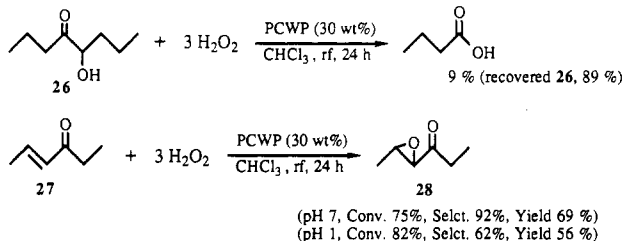
of olefins, was inadequate for the oxidation of alkynes.

Table II shows the oxidations of several alkynes by the PCWP-H₂O₂ system.

Although unsymmetrical internal alkynes such as 3-octyne (**6**) afforded all possible isomers, **7** and **9** were formed in preference to **8** and **10**, respectively (run 2). The oxidation of 2,2-dimethyl-3-octyne (**16**) bearing a branched methyl group afforded a complex mixture of products, but a normal epoxy ketone **17** (13%) was obtained together with a rearranged **18** (6%), in which the methyl group migrated to the adjacent carbon atom. A similar 1,2-methyl migration has been observed in the epoxidation of di-*tert*-butylacetylene with MCPBA.^{6b} Due to the poor selectivity of the reaction, α,β -unsaturated ketone was difficult to be isolated.

In the oxidation of alkynes involving phenyl group, 1,2-dicarbonyl compounds were formed in fair yields. For instance, diphenyl acetylene (**20**) was selectively oxidized to benzyl (**21**), though the conversion was low (45%). However, the same oxidation in *t*-BuOH resulted exclusively in a cleaved product, benzoic acid (**22**), without formation of **21**. The reaction of alkylaryl acetylene, **23**, took place with difficulty to afford the 1,2-dicarbonyl compound, **24**, in low yield (run 8). Terminal alkynes were cleaved to carboxylic acids (runs 5 and 9).

In order to obtain information about the reaction path, 5-hydroxy-4-octanone (**26**) and an α,β -unsaturated ketone, **27**, were oxidized by the PCWP-H₂O₂ system under the same conditions as the alkynes (eq 2).



The reaction of **26** gave a small amount of butyric acid, but most of **26** was recovered unchanged. This finding suggests that the α,β -unsaturated ketone obtained in the oxidation of alkynes is not formed via dehydration of α -hydroxy ketone, but by an alternative route that remains uncertain.

On the other hand, **27** afforded the corresponding epoxide, **28**, in 69% yield (75% conversion and 92% selectivity). Conventionally, such an epoxidation is carried out with the sodium salt of hydrogen peroxide (NaOOH)¹⁷ or the sodium salt of *tert*-butylhydroperoxide (NaOOBu^t),¹⁸ and the reaction is believed to proceed via nucleophilic addition of the hydroperoxide anion at the β -carbon followed by intramolecular displacement of hydroxide ion.¹⁹ However, the present epoxidation of an α,β -unsaturated ketone by the PCWP-H₂O₂ appears to proceed via a different path than that of the alkaline hydrogen peroxide, NaOOH, i.e., it seems likely that the PCWP-catalyzed epoxidation proceeds via an electrophilic attack of peroxy oxygen to the double bond of **27**. This is because the epoxidation of **27** to **28** was effected even under the two-phase system whose aqueous phase was adjusted to pH 1 with sulfuric acid (eq 2). Under such a condition the epoxidation with nucleophilic species such as Q⁺OOH⁻ (Q⁺: cetylpyridinium ion) may be excluded, since the existence of such a species in the acidic medium is unlikely.²⁰ Furthermore, the epoxidation of the simple olefin like 1-octene (**29**) to 1,2-epoxyoctane (**30**) by the PCWP-H₂O₂ system, where the reaction involves an electrophilic attack of the peroxy species to the double bond, was completed more rapidly than that of the electron deficient olefin **27** under the same reaction conditions, i.e., **29** was epoxidized to **30** in almost quantitative yield (>98%) within 3 h, while the yield of **28** from **27** was 69% even after 24 h.

It is important to note that the stoichiometric reaction of **27** with PCWP in chloroform gave **28** in 49% yield without any side product. This finding indicates that the peroxy oxygen involving the PCWP possesses a strong electrophilicity which can even epoxidize an electron-deficient olefin such as **27**, and that α,β -unsaturated ketone is a possible precursor of an epoxy ketone.

Although the detailed reaction path is uncertain, the present epoxidation of acetylenes has been of considerable interest from the synthetic and mechanistic points of view as a new class of oxidation by aqueous hydrogen peroxide.

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(20) No product was obtained under basic conditions, since PCWP prompted a rapid decomposition of H₂O₂.

Chemical Synthesis of Oligoribonucleotides Containing 2-Aminopurine: Substrates for the Investigation of Ribozyme Function

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Summary: The chemical synthesis of a fully protected ribonucleoside phosphoramidite, containing 2-aminopurine as the base component, and its incorporation into short oligoribonucleotides as substrates for an engineered ribozyme from *Tetrahymena* is described.

The ability to chemically synthesize RNA oligomers has made it possible to incorporate modified or unnatural base

analogues into short RNA chains. These analogues will be useful for studying details of molecular structure in a number of RNA-protein systems such as tRNA-synthetase interactions, as well as the mechanisms used by various RNA catalysts.^{1,2} Analogues of naturally occurring deoxyribonucleotides have recently been prepared for the study of protein-DNA interactions and the development

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