Chem. Pharm. Bull.
29(1) 35—42 (1981)

The Reactions of Cholesteryl Acetate with *tert*-Butyl Hydroperoxide and Molybdenum Complexes[1]

Michiya Kimura* and Toshiki Muto

Faculty of Pharmaceutical Sciences, Hokkaido University,[2] Nishi-6-chome, Kita-12-jo, Kita-ku, Sapporo, 060, Japan

(Received May 26, 1980)

Epoxidation and allylic oxidation of cholesteryl acetate were studied with *tert*-butyl hydroperoxide (^{t}BuOOH) in the presence of molybdenum complexes. 1. Among the acetylacetonates of various transition metals, $MoO_2(acac)_2$ was unique in that it greatly facilitated the formation of an epoxide as well as its further conversion to the B-nor-5-carboxaldehyde. Since similar results were obtained in the presence of $Mo(CO)_6$ or $MoCl_5$, the effect seems to be independent of the valency and the ligand of the molybdenum catalyst. 2. The reactions using $Mo(CO)_6$ were carried out in various solvents, and it was found that epoxidation or allylic oxidation occurred almost exclusively in benzene or in *tert*-butyl alcohol (^{t}BuOH), respectively. The reaction probably proceeds by a radical mechanism in ^{t}BuOH, but not in benzene. In acetonitrile as a solvent, on the other hand, homolytic and heterolytic decomposition of ^{t}BuOOH seemed to occur simultaneously.

Keywords——allylic oxidation; cholesteryl acetate; epoxidation; metal acetylacetonate; molybdenum complex-catalyzed oxidation; radical pathway; rotational isomer; solvent effect; stilbene

In the preceding paper, we reported the epoxidation and allylic oxidation of cholesteryl acetate (**1**) with various hydroperoxides (ROOH: R=H, ethyl, iso-propyl, *tert*-butyl, and cumenyl) and metal complexes such as tris (acetylacetonato)iron (III), Fe $(acac)_3$, and hexacarbonylmolybdenum, $Mo(CO)_6$.[1] The iron chelate, in both benzene and acetonitrile media, catalyzed the characteristic β-epoxidation[3] and oxy-functionalization at C(7) of **1** in these reactions. In contrast, epoxidation occurred exclusively when these reactions were catalyzed by $Mo(CO)_6$ in a non-polar medium, benzene. Formation of the epoxide, 5,6-epoxycholestan-3β-ol acetate (**2**), and allylic oxidation occurred simultaneously, as with the iron catalysis, when the non-polar solvent was replaced by acetonitrile. In all cases examined, the molybdenum catalyst failed to show β-stereoselectivity in epoxidation with alkyl hydroperoxide.[1] These phenomena prompted us to investigate further the reactions catalyzed by molybdenum. In this study, we observed the reactions of **1** with *tert*-butyl hydroperoxide and various metal acetylacetonates, and examined the effects of metal valency, ligand group, and solvent, as well as radical scavenger, on the title reactions. The modes of formation of the oxidation products are discussed briefly.

Results and Discussion

Reactions using Various Metal Acetylacetonates

In the reactions of olefins with organic peroxides, the extents of allylic oxidation and epoxidation depend on the metallic catalyst.[4] Indictor and Brill studied the reactions of four olefins with *tert*-butyl hydroperoxide (^{t}BuOOH) using sixteen metal acetylacetonates and reported that Cr(III), MoO_2(II), VO(II), and V(III) complexes gave quantitative yields of epoxide from 2,4,4-trimethyl-1-pentene.[5] The hydroperoxide, ^{t}BuOOH, has been widely used in mechanistic studies.[6] We examined the reactions of cholestryl acetate (**1**) with ^{t}BuOOH and the acetylacetonates of transition metal ions such as TiO(II), VO(II), Cr(III), Mn(II, III), Fe(III), Co(II, III), Ni(II), Cu(II), MoO_2 (II), and Ce(III). In the absence of

Table I. Reactions of Cholesteryl Acetate with *tert*-Butyl Hydroperoxide in the Presence of Various Metal Acetylacetonates

Metal	Conversion (%)	Yield (%) Epoxide **2**	C(7)=O **3**	C(7)–OH **4**	C(7)–OO^{t}Bu **5**	C(5)–CHO **6**	Allylic oxidation (%)
TiO(II)	73	4	25	8	36	0	95
VO(II)	55	8	26	10	11	0	85
Cr(III)	64	5	52	3	4	0	92
Mn(II)	26	1	11	7	7	0	96
Mn(III)	29	3	10	9	7	0	90
Fe(III)	100	13	74	3	11	0	87
Co(II)	24	3	12	7	2	0	88
Co(III)	74	3	43	5	23	0	96
Ni(II)	81	4	38	0	39	0	95
Cu(II)	97	5	83	6	5	0	95
Ce(III)	49	5	24	10	10	0	90
MoO_2(II)	100	34	0	7	0	59	7

Figures are the means of three runs in benzene at 80° for 24 hr.

metal acetylacetonate no reaction occurred under the conditions used. Table I shows the product distribution in these reactions. 7-*tert*-Butylperoxycholest-5-en-3β-ol acetate (**5**) was regarded as an intermediate in the formation of the major products, 3β-acetoxycholest-5-en-7-one (**3**) and 3β-acetoxycholest-5-en-7-ols (**4**), in the same reaction of **1** catalyzed by Fe(acac)$_3$.$^{7)}$ When freshly prepared **5** was similarly treated with ^{t}BuOOH, in the presence of Cr(acac)$_3$, Co(acac)$_2$, or MoO_2(acac)$_2$, the results were the same as with Fe(acac)$_3$; there was no detectable formation of **2**. Among the metal acetylacetonates examined herein, the molybdenum complex was unique in that it greatly facilitated the epoxidation and retarded the allylic oxidation in the title reaction.

Reactions using Different Types of Molybdenum Complexes

Molybdenum catalysts are well known to facilitate epoxidation in the reaction of an olefin with hydroperoxide.$^{8c)}$ The reactions of **1** with ^{t}BuOOH were carried out by using molybdenum complexes with different ligand groups and different oxidation states of the metal, and the results are shown in Table II.$^{9)}$ Epoxidation occurred exclusively and the ratio of β-epimer to the total epoxides (**2**) was almost constant (0.50—0.55) in these reactions. Thus, the reactions seemed to be unaffected by the valency and ligand of molybdenum.

Table II. Epoxidation of Cholesteryl Acetate by Mo·Complex-^{t}BuOOH Systems

Mo·Complex	Conversion (%)	Yield (%) Epoxide **2**	C(5)-CHO **6**	Ratio of epimer 2 ($\beta/\alpha+\beta$)
$MoO_2(acac)_2$	100	94	6	0.55
$MoCl_5$	65	65	0	0.55
$Mo(CO)_6$	100	97	3	0.50

Figures are the means of three runs in benzene at 80° for 24 hr.

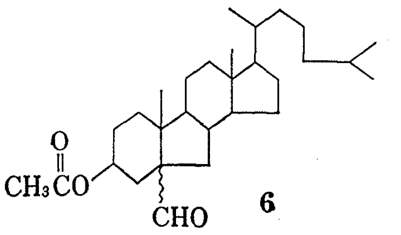
Tolstikov *et al.* reported the epoxidation of **1** in the *tert*-pentyl hydroperoxide–molybdenum pentachloride–benzene system, giving an epimeric ratio (α: β) of 1: 1, and proposed the participation of a neighboring acetoxyl group in the β-epoxidation.$^{10a)}$ The use of molybdenum pentoxide (MoO_5), in contrast, predominantly gave the α-epoxide (α: β=4: 1) from **1**,$^{10b)}$ as in the well-documented epoxidation (for instance, α: β=7: 3$^{10c)}$) by organic peracids. In

NII-Electronic Library Service

the reaction of ^{t}BuOOH and $MoO_2(acac)_2$, the intermediate was proposed to be peroxomolybdate ($MoO_3 \cdot 2H_2O$ or $H_2MoO_4 \cdot H_2O$),[11a] which is known to give an epoxide by a mechanism similar to that of the organic peracid.[11b] The metal hydroperoxide complex, $[M^{n+} \cdot ROOH]$, was, on the other hand, regarded as an epoxidizing species in the reaction of olefin with the molybdenum complex-alkylhydroperoxide system.[12] The formation of peroxomolybdate was inhibited by a radical scavenger[11a] but the title reaction in benzene gave the epoxide by a non-radical mechanism, as described later in this paper. Thus, it seems plausible that, in the reactions of **1** with ^{t}BuOOH and the molybdenum complexes in benzene, decomposition of the ligand moiety and/or oxidation of the metal ion by the hydroperoxide result in the formation of a common peroxidative species, which may facilitate the β-epoxidation with participation of the C(3)-acetoxyl group.

Formation of the Aldehyde (6) from the Epoxide (2)

The reaction of **1** with the $MoO_2(acac)_2$–^{t}BuOOH–benzene system gave an oily product (**6**), proton magnetic resonance (PMR) in $CDCl_3$ δ: 9.57 and 9.74 (C(5)–CHO) and infrared (IR) spectrum $\nu_{\max}^{\text{film}}$ cm^{-1}: 2720 (CHO), 1700—1740 (C=O), as shown in Tables I and II. From the spectral data, the oil appeared to be a mixture of 3β-acetoxy-B-nor-5α- and -5β-cholestane-5-carboxaldehydes[1] (Fig. 1). The aldehyde (**6**) was also found to be produced as an epimeric mixture when the freshly prepared α- and β-epoxides (**2**) came into contact with the $Mo(CO)_6$-^{t}BuOOH–benzene system. In contrast to the molybdenum catalysts,[1] no other transition metal catalyzed such formation of **6**, as shown in Table I. The rearrangement of steroidal 5,6-epoxides was reported to be induced by Lewis acids.[13] It is known that molybdenum can act as a strong Lewis acid.[6] The title reaction is, therefore, likely to yield **6** *via* **2** when catalyzed by the molybdenum complex.



6

Fig. 1

Solvent Effects

The title reactions, with $Mo(CO)_6$ as a catalyst, were carried out in various solvents such as benzene, acetonitrile, and *tert*-butyl alcohol (^{t}BuOH) and the results are summarized in Table III. Epoxidation and allylic oxidation were exclusive or predominant in benzene and ^{t}BuOH, respectively. Both types of oxidation proceeded in acetonitrile medium. Formation of a metal-alkyl hydroperoxide complex was proposed to be responsible for the epoxidation.[8b] Acetonitrile under reflux is known to displace three carbonyl ligands from $Mo(CO)_6$.[14] The complexation of molybdenum with ^{t}BuOOH may, therefore, be interfered with the solvent,

Table III. Effects of Solvent and Radical Scavenger on the Product Distribution

Solvent	Radical scavenger	Conversion (%)	Yield (%)				Allylic oxidation (%)
			2 (β/α+β)	3	4	5	
PhH	–	100	97(0.50)	0	0	0	0
	+	100	97(0.50)	0	0	0	0
CH_3CN	–	36	21(0.44)	8	4	3	42
	+	14	14(0.41)	0	0	0	0
^{t}BuOH	–	90	11(0.78)	66	2	11	88
	+	0	0	0	0	0	0

Figures are the means of three runs under reflux for 24 hr.

NII-Electronic Library Service

resulting in greatly decreased conversion of the substrate and the occurrence of allylic oxidation. Solvent effect was also observed on the stereoselectivity in the epoxidation of **1**, altering the epimer distribution in the epoxide mixture (**2**), as shown in Table III.

Effects of a Radical Scavenger

Radicals such as ^{t}BuO· and ^{t}BuOO· are known to be produced from ^{t}BuOOH through its metal-catalyzed(eqs. 1 and 2)[15] and radical-induced(eqs. 3 and 4)[16] decomposition:

$$M^{n+} + {}^{t}BuOOH \longrightarrow M^{(n+1)+} + {}^{t}BuO\cdot + OH^{-} \quad (1)$$

$$M^{(n+1)+} + {}^{t}BuOOH \longrightarrow M^{n+} + {}^{t}BuOO\cdot + H^{+} \quad (2)$$

$${}^{t}BuO\cdot + {}^{t}BuOOH \longrightarrow {}^{t}BuOH + {}^{t}BuOO\cdot \quad (3)$$

$$2{}^{t}BuOO\cdot \longrightarrow 2{}^{t}BuO\cdot + O_2 \quad (4)$$

Homolytic decomposition of ^{t}BuOOH by molybdenum catalyst is known to proceed in ^{t}BuOH medium.[17] Olefins can, generally, be epoxidized by an alkylperoxy radical (ROO·).[18] The radical scavenger, 2,6-di-*tert*-butyl-4-methylphenol (BHT), completely inhibited the reaction of **1** with ^{t}BuOOH and $Mo(CO)_6$ in ^{t}BuOH, as expected. In contrast, BHT did not affect the reaction of **1** with the same reagent system in benzene medium. No allylic oxidation occurred in acetonitrile medium containing the same reaction mixture, but **2** was the only product in a reduced yield. These results, summarized in Table III, indicate that the title reaction in benzene gave the epoxide (**2**) by a non-radical mechanism, while the reaction in ^{t}BuOH proceeded *via* a radical pathway, and homolytic and heterolytic decompositions of ^{t}BuOOH occurred simultaneously in acetonitrile.

Epoxidation of Stilbenes

In a previous study of this series, the epoxidation reactions of geometrically isomeric stilbenes were examined in order to investigate the homolytic mode of the reaction.[19] Forma-

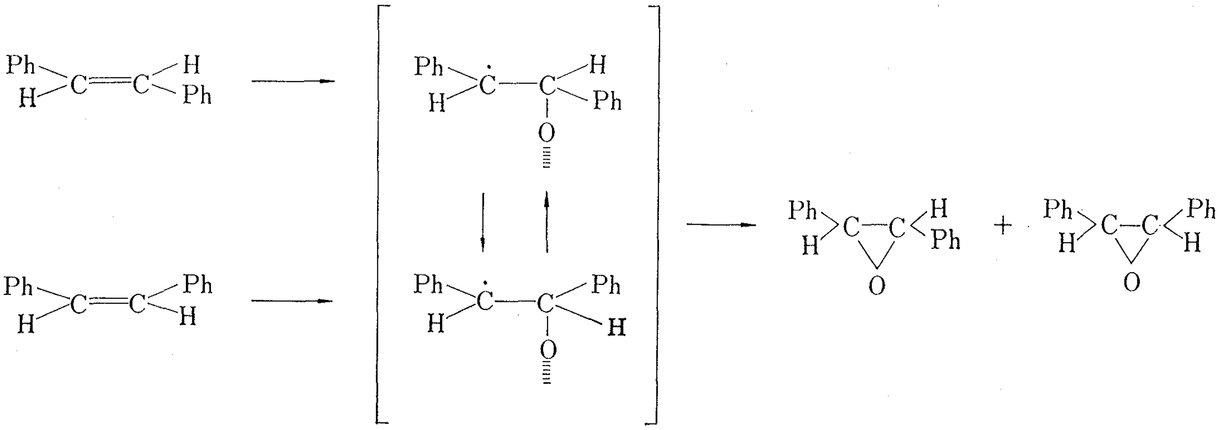


Chart 1

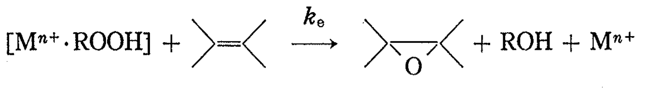
TABLE IV. Epoxidation of Stilbenes by the $Mo(CO)_6$-^{t}BuOOH System

Solvent	Stilbene	Yield of epoxide (%)	*trans*: *cis*
PhH	*trans*	100	100: 0
	cis	84	0:100
CH_3CN	*trans*	66	100: 0
	cis	10	73: 27
^{t}BuOH	*trans*	87	94: 6
	cis	42	88: 12

Figures are the means of three runs under reflux for 24 hr.

tion of a radical intermediate, which can rotate around the C–C bond and thus attain conformational equilibrium, should result in the two stilbenes giving epoxide mixtures with similar isomeric ratios (Chart 1). The reactions of *cis*- as well as *trans*-stilbenes were carried out with an $Mo(CO)_6$-^tBuOOH system in various solvents and the results are summarized in Table IV. The olefin in benzene gave its epoxide with retention of geometry. The same reactions of these olefins in ^tBuOH gave, in contrast, similar isomeric ratios (9: 1) in the epoxide mixtures. Metal-catalyzed oxidation of olefins with organic hydroperoxides can be rationalized in terms of a scheme involving competing homolytic decomposition of a catalyst-hydroperoxide complex (eq. 7) and its reaction with the olefin (eq. 6):6,8,11b,12,20)

$$M^{n+} + ROOH \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} [M^{n+}\cdot ROOH] \qquad (5)$$



(6)

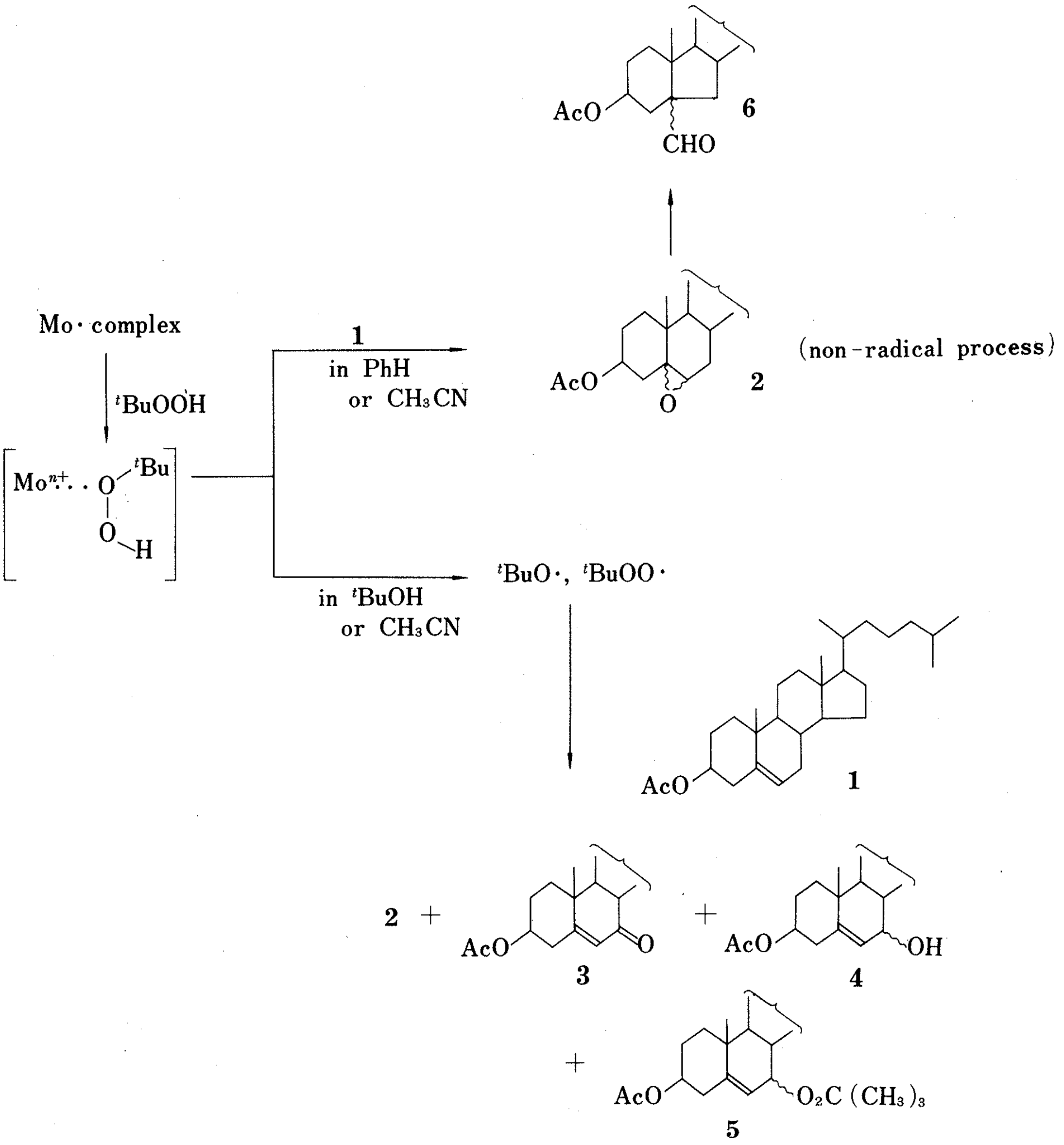


Chart 2

$$[\mathrm{M}^{n+}\cdot\mathrm{ROOH}] \xrightarrow{k_d} \mathrm{M}^{(n-1)+} + \mathrm{ROO}\cdot + \mathrm{H}^+ \tag{7}$$

$$\mathrm{M}^{(n-1)+} + \mathrm{ROOH} \xrightarrow{\text{fast}} \mathrm{M}^{n+} + \mathrm{RO}\cdot + \mathrm{OH}^- \tag{8}$$

Factors affecting k_e and k_d are considered to include oxidation potential and Lewis acidity. Since these factors are known to be affected by the ligand group,[11b] the coordinating ability of the solvent to the metal catalyst may also affect the rates of the reactions (eqs. 6 and 7). Thus, it seems reasonable that k_e is much larger than k_d in benzene, which is inert to metal ions, and thus allows the exclusive epoxidation of **1** (Table III) as well as stilbenes (Table IV) by a non-radical mechanism. In contrast, the radical reactions proceeded in ^{t}BuOH which is known to coordinate molybdenum[8,12] and thus may facilitate the homolytic decomposition of ^{t}BuOOH, resulting in epoxidation (Tables III and IV) and allylic oxidation (Table III). In acetonitrile medium, the reactions seemed to proceed by both radical and non-radical mechanisms.

Conclusion

From these results the reaction of cholesteryl acetate (**1**) with ^{t}BuOOH in the presence of molybdenum complex may be rationalized in terms of the scheme shown in Chart 2.

Experimental

General Methods——PMR spectra were measured with a JEOL JNM-FX 100 FT spectrometer at 100 MHz with tetramethylsilane as an internal standard. Abbreviations used: s=singlet and m=multiplet. IR spectral measurements were run on a JASCO IRA-2 spectrometer. Melting points were taken on a micro hot-stage apparatus and are uncorrected. Thin-layer chromatography (TLC) was carried out on silica gel (Wako-gel B5F) plates developed with PhH/AcOEt (19: 1) and stained with 10% H_2SO_4 with heating at about 130° for 5 min.

Determination of the product distribution and the epimeric ratio of the epoxide (**2**) in the reaction mixture were carried out by the reported method using an Iatron TFG-10 Thinchrograph and PMR spectrometer, respectively.[1]

Materials——Metal acetylacetonates (Dozin Yakkagaku Lab.), $Mo(CO)_6$ (Strem Chim. Inc.), $MoCl_5$ (Wako Pure Chem. Ind. Ltd.), stilbenes (Aldrich Chem. Comp. Inc.), and BHT (Wako Pure Chem. Ind. Ltd.) were obtained commercially and used without purification. *tert*-Butyl hydroperoxide (Nakarai Chem. Co.) was purified by distillation under reduced pressure and its purity was determined by iodometry. Cholesteryl acetate (**1**, mp 117—118°, lit.[21a] 116°) was prepared by the cited method. Authentic specimens of 3β-acetoxycholest-5-en-7-one (**3**, mp 154—156°, lit.[21b] 157—158°), cholest-5-ene-$3\beta,7\alpha$-diol 3-monoacetate (**4a**, mp 136—139°, lit.[21c] 139°), and cholest-5-ene-$3\beta,7\beta$-diol 3-monoacetate (**4b**, mp 109—110°, lit.[21d] 110—111°) were prepared by the cited methods. $5\alpha,6\alpha$- and $5\beta,6\beta$-Epoxycholestan-3β-ol acetates (**2a**, mp 98—99°, lit.[21e] 96—97° and **2b**, mp 111—112°, lit.[21e] 112—113°, respectively) were prepared by the reaction of **1** with the $Mo(CO)_6$–^{t}BuOOH system in benzene and purified by preparative TLC.

Reaction of Cholesteryl Acetate with Metal Acetylacetonate and *tert*-Butyl Hydroperoxide (Table I)——A benzene solution (5 ml) of cholesteryl acetate (**1**, 0.130 mmol), metal acetylacetonate (0.012 mmol), and ^{t}BuOOH (0.98 mmol) was refluxed under an Ar atmosphere for 24 hr. The reaction mixture was diluted with ether and the solution was washed with saturated aqueous Na_2SO_3, sat. aq. NaCl, dried on anhydrous Na_2SO_4, filtered, and finally evaporated to dryness. The residue was subjected to TLC and the product distribution was determined by the FID method.[1]

Reaction of 7-*tert*-Butylperoxycholest-5-en-3β-ol Acetate (5) with *tert*-Butyl Hydroperoxide in the Presence of Dioxobis(acetylacetonato)molybdenum (VI)——A benzene solution (5 ml) of the dialkylperoxide (**5**, 50 mg, 0.12 mmol), $MoO_2(acac)_2$ (4.01 mg, 0.012 mmol), and ^{t}BuOOH (0.1 ml, 0.98 mmol) was refluxed for 24 hr under an Ar atmosphere. The reaction mixture was worked up as described above, and the residue was subjected to TLC. The ketone (**3**) and an unidentified substance were the main products, and no indication of the formation of the epoxide (**2**) in question was obtained by the TLC-FID method.[1]

Reaction of Cholesteryl Acetate with *tert*-Butyl Hydroperoxide and Molybdenum Complex (Table II)——A benzene solution (5 ml) of **1** (0.13 mmol), ^{t}BuOOH (0.98 mmol), and molybdenum complex [$Mo(CO)_6$ (0.652×10^{-3} mmol), $MoCl_5$ (3.3×10^{-3} mmol), or $MoO_2(acac)_2$ (1.9×10^{-3} mmol)] was refluxed under an Ar atmosphere for 24 hr. The reaction mixture was worked up as described above, and the residue was subjected to preparative TLC to obtain the epoxide (**2**) fraction. The amount of **2** extracted from the fraction was 46 mg, 30 mg, or 41 mg from the $Mo(CO)_6$-, $MoCl_5$-, or $MoO_2(acac)_2$-catalyzed reaction mixture, respectively.

Effect of Solvent on the Reaction (Table III)——A mixture of **1** (0.128 mmol), $Mo(CO)_6$ (0.652×10^{-3}

mmol), ${}^tBuOOH$ (0.98 mmol), and organic solvent (5 ml) was refluxed under an Ar atmosphere for 24 hr. The reaction mixture was then treated as described above. The amount of **2** thus obtained was 46 mg, 11 mg, or 6 mg from the reaction mixture dissolved in benzene, CH_3CN, or ${}^tBuOH$, respectively.

Effect of Radical Scavenger on the Reaction (Table III)——BHT (0.59 mmol) was added to a mixture of **1** (0.128 mmol), $Mo(CO)_6$ (0.652×10^{-2} mmol), ${}^tBuOOH$ (0.98 mmol), and organic solvent (5 ml). The solution was refluxed under an Ar atmosphere for 24 hr, and the reaction mixture was treated as described above. The amounts of **2** thus obtained were 44 mg and 7 mg from the reaction mixtures dissolved in benzene and CH_3CN, respectively. No reaction occurred in ${}^tBuOH$.

Epoxidation of Stilbene with Hexacarbonylmolybdenum and *tert*-Butyl Hydroperoxide (Table IV)——Stilbene (0.26 mmol), $Mo(CO)_6$ (0.134×10^{-2} mmol), and ${}^tBuOOH$ (1.96 mmol) were dissolved in organic solvent (10 ml) and the reaction mixture was refluxed under an Ar atmosphere for 24 hr, then worked up as usual. Yields of the epoxides were determined by the TLC-FID method.[1] The epimeric ratio of the epoxide mixture was determined by using the PMR peak area due to the proton adjacent to the epoxidized carbon atom.

3β-Acetoxy-B-nor-5ξ-cholestane-5-carboxaldehyde (6)——A benzene solution (50 ml) of **1** (500 mg, 1.2 mmol), $MoO_2(acac)_2$ (40.1 mg, 0.12 mmol), and ${}^tBuOOH$ (1 ml, 9.8 mmol) was refluxed under an Ar atmosphere for 24 hr. The reaction mixture was treated as described above and subjected to preparative TLC. An oil (290 mg) was obtained from the fraction of *Rf* 0.25. IR ν_{max}^{film} cm^{-1}: 2720 (CHO), 1700—1740 (C=O). *Anal.* Calcd for $C_{29}H_{48}O_3 \cdot H_2O$: C, 75.27; H, 10.91. Found: C, 75.09; H, 10.64. PMR (in $CDCl_3$) δ: 0.68 [3H, s, C(13)–CH_3], 0.94 [3H, s, C(10)–CH_3], 2.01 [3H, s, C(3)β–Ac], 5.02 [m, C(3)α–H],[22] 5.33 [m, C(3)α–H],[22] 9.57 [s, C(5)ξ–CHO][22] 9.74 [s, C(5)ξ-CHO].[22]

Methyl 3β-acetoxy-B-nor-5ξ-cholestane-5-carboxylate: A 95% AcOH solution (1 ml) of **6** (40 mg) and CrO_3 (10 mg) was allowed to stand overnight at room temperature, then AcOH was evaporated off *in vacuo* and Et_2O (80 ml) was added to the reaction mixture. The ether solution was worked up as usual and the oily residue (47 mg) obtained was dissolved in Et_2O (1 ml). Diazomethane (0.5 ml) was added to the ice-cold ether solution and the reaction mixture was allowed to stand for 1 hr. The solution was worked up as usual to obtain the residue which was purified by preparative TLC, giving an oily product (34.5 mg). *Anal.* Calcd for $C_{30}H_{50}O_4 \cdot H_2O$: C, 73.12; H, 10.64. Found: C, 72.56; H, 10.11. MS *m/e*: 414 ($M^+ - AcOH$). IR ν_{max}^{film} cm^{-1}: 1735 (C=O), 1245 (CO–O–C). PMR (in $CDCl_3$, measured with a Hitachi R-24A machine at 60 MHz) δ: 0.67 [3H, s, C(13)–CH_3], 1.03 [3H, s, C(10)–CH_3], 2.00 [3H, s, C(3)β–Ac], 3.55 [3H, s, C(5)ξ–$COOCH_3$], 5.02 [m, C(3)α–H],[22] 5.33 [m, C(3)α–H].[22]

A benzene solution (5 ml) of 5,6-epoxycholestan-3β-ol acetate (**2**, 0.12 mmol), $Mo(CO)_6$ [or $MoO_2(acac)_2$, 1.21×10^{-2} mmol], and ${}^tBuOOH$ (0.98 mmol) was refluxed under an Ar atmosphere for 24 hr. The reaction mixture was worked up as usual and the oily residue was purified by preparative TLC. Yields: 28 and 31 mg from α- and β-epoxides, respectively. In the PMR spectrum of the epimeric mixture of **6** derived from α-epoxide, the ratio of the peak area at 9.57 to that at 9.74 ppm was 7: 1. The product of the same reaction of β-epoxide, on the other hand, gave a ratio of 3: 1.

Acknowledgement We wish to thank Mr. A. Onodera for his technical assistance. A part of this work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan, for which we are grateful.

References and Notes

1) This paper constitutes Part XIII of a series entitled "Metal Ion-catalyzed Oxidation of Steroids"; Part XII: M. Kimura and T. Muto, *Chem. Pharm. Bull.*, **28**, 1836 (1980).
2) Location: *Nishi-6-chome, Kita-12-jo, Kita-ku, Sapporo, 060, Japan.*
3) M. Tohma, T. Tomita, and M. Kimura, *Tetrahedron Lett.*, **1973**, 4359.
4) G. Sosnovsky and D.J. Rawlinson, "Organic Peroxides," Vol. II, ed. by D. Swern, John Wiley and Sons, Inc., New York, 1971, pp. 195—211.
5) N. Indictor and W.F. Brill, *J. Org. Chem.*, **30**, 2074 (1965).
6) R.A. Sheldon and J.A. van Doorn, *J. Catal.*, **31**, 427 (1973) and references cited therein.
7) M. Kimura and T. Muto, *Chem. Pharm. Bull.*, **27**, 109 (1979).
8) *a*) M.N. Sheng and J.J. Zajacek, *J. Org. Chem.*, **35**, 1839 (1976); *b*) T.N. Baber III, G.T. Mains, M.N. Sheng, and T.G. Zajacek, *ibid.*, **38**, 1145 (1973); *c*) G.R. Howe and R.R. Hiatt, *ibid.*, **36**, 2493 (1971).
9) Reduction in the amount of the molybdenum catalyst was essential to minimize the transformation of the epoxide (**2**) to the aldehyde (**6**). Since the $Mo(CO)_6$ catalyst is readily soluble and does not interfere the product analysis, the $Mo(CO)_6$–${}^tBuOOH$–benzene system was most convenient.
10) *a*) G.A. Tolstikov, V.P. Yur'ev, J.A. Gailyunus, and U.M. Dzhemilev, *Zh. Obshch. Khim.*, **44**, 215 (1974); *b*) G.A. Tolstikov, U.M. Dzhemilev, V.P. Yur'ev, and S.R. Razfikov, *Dokl. Akad. Nauk SSSR.*, **208**, 376 (1973); *c*) M. Kimura and T. Muto, unpublished data.
11) *a*) J. Koloustrian, L. Lena, and J. Metzger, *Tetrahedron Lett.*, **1975**, 599; *b*) R.A. Sheldon and J.K. Kochi, *Adv. Catal.*, **25**, 272 (1976).

NII-Electronic Library Service

12) P.M. Henry and G.L. Lange, "The Chemistry of Double-bonded Functional Groups," Part 2, ed. by S. Patai, John Wiley and Sons, Inc., London, 1977, p. 1028.
13) T.G. Halsall, E.R.H. Jones, E.L. Tan, and G.R. Chaudhry, *J. Chem. Soc.* (*C*), **1966**, 1374; J.W. Blunt, M.P. Hartshorn, and D.N. Kirk, *ibid.*, **1968**, 635.
14) J.P. Cardlin, K.A. Taylor, and D.T. Thompson, "Reactions of Transition-Metal Complexes," Elsevier Publishing Co., Amsterdam, 1968, p. 358.
15) J.K. Kochi, "Free Radicals," Vol. I, ed. by J.K. Kochi, John Wiley and Sons, Inc., New York, 1973, p. 591.
16) R. Hiatt, J. Chipsham, and T. Visser, *Can. J. Chem.*, **42**, 2754 (1964).
17) R.A. Sheldon, J.A. van Doorn, C.W.A. Schram, and A.J. Dejong, *J. Catal.*, **31**, 438 (1973).
18) W.F. Brill, *J. Am. Chem. Soc.*, **85**, 141 (1963); J.A. Howard and K.U. Ingold, *Can. J. Chem.*, **46**, 2661 (1968); F.R. Mayo, *Acc. Chem. Res.*, **1**, 193 (1968).
19) T. Yamamoto and M. Kimura, *J.C.S. Chem. Commun.*, **1977**, 984.
20) K.B. Sharples and R.C. Michaelson, *J. Am. Chem. Soc.*, **95**, 6136 (1973).
21) *a*) W. Buser, *Helv. Chim. Acta*, **30**, 1379 (1947); *b*) A. Nichon and W.L. Mendelson, *J. Am. Chem. Soc.*, **87**, 3921 (1965); *c*) H.B. Henbest and E.R.H. Jones, *J. Chem. Soc.*, **1948**, 1792; *d*) *Idem*, *ibid.*, **1948**, 1798; *e*) P.A. Plattner, T. Petrzilka, and W. Lang, *Helv. Chim. Acta*, **27**, 513 (1944).
22) Each pair of signals showed a total peak area corresponding to 1H, and probably arises from the presence of a mixture of C(5)-epimers.

NII-Electronic Library Service