Synthesis and reaction of cyano-substituted 1,2,4-trioxolanes

Hajime Kuwabara, Yoshihiro Ushigoe and Masatomo Nojima *

Department of Material Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan

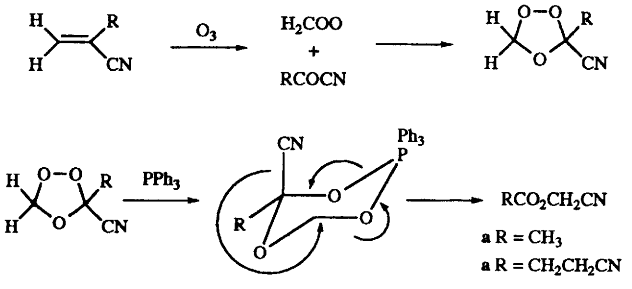
Carbonyl oxides, derived from the ozonolyses of vinyl ethers, readily undergo [3 + 2] cycloadditions with acyl cyanides affording the corresponding cyano-substituted 1,2,4-trioxolanes in isolated yields of 34–88%. In competition experiments, a relative order of reactivity of the carbonyl oxide trapping agents was tentatively deduced; trifluoroacetophenone > α,α-diphenyl-*N*-methylnitrone (*N*-methyldiphenylmethylideneamine *N*-oxide) > benzoyl cyanide > methyl benzoylformate > α,α,*N*-triphenylimine [*N*-(diphenylmethylidene)aniline] ≫ benzaldehyde. As expected from the electron-withdrawing ability of the cyano group, 3-cyano-3-phenyl-1,2,4-trioxolane oxidized not only triphenylphosphine but also methyl *p*-tolyl sulfide and 2,3-dimethylbut-2-ene very easily.

The basic mechanism that describes the ozonolysis of an alkene to produce a 1,2,4-trioxolane (secondary ozonide) evolved during the 1950s and is known as the Criegee mechanism.[1] At the final step, recombination of the carbonyl oxide and the carbonyl compound occurs to give the 1,2,4-trioxolane. As the partner of the cycloaddition, carbonyl compounds with electron-withdrawing substituent(s) at the α-position have been found to exhibit greater reactivity toward carbonyl oxides compared with unsubstituted ones. Thus, ozonolyses of vinyl ethers in the presence of α-halo ketones, α-diketones and α-keto esters give in each case the corresponding ozonides in excellent yields.[2] For esters also, α-halo substituents lead to enhanced reactivity.[3] It is, therefore, of interest to investigate (i) if acyl cyanides can undergo cycloaddition with carbonyl oxides, (ii) the reactivity order of a series of carbonyl compounds including acyl cyanides toward carbonyl oxides, and (iii) the substituent electronic effects on the oxidizing ability of the derived ozonides. In connection with this, Griesbaum and co-workers have found that ozonolyses of vinyl cyanides provide the expected cyano-substituted ozonides, which readily react with triphenylphosphine by a novel pathway (Scheme 1).[4]

Results and discussion

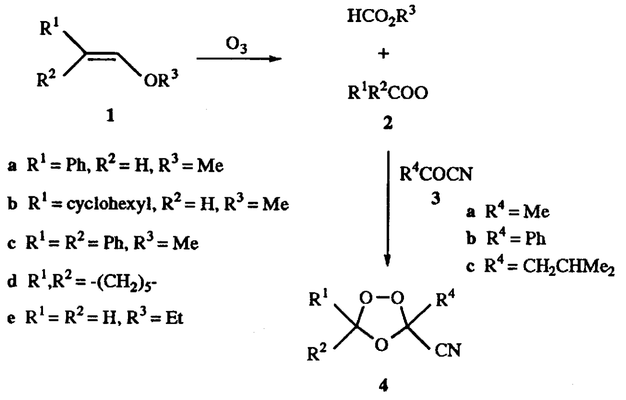
Ozonolyses of vinyl ethers in the presence of acyl cyanides

A solution of the appropriate vinyl ether **1** (1 mmol) and the appropriate acyl cyanide **3** in diethyl ether was ozonized at −70 °C. The resulting products were isolated by column chromatography on silica gel. In general, the reactions were clean; ^{1}H NMR spectra of the crude product mixture showed the presence of only the adduct **4**. Thus, by this method a variety of cyano-substituted 1,2,4-trioxolanes **4a–m** were conveniently prepared in reasonable yields (34–88%) (Scheme 2). The steric bulk of the carbonyl oxides **2** did not appear important, as the isolated yields of the cyano-substituted ozonides **4g–i** obtained from the reactions involving bulky benzophenone *O*-oxide were moderate. This is in marked contrast to the fact that in the cycloadditions with benzophenone, imines and nitrones (imine *N*-oxides), benzophenone *O*-oxide shows negligible reactivity.[5]



Scheme 1

Cycloadditions involving aldehyde *O*-oxides and acyl cyanides gave rise to the 3,3,5-trisubstituted 1,2,4-trioxolanes as mixtures of stereoisomers (Scheme 2). Ozonolysis of *tert*-butylethene in the presence of benzoyl cyanide **3b** gave, together with 3-cyano-3-phenyl-1,2,4-trioxolane **4m** (55%), the *tert*-butyl-substituted 1,2,4-trioxolane **4n** as a mixture of two stereoisomers (13% yield; **4m**:**4n** = 53:47) (Scheme 3). The structural assignments were made on the basis of NOEs (Fig. 1). In the case of the *trans*-isomer of the ozonide **4n** the irradiation



Compound 4

	R^1	R^2	R^4	Yield (%)	Ratio of the two isomers
a	Ph	H	Me	87	65:35
b	Ph	H	Ph	87	57:43
c	Ph	H	Bu^i	90	66:34
d	cyclohexyl	H	Me	84	53:47
e	cyclohexyl	H	Ph	67	50:50
f	cyclohexyl	H	Bu^i	68	55:45
g	Ph	Ph	Me	59	
h	Ph	Ph	Ph	77	
i	Ph	Ph	Bu^i	34	
j	-(CH$_2$)$_5$-		Me	77	
k	-(CH$_2$)$_5$-		Ph	79	
l	-(CH$_2$)$_5$-		Bu^i	81	
m	H	H	Ph	88	

Scheme 2

Table 1 Competitive reaction of two trapping agents of carbonyl oxides[a]

Vinyl ether	Trapping agents	Products (% yield)
1a	**3b**, **5a**	**4b** (32), **8a** (45)
1a	**3b**, **5b**	**4b** (44), **8b** (19)
1a	**3b**, **5c**	**4b** (45)
1b	**3b**, **7**	**4b** (20), **10** (39)
1a	**5a**, **5b**	**8a** (55), **8b** (15)
1a	**5a**, **5c**	**8a** (81)
1a	**5b**, **5c**	**8b** (48), **8c** (4)
1a	**5b**, **6**	**8b** (52), **9** (28)

[a] A 1 : 1 : 1 mixture of a vinyl ether and two tapping agents in diethyl ether was treated with 1 equiv. of ozone at −70 °C.

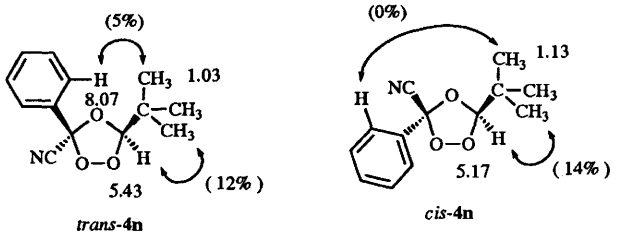
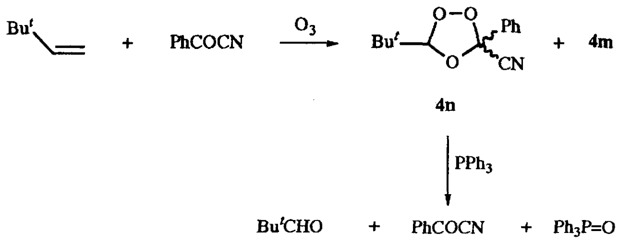


Fig. 1 The chemical shifts and NOE data for the specified hydrogens in the two isomers of 3-cyano-3-phenyl-5-*tert*-butyl-1,2,4-trioxolane **4n**

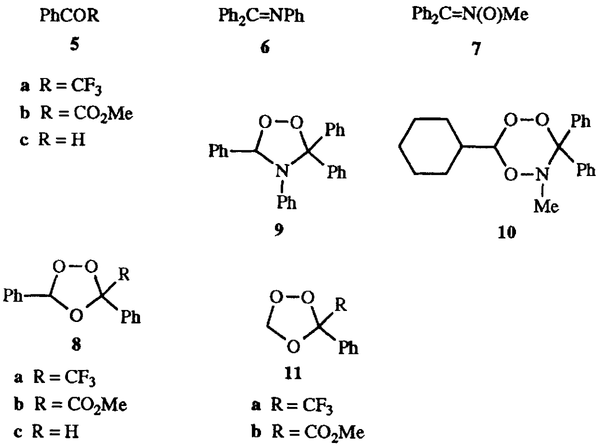


Scheme 3

and the phenyl proton at δ 8.10. In the case of the *cis*-isomer, however, no NOE was observed between the *tert*-butyl protons at δ 1.13 and the phenyl protons. These assignments were further supported by the difference in reactivity of the two isomers toward triphenylphosphine. When a 1 : 1 mixture of the *cis*- and *trans*-**4n** was treated with 0.5 equiv. of triphenylphosphine in CDCl$_3$, the sterically less-congested isomer *trans*-**4n** was immediately reduced by triphenylphosphine, while the *cis*-isomer remained intact (Scheme 3). However, treatment of a *cis–trans* mixture of the ozonide **4n** with 1 equiv. of triphenylphosphine led to the reduction of both isomers. The reduction proceeded by the conventional pathway providing a mixture of trimethylacetaldehyde and benzoyl cyanide. This was in marked contrast to the behaviour of 3-cyano-3-methyl-1,2,4-trioxolane discovered by Griesbaum *et al.*[4] (Scheme 1).

Relative reactivity of acyl cyanides and other 1,3-dipolarophiles in reactions with carbonyl oxides

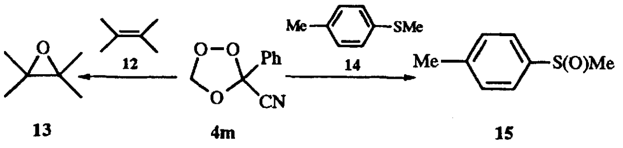
In addition to carbonyl compounds, carbonyl oxides are known to form cycloadducts with imines **5** and nitrones **6**.[5] Since acyl cyanides were found to be efficient trapping agents of carbonyl oxides, it was of interest to establish, at least qualitatively, an order of relative reactivity for acyl cyanides in comparison with these other carbonyl oxide trapping reagents. When the ozonolysis of a vinyl ether **1a** was carried out in the presence of an equimolar mixture of benzoyl cyanide **3b** and 2,2,2-trifluoroacetophenone **5a** in diethyl ether at −70 °C, two ozonides **4b** and **8a** were obtained in yields of 32% and 45%, respectively. Similar competitive experiments were conducted for several pairs of trapping agents. The results from these competition experiments suggest an order of reactivity: PhCOCF$_3$ > Ph$_2$C=N(O)Ph > PhCOCN > PhCOCO$_2$Me > Ph$_2$C=NPh ≫ PhCHO (Table 1). Compared with conventional carbonyl compounds such as benzaldehyde, nitrones and imines are remarkably efficient trapping agents of carbonyl oxides. However, it is noted that the reactivities of carbonyl compounds with electron-withdrawing substituents at the α-position are very similar to those of nitrones and imines.



Reduction of cyano-substituted ozonides with triphenylphosphine, methyl *p*-tolyl sufide and 2,3-dimethylbut-2-ene

With the easy reduction of the cyano-substituted ozonide **4n** by triphenylphosphine in mind, competitive reductions of the cyano-substituted ozonide **4b** and other ozonides **8a–c** and **11a,b** were conducted in CDCl$_3$ using toluene as an internal standard. For different pairs of ozonides, the percentages of the unreacted ozonides, as determined by ^{1}H NMR spectroscopy, were as follows: **4b**:**8a**, 36:44; **4b**:**8b**, 22:53; **4b**:**8c**, 0:54; **8a**:**8b**, 24:40 and **8b**:**8c**, 34:51. Thus, the reactivity seems to follow the sequence: **4b** > **8a** > **8b** > **8c**. This order is consistent with the substituent inductive effects σ_I: CN (0.56) > CF$_3$ (0.42) > CO$_2$Me (0.26) > H (0).[6]

Methyl *p*-tolyl sulfide **14** also could reduce the cyano-substituted ozonide very readily. During the reaction in CDCl$_3$ for 24 h, the ozonide **4m** was completely consumed. In accordance with this, the sulfoxide **15** was quantitatively isolated from the reaction mixture (Scheme 4). As expected, ozonides **11a,b** were also reduced by methyl *p*-tolyl sulfide, albeit more slowly. Even after 24 h, some of the sulfide **14** remained intact (46% for **11a** and 34% for **11b**).



Scheme 4

The cyano-substituted ozonide **4m** was found to oxidize 2,3-dimethylbut-2-ene **12** affording the corresponding epoxide **13** (Scheme 4). This is in agreement with the fact that alkyl hydroperoxides containing electron-withdrawing substituents work as powerful epoxidizing agents.[7] The ^{1}H NMR spectra suggested that treatment of the ozonide **4m** with the alkene **12** in CDCl$_3$ resulted in the formation of the epoxide **13** in 52% yield. In contrast, under similar conditions the more bulky ozonide **4b** did not epoxidize the alkene **12**. Also, the oxidizing power of the ozonides **11a** and **11b** was found to be rather limited. For example, the reaction of the ozonide **11a** with the same alkene **12** for 24 h led to the formation of the epoxide **13**, albeit in a low yield of 11%.

Experimental

General

^{1}H NMR and ^{13}C NMR spectra were obtained in $CDCl_3$ (unless otherwise noted) with $SiMe_4$ as standard, using a JEOL JNM-EX-270 spectrometer; *J* values are given in Hz. Infrared spectra were obtained with a Hitachi 215 spectrometer. Vinyl ethers **1a–c**,[8] **1d**,[9] α,α,*N*-triphenylimine [*N*-(diphenylmethylidene)aniline] **6**[10] and α,α-diphenyl-*N*-methylnitrone (*N*-methyldiphenylmethylideneamine *N*-oxide) **7**[11] were prepared by the reported methods.

Ozonolysis of a vinyl ether in the presence of an acyl cyanide in diethyl ether

Ozonolysis of a mixture of 1-methoxy-2-phenylethene **1a** and acetyl cyanide **3a** is representative. Through a solution of the vinyl ether **1a** (201 mg, 1.5 mmol) and the acyl cyanide **3a** (97 mg, 1.4 mmol) in diethyl ether (20 cm^3) at −70 °C was passed a slow stream of ozone (2 mmol; Nippon Ozone Model ON-1-2 ozonator). After evaporation of the solvent *in vacuo*, the crude products were separated by column chromatography on silica gel. Elution with benzene–hexane (1 : 4) gave 3-cyano-3-methyl-5-phenyl-1,2,4-trioxolane **4a** (250 mg, 87%).

3-Cyano-3-methyl-5-phenyl-1,2,4-trioxolane 4a. Oil (a 65 : 35 mixture of two isomers) (Found: C, 62.7; H, 4.6; N, 7.4. $C_{10}H_9NO_3$ requires C, 62.8; H, 4.75; N, 7.3%); δ_H 1.90 (3 H, s), 6.05 (0.65 H, s), 6.45 (0.35 H, s) and 7.4–7.8 (5 H, m); δ_C(major) 21.13, 99.40, 106.29, 116.81, 126.49, 128.53, 128.70, 128.86, 128.96 and 131.60; (minor) 20.97, 98.62, 104.65, 126.49, 128.53, 128.70, 128.86, 128.96 and 131.60; ν_{max}/cm^{-1} 3050, 2950, 2250, 1700, 1610, 1460, 1380, 1320, 1200, 1180, 1250, 1040, 1020, 980, 920, 890, 760 and 700.

3-Cyano-3,5-diphenyl-1,2,4-trioxolane 4b. Oil (a 57 : 43 mixture of two isomers) (Found: C, 70.95; H, 4.5; N, 5.65. $C_{15}H_{11}NO_3$ requires C, 71.15; H, 4.35; N, 5.5%); δ_H 6.31 (0.57 H, s), 6.70 (0.43 H, s) and 7.3–8.2 (m, 10 H); δ_C(major) 102.02, 107.61, 116.23, 126.64, 127.09, 127.13, 128.65, 128.80, 129.02, 129.09, 129.13, 131.71 and 132.17; (minor) 104.23, 108.18, 115.33, 126.64, 127.09, 127.13, 128.65, 128.80, 129.02, 129.09, 129.13, 131.71 and 132.16.

3-Cyano-3-isobutyl-5-phenyl-1,2,4-trioxolane 4c. Oil (a 66 : 34 mixture of two isomers) (Found: C, 66.5; H, 6.65; N, 5.5. $C_{13}H_{15}NO_3$ requires: C, 66.9; H, 6.5; N, 6.0%); δ_H 1.08 (6 H, d, *J* 6.5), 2.0–2.2 (3 H, m), 6.06 (s, 0.66 H), 6.52 (s, 0.34 H) and 7.3–7.6 (m, 5 H); δ_C(major) 23.52, 23.49, 24.82, 43.00, 102.86, 106.49, 116.98, 126.94, 129.06, 129.13, 129.40, 129.47 and 132.00; (minor) 23.49, 23.52, 24.96, 42.70, 102.09, 104.58, 115.96, 126.94, 129.06, 129.13, 129.40, 129.47 and 132.00.

3-Cyano-5-cyclohexyl-3-methyl-1,2,4-trioxolane 4d. Oil (a 53 : 47 mixture of two isomers) (Found: C, 61.0; H, 7.9; N, 6.6. $C_{10}H_{15}NO_3$ requires: C, 60.9; H, 7.67; N, 7.10%); δ_H 1.2–1.9 (14 H, br s), 5.01 (0.53 H, d, *J* 4.6) and 5.31 (0.47 H, d, *J* 5.3); δ_C 20.58, 20.95, 25.05, 25.18, 25.21, 25.29, 25.82, 26.67, 26.74, 26.79, 26.92, 38.26, 41.17, 97.75, 98.17, 108.93, 108.97, 116.05 and 116.64.

3-Cyano-5-cyclohexyl-3-phenyl-1,2,4-trioxolane 4e. Oil (a 50 : 50 mixture of two isomers) (Found: C, 69.3; H, 6.7; N, 5.4. $C_{15}H_{17}NO_3$ requires: C, 69.5; H, 6.6; N, 5.4%); δ_H 1.0–2.0 (11 H, m), 5.29 (0.5 H, d, *J* 4.6), 5.49 (0.5 H, d, *J* 6.9) and 7.4–8.2 (5 H, m); δ_C 24.93, 25.16, 25.25, 25.32, 25.82, 26.81, 26.94, 27.08, 38.47, 41.06, 100.45, 100.88, 109.83, 110.37, 115.51, 115.96, 126.86, 127.01, 128.66, 128.95, 129.00, 129.43, 130.37, 131.88, 131.93, 133.23 and 136.78.

3-Cyano-5-cyclohexyl-3-isobutyl-1,2,4-trioxolane 4f. Oil (a 55 : 45 mixture of two isomers) (Found: C, 65.4; H, 9.0; N, 5.7. $C_{13}H_{21}NO_3$ requires: C, 65.25; H, 8.85; N, 5.85%); δ_H 1.0–1.1 (6 H, m), 1.1–1.9 (11 H, m), 1.9–2.1 (3 H, m), 4.96 (0.45 H, d, *J* 4.3) and 5.29 (0.55 H, d, *J* 6.3).

3-Cyano-3-methyl-5,5-diphenyl-1,2,4-trioxolane 4g. Mp 201–202 °C (from methanol) (Found: C, 72.1; H, 4.9; N, 5.2. $C_{16}H_{13}NO_3$ requires C, 71.9; H, 4.9; N, 5.2%); δ_H 1.80 (3 H, s) and 7.3–7.7 (10 H, m); δ_C 17.52, 95.89, 108.95, 112.63, 122.14, 124.19, 124.26, 124.44, 124.94, 126.34, 129.85 and 135.26.

3-Cyano-3,5,5-triphenyl-1,2,4-trioxolane 4h. Mp 99–100 °C (from methanol) (Found: C, 76.5; H, 4.5; N, 4.25. $C_{21}H_{15}NO_3$ requires: C, 76.6; H, 4.6; N, 4.2%); δ_C 103.12, 114.27, 115.98, 126.37, 127.58, 128.35, 128.42, 128.48, 128.59, 128.71, 128.93, 129.09, 130.48, 131.92, 134.20 and 139.34; ν_{max}/cm^{-1} 1700, 1670, 1600, 1580, 1500, 1480, 1320, 1280, 1180, 1060, 1000, 950, 920, 820, 770, 650 and 600.

3-Cyano-3-isobutyl-5,5-diphenyl-1,2,4-trioxolane 4i. Oil (Found: C, 73.5; H, 6.3; N, 4.5. $C_{19}H_{19}NO_3$ requires: C, 73.8; H, 6.2; N, 4.5%); δ_H 0.96 (3 H, d, *J* 11.2), 0.99 (3 H, d, *J* 11.21), 1.18 (2 H, d, *J* 6.6), 1.9–2.1 (1 H, m) and 7.3–7.6 (10 H, m), δ_C 22.81, 22.93, 24.49, 42.75, 103.06, 112.56, 116.30, 126.18, 127.08, 127.19, 127.80, 127.87, 128.23, 128.37, 128.46. 128.70, 128.93, 130.35, 134.07 and 139.43.

5′-Cyano-5′methylspiro[cyclohexane-1,3′-(1,2,4-trioxolane)] 4j. Oil (Found: C, 58.9; H, 7.3; N, 7.6. $C_9H_{13}NO_3$ requires: C, 59.0; H, 7.15; N, 7.65%); δ_H 1.83 (3 H, s) and 0.9–1.9 (10 H, br s); δ_C 21.74, 23.68, 24.28, 24.87, 32.87, 35.78, 98.31, 113.60 and 117.47.

5′-Cyano-5′-phenylspiro[cyclohexane-1,3′-(1,2,4-trioxolane)] 4k. Oil (Found: C, 68.2; H, 6.26; N, 5.7. $C_{14}H_{15}NO_3$ requires: C, 68.56; H, 6.2; N, 5.7%); δ_H 0.9–2.1 (10 H, m) and 7.4–7.8 (5 H, m); δ_C 23.18, 23.78, 24.33, 32.53, 35.10, 100.59, 114.02, 116.35, 126.94, 128.94, 128.90, 129.38, 130.30 and 131.81.

5′-Cyano-5′-isobutylspiro[cyclohexane-1,3′-(1,2,4-trioxolane)] 4l. Oil (Found: C, 63.7; H, 8.5; N, 6.2. $C_{12}H_{19}NO_3$ requires: C, 64.0; H, 8.5; N, 6.2%); δ_H 1.03 (3 H, d, *J* 4.0), 1.05 (3 H, d, *J* 4.0), 1.4–1.9 (10 H, br s), 1.91 (2 H, d, *J* 1.32) and 2.0–2.1 (1 H, m); δ_C 22.81. 22.95, 23.18, 23.81, 24.17, 24.37, 32.38, 35.24, 42.63, 100.79, 112.42 and 116.57.

3-Cyano-3-phenyl-1,2,4-trioxolane 4m. Oil (Found: C, 61.4; H, 4.05; N, 7.9. $C_9H_7NO_3$ requires: C, 61.0; H, 4.0; N, 7.9%); δ_H 5.32 (1 H, s), 5.79 (1 H, s) and 7.5–7.8 (5 H, m); δ_C 96.57, 100.25, 115.35, 127.10, 128.12, 129.11, 129.47, 130.44 and 132.18.

Ozonolysis of *tert*-butylethene in the presence of benzoyl cyanide

Through a solution of *tert*-butylethene (793 mg, 9.44 mmol) and benzoyl cyanide **3b** (1.237 g, 9.44 mmol) in diethyl ether (20 cm^3) at −70 °C was passed a slow stream of ozone (2 mmol). After evaporation of the solvent *in vacuo*, the crude products were separated by column chromatography on silica gel. Elution with diethyl ether–hexane (2 : 98) gave 3-cyano-3-phenyl-5-*tert*-butyl-1,2,4-trioxolane **4n** (286 mg, 13%). Subsequent elution with diethyl ether–hexane (4 : 96) gave 3-cyano-3-phenyl-1,2,4-trioxolane **4m** (916 mg, 55%, a 53 : 47 mixture of two isomers). Treatment of a solution of the ozonide **4n** (160 mg, 0.69 mmol) in $CDCl_3$ with triphenylphosphine (90 mg, 0.35 mmol) for 0.5 h resulted in the disappearance of the methine signal (δ 5.43) attributable to the ozonide *trans*-**4n**, with the appearance of signals attributable to trimethylacetaldehyde (δ_H 9.53). However, both of the isomeric ozonides were completely reduced by treatment with 1 equiv. of triphenylphosphine in $CDCl_3$ for 1 h.

3-Cyano-3-phenyl-5-*tert*-butyl-1,2,4-trioxolane 4n. Oil (a 53 : 47 mixture of two isomers); δ_H 1.03 (4.2 H, s), 1.13 (4.8 H, s), 5.17 (0.53 H, s), 5.43 (0.47 H, s) and 7.4–8.3 (5 H, m); δ_C(major) 24.57, 33.34, 101.29, 112.92, 115.87, 126.75, 127.08, 129.00, 131.88 and 131.97; (minor) 24.23, 34.97, 100.56, 111.88, 115.38, 128.61, 129.34, 129.49, 130.42 and 136.80. The irradiation of the *tert*-butyl protons at δ 1.03 resulted in the enhancement of the signals at δ 5.43 (13%) and 7.60 (5%). The irradiation of the *tert*-

butyl protons at δ 1.13 resulted in the enhancement of the signal at δ 5.17 (14%).

Ozonolysis of 1-phenyl-2-methoxyethene in the presence of 2,2,2-trifluoroacetophenone

Through a solution of the vinyl ether **1a** (268 mg, 2 mmol) and the ketone **5a** (348 mg, 2 mmol) in diethyl ether (20 cm^3) at −70 °C was passed a slow stream of ozone (2 mmol). After evaporation of the solvent *in vacuo*, the crude products were separated by column chromatography on silica gel. Elution with diethyl ether–hexane (2:98) gave 3,5-diphenyl-3-trifluoromethyl-1,2,4-trioxolane **8a** (994 mg, 84%).

3,5-Diphenyl-3-trifluoromethyl-1,2,4-trioxolane 8a. Oil (a 34:66 mixture of two isomers); δ_H 6.05 (0.34 H, s), 6.36 (0.66 H, s) and 7.3–7.9 (10 H, m); δ_C 104.50 (q, *J* 34), 105.63, 106.77, 121.70 (q, *J* 288), 126.69, 126.95, 128.15, 128.43, 128.49, 128.52, 128.71, 128.87, 130.41, 130.61, 130.18 and 131.59.

Ozonolysis of 1-ethoxyethene in the presence of 2,2,2-trifluoroacetophenone or methyl benzoylformate

The reaction in the presence of 2,2,2-trifluoroacetophenone is representative. Through a solution of the vinyl ether **1e** (240 mg, 4 mmol) and the ketone **5a** (696 mg, 4 mmol) in diethyl ether (20 cm^3) at −70 °C was passed a slow stream of ozone (4 mmol). After evaporation of the solvent *in vacuo*, the crude products were separated by column chromatography on silica gel. Elution with diethyl ether–hexane (3:97) gave 3-phenyl-3-trifluoromethyl-1,2,4-trioxolane **11a** (496 mg, 56%).

3-Phenyl-3-trifluoromethyl-1,2,4-trioxolane 11a. Oil (Found: C, 49.0; H, 3.0. $C_9H_7F_3O_3$ requires: C, 49.1; H, 3.2%); δ_H 5.13 (1 H, s), 5.45 (1 H, s) and 7.3–7.7 (5 H, m); δ_C 95.58, 103.07 (q, *J* 34), 121.55 (q, *J* 288), 126.79, 128.45, 129.09, 130.60 and 130.67.

3-Methoxycarbonyl-3-phenyl-1,2,4-trioxolane 11b. Oil (Found: C, 57.3; H, 3.9. $C_{10}H_{10}O_5$ requires: C, 57.7; H 3.9); δ_H 3.72 (3 H, s), 5.17 (1 H, s), 5.50 (1 H, s) and 7.3–7.8 (5 H, m); δ_H 53.73, 96.07, 105.09, 126.76, 129.11, 129.34, 130.93, 131.93 and 168.37; ν_{max}/cm^{-1} 2975, 2925, 1700, 1500, 1460, 1440, 1380, 1270, 1090, 1010, 940, 840, 820, 750, 720, 700 and 650.

Competitive reaction between two 1,3-dipolarophiles

Through a 1:1:1 mixture of the vinyl ether and two dipolarophiles in diethyl ether at −70 °C was passed a stream of ozone. After evaporation of the solvent, the products were separated by column chromatography on silica gel. The ratio of the isolated mixture of the cycloadducts was determined by comparing the peak areas of the characteristic signals of each adduct in ^1H NMR spectra. **4b**: δ 6.31 (s) and 6.70 (s); **4e**: δ 5.29 (d) and 5.49 (d); **8a**: δ 6.05 (s) and 6.36 (s); **8b**: δ 6.32 (s)[2] and 6.55 (s); **8c**: δ 6.33 (s) and 6.36 (s);[12] **10**: δ 5.72 (d);[13] **9**: δ 6.62 (s).[5]

Competitive reduction between two ozonides

The reaction of a mixture of the ozonides **4b** and **8b** is representative. To a $CDCl_3$ solution (1 cm^3) of the ozonide **4b** (129 mg, 0.51 mmol) and the ozonide **8b** (134 mg, 0.47 mmol) and toluene (15 mg, 0.17 mmol) in an NMR tube at 0 °C was added triphenylphosphine (131 mg, 0.5 mmol). The mixture was kept at 20 °C for 24 h, after which the ^1H NMR spectrum showed the presence of the unreacted ozonides **4b** (0.1 mmol) and **8b** (0.25 mmol).

Reaction of ozonides with methyl *p*-tolyl sulfide

The reaction of the ozonide **4m** is representative. A mixture of the ozonide **4m** (170 mg, 0.96 mmol) and methyl *p*-tolyl sulfide **14** (176 mg, 0.96 mmol) in carbon tetrachloride (1 cm^3) was stirred at 20 °C for 24 h. The ^1H NMR spectra of the mixture suggested that after 0.5 h 63% of the sulfide **14** had been oxidized. After 24 h the sulfide was completely oxidized to the corresponding sulfoxide **15**. Purification by column chromatography on silica gel gave methyl *p*-tolyl sulfoxide **15** as an oil; δ_H 2.45 (3 H, s,), 2.62 (3 H, s) and 7.28–7.65 (4 H, m).[7]

Reaction of ozonides with 2,3-dimethylbut-2-ene

The reaction of an ozonide **4m** is representative. A solution of the ozonide **4m** (100 mg, 0.56 mmol) and the alkene **12** (39 mg, 0.56 mmol) in CCl_4 was stirred at 20 °C for 24 h. The peak area of characteristic signal of the methyl protons at δ 1.25[7] showed the formation of the corresponding epoxide **13** in 52% yield.

References

1 (*a*) P. S. Bailey, *Ozonation in Organic Chemistry*, Academic Press, New York, 1978, vol. 1; 1982, vol. 2; (*b*) R. L. Kuczkowski, in *1,3-Dipolar Cycloaddition Chemistry*, ed. A. Padwa, Wiley, New York, vol. 2, 1984; (*c*) W. H. Bunnelle, *Chem. Rev.*, 1991, **91**, 335; (*d*) R. L. Kuczkowski, in *Advances in Oxygenated Processes*, ed. A. L. Baumstark, JAI Press, Greenwich, 1991, vol. 3; (*e*) K. J. McCullough and M. Nojima, *Organic Peroxides*, ed. W. Ando, Wiley, New York, 1992.

2 T. Tabuchi and M. Nojima, *J. Org. Chem.*, 1991, **56**, 6591.

3 T. Sugiyama, M. Nojima, P. Krieger-Beck, W.-S. Kim and K. Griesbaum, *J. Org. Chem.*, 1992, **57**, 3487.

4 K. Griesbaum, T.-S. Huh and S. H. Gutsche, *Tetrahedron Lett.*, 1990, **31**, 3299.

5 K. J. McCullough, M. Mori, T. Tabuchi, H. Yamakoshi, S. Kusabayashi and M. Nojima, *J. Chem. Soc., Perkin Trans. 1*, 1995, 41.

6 F. R. Carey and R. J. Sundberg, *Advanced Organic Chemistry*, Plenum, New York, 1993, Part A, ch. 4.

7 H. Yamamoto, M. Miura, M. Nojima and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 1*, 1986, 173.

8 G. Wittig and M. Schlosser, *Chem. Ber.*, 1961, **94**, 1373.

9 G. Earnshaw, C. J. Wallis and S. Warren, *J. Chem. Soc., Perkin Trans. 1*, 1979, 3099.

10 J. H. Billman and K. M. Tai, *J. Org. Chem.*, 1958, **23**, 535.

11 L. Semper and L. Lichtenstadt, *Chem. Ber.*, 1918, **51**, 928.

12 K. Griesbaum, W.-S. Kim, N. Nakamura, M. Mori, M. Nojima and S. Kusabayashi, *J. Org. Chem.*, 1990, **55**, 6153.

13 M. Mori, T. Sugiyama, M. Nojima, S. Kusabayashi and K. J. McCullough, *J. Org. Chem.*, 1992, **57**, 2285.

Paper 5/06670K
Received 9th *October* 1995
Accepted 1st *December* 1995