Dicarboxylic Acids from Ozonolysis of Cycloalkenes

Ramzi M. Habib, Chin-Yun Chiang, and Philip S. Bailey*

Department of Chemistry, The University of Texas at Austin, Austin, Texas 78712

Received December 20, 1983

The "superior" method for the synthesis of dicarboxylic acids by ozonolysis of cycloalkenes with 1 molar equiv of ozone in an ether-type solvent, followed by hydrogenation over Lindlar's catalyst, has been found not to yield dicarboxylic acids directly, as claimed in the Soviet literature,[1-4] unless excess ozone is employed. The peroxidic ozonolysis products obtained by us have been characterized and are quite different from those reported by the Russians. Thus, their mechanisms do not appear to be applicable. Ozonolysis of cycloalkenes in an acetic acid–formic acid mixture, followed by further oxidation with molecular oxygen, is a much better method for dicarboxylic acid syntheses.

Recently, curious reports have come from the Soviet literature[1-4] concerning the ozonolysis of cycloalkenes and 1-alkenes. According to Odinokov and co-workers,[1-3] ozonolysis in ether- or ester-type solvents (e.g., diethyl ether, dioxane, tetrahydrofuran, ethyl acetate, and various acetals) with one molar equiv of ozone, followed by hydrogenation over Lindlar's catalyst ($Pd-CaCO_3-PbO$), produces, from cycloalkenes, high yields of the corresponding dicarboxylic acids and, from 1-alkenes, monocarboxylic acids. Most of the work was done with cyclohexene and cyclooctene. The corresponding dicarboxylic acid reportedly crystallizes immediately upon evaporation on the reaction mixture. Odinokov et al.[2,3] state that if any one of the essential reagents, an ethereal or ester-type solvent, Lindlar's catalyst, or hydrogen, is omitted, the ozonolysis affords only dialdehydes or aldehyde acids. The dicarboxylic acid yield reportedly is increased if a small amount of methanol (2 molar equiv) is present in the solvent.

This report is amazing since it is well-known that 1 molar equiv of ozone oxidizes a cycloolefin to the equivalent of an aldehyde acid, and reduction of the corresponding peroxidic ozonolysis product gives rise to a dialdehyde.[5] Odinokov and co-workers[2,3] acknowledge that this is true under conditions other than those just described. As an explanation for their remarkable results, the Russian chemists[2,3] proposed that the purpose of the ethereal-type solvent is to react with oxygen, in the ozone–oxygen stream employed, to produce a hydroperoxide (e.g., **4** from diethyl ether, **2**). This, in turn, supposedly reacts with the ozonolysis intermediates, simultaneously generated from the cycloalkenes, to produce higher peroxides, which rearrange, in the presence of Lindlar's catalyst and hydrogen, to yield dicarboxylic acids.

The mechanism proposed by Odinokov et al.[2,3] is not clear in all aspects. Using cyclooctene (**1**) as an example, however, it appears to be as shown in Scheme I. First, a dimeric zwitterion (**5**) is produced, presumably via **3**. In the absence of both an ethereal solvent and methanol, the peroxidic ozonolysis product was described as either **7a** or **8a**, which are the oxidation equivalents of an aldehyde acid. Obviously, however, only **7a** could arise from **5**. In the presence of methanol, but not an ethereal solvent, **9a** is the described product (directly from **5**). When an ethereal solvent, but no methanol is present, hydroperoxide **4**, or a similar alkoxyalkyl hydroperoxide, is believed to add to **5** to produce **6**, which further cyclizes, with loss of a hemiacetal moiety, to furnish **7b** or **8b**. The authors[2,3] seem to prefer **8b**, but this seems unlikely because of the distances involved. Intermediate **7b** (or **8b**) is then assumed to rearrange, via **10**, to dicarboxylic acid **11**, with the help of Lindlar's catalyst and hydrogen. In the presence of both methanol and an ethereal solvent, the assumed peroxidic product is **9b**, somehow produced from the reaction of **6** with methanol.[2,3] In one paper Odinokov et al.[3] cite evidence for the molecular oxygen involvement in the formation of entities corresponding to **4**, **6**, **7b**, or **8b**, **9b**, and **11**. After ozonizing cyclohexene in an oxygen carrier enriched with O^{18}, the entities corresponding to **7b** or **8b** and **11** were reported to be enriched with O^{18}.

Although some of the mechanisms proposed by Odinokov et al.[2,3] are reasonable, several of their key concepts are doubtful. First, catalytic hydrogenation of **7a**, **7b**, **8a**, **8b**, **9a**, or **9b** should produce dialdehydes, not dicarboxylic acids. Second, oxidation of ethers to hydroperoxides should be considerably slower than ozonolysis of cycloalkenes, thereby precluding the opportunity of either **3** or **5** to react with **4**. Contrary to the statement of Odinokov et al.[2,3] ozonation of ethers with ozone–oxygen mixtures utilizes more ozone than oxygen.[5-8] Therefore, much more than 1 mol of ozone per mol of cycloalkene would be required to produce both **3** and **4**, the latter from **2**. Furthermore, ethyl acetate, a superior solvent, according to the Russian chemists[2,3] for their described results, does not produce hydroperoxides such as **4** readily, even with ozone itself.[5b] Third, the proposed reaction of **6** with methanol to yield **9b** appears highly unlikely to say the least. Finally, ozonolysis of cyclohexene in the presence of methanol yields linear peroxide oligomers[5a,9] rather than the cyclic oligomers proposed by Odinokov et al.[2,3] By analogy to phenanthrene, the same is likely to be true in nonparticipating solvents.[5,10]

We have performed ozonolyses of cyclohexene, cyclooctene, and cyclopentene under the conditions described by Odinokov et al.[2,3] using diethyl ether, ethyl acetate,

(1) Odinokov, V. N.; Zhemaiduk, L. P.; Tolstikov, G. A. *Izv. Acad. Nauk SSSR, Ser. Khim.* **1976**, 1900; *Bull. Acad. Sci. USSR Div. Chem. Sci. (Engl. Transl.)* **1976**, 1790.

(2) Odinokov, V. N.; Zhemaiduk, L. P.; Tolstikov, G. A. *Zh. Org. Khim.* **1978**, *14*, 54; *J. Org. Chem. USSR (Engl. Transl.)* **1978**, *14*, 48.

(3) Odinokov, V. N.; Botsman, L. P.; Ishmuratov, G. Y.; Tolstikov, G. A. *Zh. Org. Khim.* **1980**, *16*, 524; *J. Org. Chem. USSR (Engl. Transl.)* **1980**, *16*, 453.

(4) Odinokov, V. N.; Tolstikov, G. A. *Usp. Khim.* **1981**, *50*, 1207; *Russ. Chem. Rev.* **1981**, *50*, 636 (especially p 640, 641, 644).

(5) Bailey, P. S. "Ozonation in Organic Chemistry"; (a) Vol. I, Academic Press: New York, 1978; (b) Vol. II, 1982.

(6) Price, C. C.; Tumulo, A. L. *J. Am. Chem. Soc.* **1964**, *86*, 4691.

(7) Erickson, R. E.; Hansen, R. T.; Harkins, J *J. Am. Chem. Soc.* **1968**, *90*, 6777.

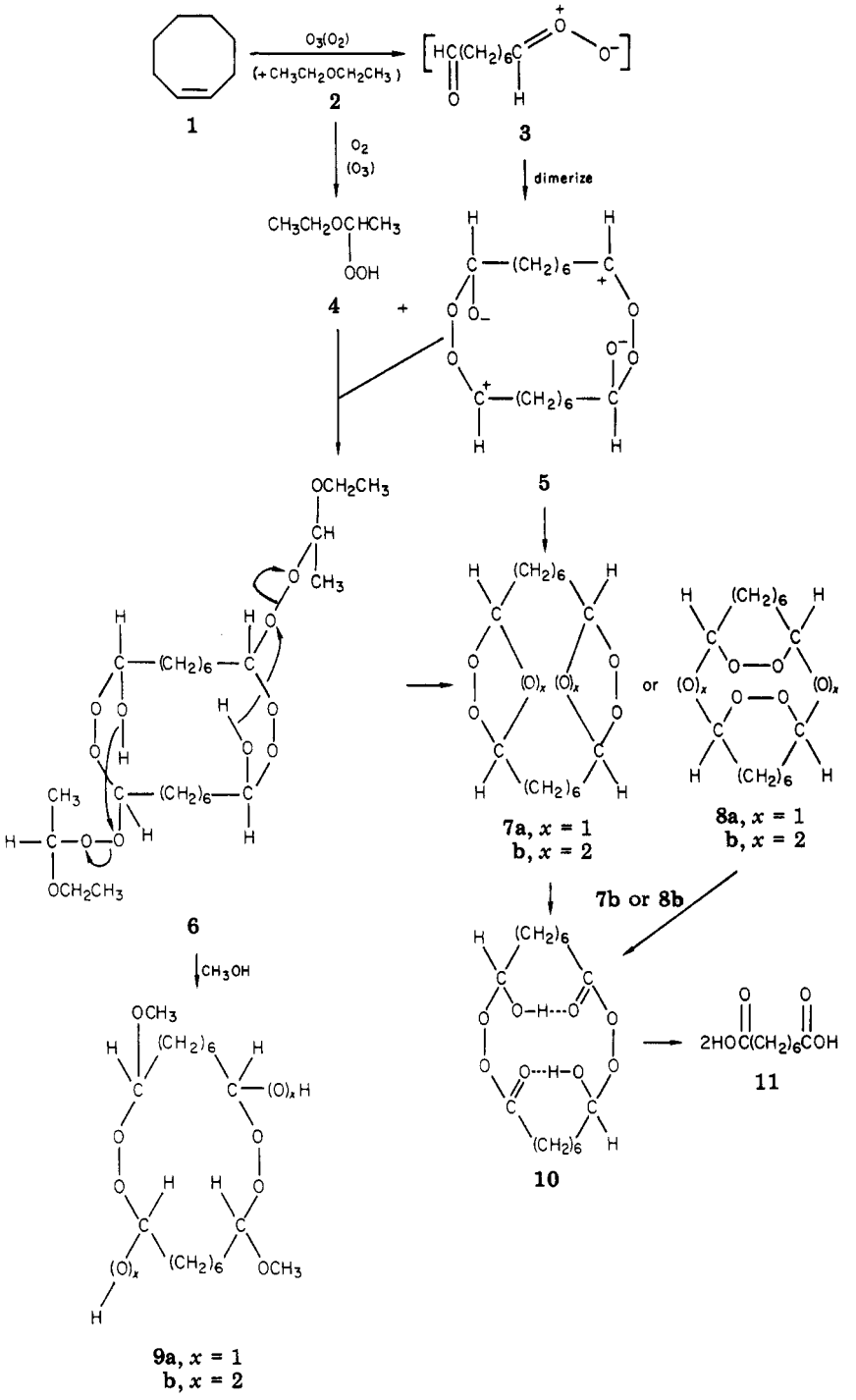
(8) Bailey, P. S.; Lerdal, D. A. *J. Am. Chem. Soc.* **1978**, *100*, 5820.

(9) (a) Bailey, P. S. *J. Org. Chem.* **1957**, *22*, 1548. (b) Bailey, P. S. *Ind. Eng. Chem.* **1958**, *50*, 993.

(10) Bailey, P. S.; Mainthia, S. B. *J. Org. Chem.* **1958**, *23*, 1089.

0022-3263/84/1949-2780$01.50/0

Scheme I



dioxane, and 1,1-dimethoxyethane as ethereal-type solvents (with and without small amounts of methanol present) and with methanol and dichloromethane as nonethereal-type solvents. In minor respects we have confirmed some of the reports of the Russian authors,[1,3] but otherwise our results are quite different from theirs. In all experiments using ethereal-type solvents (with and without small amounts of methanol present) ozonolysis with 1 molar equiv of ozone followed by hydrogenation of the reaction mixture over Lindlar's catalyst yielded largely the dialdehyde expected from the cycloalkene, contaminated with very small amounts (ca. 10%) of the corresponding aldehyde acid (or methyl ester thereof) and dicarboxylic acid (or methyl esters thereof). These materials were isolated and identified by gas chromatographic analysis, by using both the reaction mixture immediately after hydrogenation and the residue remaining after rapid evaporation of the reaction mixture. Contrary to the report of Odinokov et al.[2,3] this residue was an oil rather than a crystalline solid. Details of the identifications are in the Experimental Section.

Only when the oily dialdehydes (plus impurities) were exposed to air for a period of a day or more did crystallization occur. The crystals were those of the corresponding dicarboxylic acid, produced from the dialdehyde by air oxidation. After several days or weeks the oxidation was complete, resulting in yields approaching or equal to those of Odinokov et al.[2,3] The process was greatly accelerated by passing oxygen through the hydrogenated reaction mixture for several hours. These yields were in the range of 60–80%, the lower values coming from experiments with no methanol present in the ethereal solvents. Some of these experiments, using cyclohexene and

Table I. Dicarboxylic Acids by Ozonolysis of Cycloalkenes

expt	cycloalkene, (50 mmol)	solvent, (100 mL)	methanol in solvent, mmol	ozone, mmol	ozonation, temp, °C	workup	yield, %
1	cyclohexene	Et_2O	100	50	−78	*a*	25[b]
2	cyclohexene	Et_2O	100	50	−78	*c*	73[b]
3	cyclohexene	Et_2O	100	85	−78	*d*	65[b]
4	cyclohexene	dioxane	100	50	5	*c*	79[b]
5	cyclohexene	dioxane	none	50	5	*c*	72[b]
6	cyclohexene	dioxane	100	50	5	*a*	27[b]
7	cyclohexene	dioxane	100	75	5	*a*	39[b]
8	cyclohexene	dioxane	100	100	5	*d*	73[b]
9	cyclohexene	AcOEt	100	50	5	*c*	76[b,e]
10	cyclohexene	AcOEt	100	50	5	*f*	0[g]
11	cyclohexene	AcOEt	none	50	5	*c*	59[b]
12	cyclohexene	MeOH		50	5	*c*	63[b]
13	cyclohexene	MeOH		50	−78	*c*	81[b]
14	cyclohexene	CH_2Cl_2	100	50	5	*a*	0[g]
15	cyclooctene	dioxane	100	50	5	*a*	28[h]
16	cyclooctene	dioxane	100	75	5	*a*	38[h]
17	cyclooctene	dioxane	100	103	5	*d*	75[h]
18	cyclooctene[i]	$MeCH(OMe)_2$	none	10[j]	−50	*a*	96[h]
19	cyclooctene[i]	$MeCH(OMe)_2$	none	20[j]	−50	*d*	96[h]

[a] Workup procedure 1 Experimental Section—i.e., hydrogenation over Lindlar's catalyst, followed by evaporation under reduced pressure with a rotary evaporator. In general the oily residue partially crystallized after 3–4 days. [b] Adipic acid, mp 151–153 °C. [c] Workup procedure 2, Experimental Section—i.e., after hydrogenation over Lindlar's catalyst, a stream of molecular oxygen was passed through the reaction mixture for 1 h, after which the solvent was removed by a stream of oxygen. [d] Same as *a* except that the dicarboxylic acid crystallized and the yield was determined immediately upon evaporation of the reaction mixture. [e] In another instance the oily residue was exposed to air for 1–2 months. The yield of adipic acid was 97%. [f] Instead of hydrogenation, the reaction mixture was treated with nitrogen over Lindlar's catalyst, then worked up as in a. [g] Crystallization never occurred. The oily residue was peroxidic. [h] Octanedioic acid, mp 138–140 °C. [i] Only 10 mmol was utilized, in 20 mmol of solvent. [j] See footnote *i*.

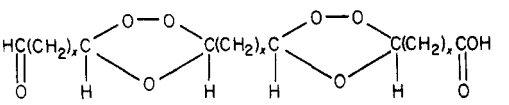
cyclooctene, are included in Table I. Similar results were obtained with cyclopentene.

In several experiments with both cyclohexene and cyclooctene, using ethereal-type solvents with and without a small amount of methanol present, the peroxidic ozonolysis products were isolated, before hydrogenation, and characterized. In no case was a peroxide with the oxygen content reported by the Soviet chemists[2,3] obtained, even when excess ozone was employed. Instead, ozonolysis of cyclooctene (1) in either dioxane or 1,1-dimethoxyethane furnished an 89% yield of a crystalline peroxide melting at 90–92 °C. Based on elementary analyses, molecular weight, and IR, NMR, and mass spectra, as described in the Experimental Section, it is assigned structure **12a** (Chart I). When 1.5 rather than 1.0 molar equiv of ozone was employed, the yield fell only slightly, to 87%. Similarly, cyclohexene yielded **12b**, which was an oily paste, in 89% yield; characterization data are given in the Experimental Section.

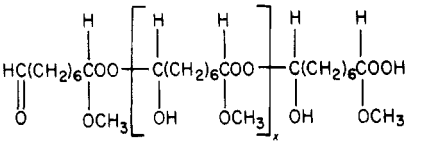
Ozonolysis of cyclooctene in diethyl ether containing 2 molar equiv of methanol yielded (95%) a liquid boiling at 130–131 °C. This is best characterized as a mixture of **13a** and its methanol hemiacetal. The IR spectrum shows a strong carbonyl band, but the aldehydic proton is relatively weak in the NMR spectrum. Another possibility is a mixture of **13a** and its cyclic hemiperacetal **14**, although it would seem unlikely that such a long open-chain compound as **13a** would cyclize to any appreciable extent. Compounds **13a** and **14** are trimeric hemiperacetals produced from addition of **15a** to itself. When cyclooctene was ozonized in methanol alone as the solvent, the liquid product (bp 120 °C 75% yield) was a dimer, probably a mixture of **13b** and its methanol hemiacetal or of **13b** and the cyclic equivalent of **14**.

Similar ozonolyses of cyclohexene in dioxane alone and in dioxane containing 2 molar equiv of methanol afforded, respectively, a paste characterized as **12b** and a liquid hydroperoxide thought to be a mixture of **15b** and its methanol hemiacetal **16a** and acetal **16b**. It is also possible that a small amount of a dimer analogous to **13b** is present in the mixture. Further evidence for the structural assignments are found in the Experimental Section.

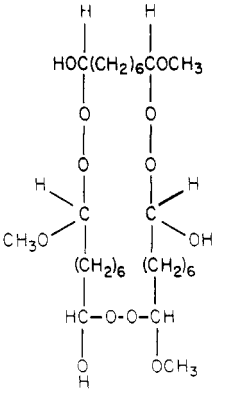
Chart I



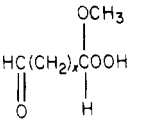
12a, $x = 6$
b, $x = 4$



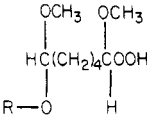
13a, $x = 1$
b, $x = 0$



14



15a, $x = 6$
b, $x = 4$



16a, $R = H$
b, $R = CH_3$

It is obvious that these results cast considerable doubt on the reported findings of the Soviet investigators.[2,3] In our hands the peroxidic ozonolysis products were not unusual but were within expectations based on previous studies.[5] It is our belief that the only purpose of the hydrogenation was to produce the dialdehyde, which is easily air or oxygen oxidized to the corresponding dicarboxylic acid. The peroxidic ozonolysis products obtained in nucleophilic solvents such as ethers, esters, and alcohols are

simpler and more easily reduced (by hydrogenation as well as by other means) than those obtained in hydrocarbon or chlorinated hydrocarbon solvents.[5] We obtained neither dialdehyde nor dicarboxylic acid from ozonation of cyclohexene in dichloromethane followed by attempted hydrogenation over Lindlar's catalyst; the reaction mixture remained peroxidic (Table I, expt 14). On the other hand, methanol solvent gave results equal to those with ether-type solvents, especially at temperatures too low for the methanol to compete for the ozone (Table I, expt 13). Use of nitrogen rather than hydrogen with Lindlar's catalyst also furnished neither dialdehyde nor dicarboxylic acid (Table I, expt 10). Thus, Odinokov et al.[2,3] were correct in stating that ethereal solvents (actually nucleophilic solvents) and hydrogenation were necessary, but not for the reasons they supposed.

It appears highly likely that part of the reason for the Russian chemist's high dicarboxylic acid yields was the use of more than 1 molar equiv of ozone. In one paper[2] they specified that 0.05 mol of ozone to 0.05 mol of cycloalkene was employed, but in a later paper,[3] they state that they ozonized until the blue color of ozone appeared. We found that the latter required several molar equivalents of ozone. When we used 2 molar equiv of ozone, the dicarboxylic acid appeared immediately upon evaporation of the solvent, as described by the Russians. Under these conditions an oxidative decomposition of the peroxidic ozonolysis product must occur, as reported in one of our earlier papers.[9b]

Table I illustrates results of ozonation of cyclohexene and cyclooctene in various solvents and conditions and shows the beneficial effect of excess ozone. In general, our dicarboxylic acid yields were not as high as those reported by the Russian chemists. This is probably due largely to their inadvertant use of excess ozone but also to determination of yield via NMR spectra rather than by direct isolation.[3] Our highest yields were obtained either by use of excess ozone or by passage of oxygen through the hydrogenated reaction mixture, as described earlier. We also found that superior results were possible by using 1,1-dimethoxyethane as solvent. This acetal would be much more readily air oxidized than would be an ordinary ether, and the resulting hydroperoxide would serve as a participating solvent in the formation of a simple and easily reduced peroxidic ozonolysis product.[5]

In our opinion the method of Odinokov and co-workers[1-4] for converting olefins and cycloolefins to carboxylic and dicarboxylic acids has no advantage over standard methods. We obtained 75–80% yields of dicarboxylic acids by the simpler and cheaper method of ozonizing cyclohexene with 1 molar equiv of ozone in a 9:1 mixture of glacial acetic and formic acids at 10 °C, followed by the passage of molecular oxygen through the reaction mixture at the reflux temperature (ca. 110 °C) until a negative peroxide test was obtained (cf. ref 9b). The dicarboxylic yield from cyclopentene was somewhat lower.

Experimental Section

General Ozonolysis Procedure. Fifty millimoles of ozone in an ozone–oxygen stream was passed through a solution of 50 mmol of cyclohexene, cyclooctene, or cyclopentene (99% pure, Aldrich) in 100 mL of one of the anhydrous reagent grade solvents shown in Table I, at the temperature indicated in Table I (see the senior author's earlier papers for general procedure).[5] The reaction mixture was purged with nitrogen, after which it was transferred to a suitable flask and stirred at room temperature in the presence of 0.1 g of Lindlar's catalyst (Aldrich) and an atomosphere of hydrogen until (8–16 h) it was no longer peroxidic (negative KI test). The catalyst was removed by filtration, after which either of two workup procedures was employed: (1) the solvent was removed on a rotary evaporator under reduced pressure; (2) a stream of oxygen was passed through the reaction mixture for 1 h after which the solvent was removed by a stream of oxygen. Except for experiments employing excess ozone (Table I, expt. 3, 7, 8, 16, 17, 19), the reaction mixture worked up by procedure 1 yielded only an oily material, which is characterized in the next experimental procedure. The oily product generally crystallized slowly upon standing in air. After 3–4 days the results shown in Table I were obtained (workup procedure 1). After a month or more, a 97% yield of adipic acid was obtained in one of the experiments with cyclohexene. When excess ozone was employed, crystallization occurred immediately. In experiments 10 and 14, where, respectively, either hydrogen or a nucleophilic solvent was omitted, the residue was peroxidic and never crystallized. The results are shown in Table I for cyclohexene and cyclooctene. Cyclopentene was ozonized only in ethyl acetate and the reaction mixture workedup by procedure 1. The results were similar to those for cyclohexene, but the yield of crystalline material was not determined. The crystalline material in each case was identified by comparison of melting points and IR spectra with those of authentic samples of adipic acid (mp 151–153 °C), octanedioic acid (11, mp 138–140 °C), and glutaric acid (mp 96–97 °C).

Investigation of the Oily Product from Ozonolysis of Cyclohexene. A sample of the oily residue obtained in the preceding experiment from ozonolysis of cyclohexene was examined by gas chromatography at 100–120 °C, using a 10 ft × $^1/_4$ in. column of silicone gum rubber (SE-30) on 100/120 mesh Chromosorb W. Two peaks were obtained, a large peak at the shorter retention time and a very minor peak at a considerably longer retention time. The two products were separated by preparative chromatography using the same column. The major peak was identified as adipaldehyde via its IR spectrum (a very strong aldehydic carbonyl band at 1725 cm^{-1}, CH bands at 2875 and 2980 cm^{-1}, and various other bands at 950, 1000, 1175, 1230, 1370, and 1425 cm^{-1}), NMR spectrum [a triplet at δ 9.73 (corresponding to two aldehydic protons) and multiplets at δ 2.42–2.52 (methylene protons next to carbonyls) and δ 1.57–1.68 (the internal methylene protons)] and mass spectrum (small molecular ion peak at m/c 114, plus various other peaks). In addition, a small portion of the dialdehyde was converted, upon exposure to air, to pure adipic acid (mp 152–153 °C).

The minor gas chromatography peak appears to consist of a mixture of the methyl ester of the aldehyde acid (corresponding to adipaldehyde and adipic acid) and dimethyl adipate. The NMR spectrum shows a small triplet (less than one proton) at δ 9.73 (an aldehydic proton), a large singlet at δ 3.62 (methyl ester protons), and multiplets at δ 2.42–2.52 (methylene protons next to aldehyde carbonyl), δ 2.27–2.37 (methylene protons next to ester carbonyl), and δ 1.58–1.68 (remainder of methylene protons). Except for the bands associated with the aldehyde group and adjacent methylene group, the NMR spectrum was identical with that for an authentic sample of dimethyl adipate. The bands associated with the aldehyde group were at the same positions as those found in the adipaldehyde NMR spectrum. The IR spectrum was also very similar to that of authentic dimethyl adipate.

Oily Product from Ozonolysis of Cyclopentene. Gas chromatographic analysis of this product, as described for that from cyclohexene, also showed a major (short retention time) and a very minor (longer retention time) peak. The retention time for the first peak was the same as that for an authentic sample of glutaraldehyde. In addition, the IR spectrum showed as significant bands a strong aldehyde carbonyl band at 1730 cm^{-1} and CH bands at 2875 and 2950 cm^{-1}. The NMR spectrum was identical with that of an authentic sample of glutaric dialdehyde, showing peaks at δ 9.73 (triplet, two aldehydic protons), 2.46–2.58 (multiplet, methylene protons next to aldehydic carbonyls), and 1.80–1.95 (multiplet, internal methylene protons). The mass spectrum showed a small molecular ion peak at m/c 100.

The minor gas chromatographic product, analogous to that from cyclohexene, appears to be a mixture of methyl esters of the aldehyde acid (corresponding to glutaric acid) and of glutaric acid. The NMR spectrum showed a minor aldehydic proton triplet at δ 9.72, a singlet at δ 3.62 (the methyl ester protons), and multiplets at δ 2.49–2.57 (methylene protons next to aldehyde carbonyl), δ

2.32–2.42 (methylene protons next to ester carbonyls), and δ 1.79–1.93 (internal methylene protons). Except for the protons associated with the aldehyde carbonyl and adjacent methylene groups, the NMR spectrum was identical with that of an authentic sample of dimethyl glutarate. The IR spectrum also was similar to that of dimethyl glutarate.

Oily Product from Ozonolysis of Cyclooctene. The gas chromatographic analysis showed two peaks analogous to those obtained from cyclopentene and cyclohexene. Mass spectroscopy showed small molecular ion peaks for octanedial (m/c 142), the corresponding aldehydic acid (158), and dimethyl octanedioate (202). After the products were separated, the NMR spectrum of the major product (octanedial) showed a triplet at δ 9.75 (two aldehydic protons) and multiplets at δ 2.25–2.55 (four protons of methylene groups next to carbonyl) and δ 1.3–1.7 (eight central methylene protons).

Peroxidic Products from Ozonolysis in Dioxane or Dimethoxyethane. A. Cyclooctene (50 mmol) in 100 mL of dioxane was ozonized with 50 mmol of ozone in an ozone–oxygen stream at 5 °C. The reaction mixture was evaporated on a rotary evaporator under reduced pressure, leaving a crystalline solid. After the material had been washed several times with acetone it melted at 90–92 °C (89% yield based on structure **12a**). The same material was obtained from ozonolysis in 1,1-dimethoxyethane at −60 °C (yield 89%). Anal. Calcd for $C_{24}H_{42}O_9$: C, 60.74; H, 8.92; O, 30.34; M_r, 474.6. Found: C, 60.79; H, 8.76; O, 30.39; M_r (cryoscopic in naphthalene), 472.5.

The material was soluble in 10% sodium hydroxide solution and gave a positive peroxide test with KI in glacial acetic acid. Characterisitic IR bands were at 1708 cm^{-1} (carbonyl), 2940 and 2860 cm^{-1} (CH), 1118 cm^{-1} (ether and peroxide groupings), and also 1540, 1460, 1258, 1005, 980, 800, and 730 cm^{-1}. NMR bands were found at δ 9.75 (triplet, aldehyde proton), 5.1–5.23 and 3.7 (multiplets, protons attached to ozonide carbons), 2.3–2.47 (multiplet, CH_2 protons next to carbonyl), and δ 1.35 and 1.7 (muliplets, remaining CH_2 protons). The mass spectrum showed no parent peak but did show a peak at m/c 430 for **12a** minus carbon dioxide.

Peroxide **12a** was also obtained (in 87% yield) from ozonolysis of cyclooctene in dioxane with 1.5 molar equiv of ozone.

B. Cyclohexene ozonized in dioxane in the same manner as cyclooctene afforded an 89% yield of a peroxidic paste which was characterized as **12b**. Anal. Calcd for $C_{18}H_{30}O_9$: C, 55.37; H, 7.75; O, 36.88; M_r, 390.4. Found: C, 54.97; H, 7.17; O, 37.38; M_r (cryoscopic in naphthalene), 390.8.

The material was soluble in 10% sodium hydroxide and gave a positive peroxide test with KI in acetic acid. Significant IR bands were at 1708 (carbonyl), 2900 (CH), and 1105 cm^{-1} (ether and peroxide groupings). NMR bands occurred at δ 9.75 (triplet, 1 H, aldehyde), δ 5.2–5.3 and 3.65 (muliplets, ozonide peroxy and ether protons), δ 2.4–2.5 (multiplet, CH_2 next to carbonyl), and 1.5–1.7 (mulitplet, remaining CH_2 protons).

Peroxidic Products from Ozonolysis in the Presence of Methanol. A. Cyclooctene (5/mmol) in 100 mL of diethyl ether plus 4 mL of methanol, ozonized with 50 mmol of ozone in an ozone–oxygen stream, afforded a syrupy liquid, boiling at 130–131 °C, in 95% yield based on structure **13a** or **14**. The material gave a positive peroxide test with KI in acetic acid. Although the material showed a strong carbonyl band in the IR spectrum, the aldehyde proton and the methylene protons next to a carbonyl were relatively weak, although distinct and definite, in the NMR spectrum. For this reason, a mixture of **13a** and **14**, or of **13a** and its methanol hemiacetal, is a possibility. Anal. Calcd for $C_{27}H_{54}O_{12}$ (**13a** or **14**): C, 56.82; H, 9.53; O, 33.64; M_r, 570.7. Calcd for $C_{28}H_{58}O_{13}$ (methanol hemiacetal of **13a**): C, 55.79; H, 9.70; 34.51 M_r, 602.7. Found: C, 56.08; H, 9.77; O, 34.11 M_r (cryoscopic in naphthalene), 566.4.

Significant IR bands were found at 3300 cm^{-1} (hydroxyl), 2960 and 2940 cm^{-1} (CH groupings), 1710 cm^{-1} (carbonyl), 1430 cm^{-1} (methyl), and 1195, 1165, 1080 cm^{-1} (ether and peroxy groupings). The NMR spectrum showed a relatively weak band at δ 9.73 (triplet, aldehyde proton), multiplets at δ 5.12–5.25 and 4.7–4.85 (peroxide protons), singlets at δ 3.43 and 3.54 (OCH_3 protons), a small multiplet at δ 2.3–2.48 (CH_2 next to carbonyl), and a multiplet at δ 1.3–1.65 (remaining CH_2 protons).

When **cyclooctene** was ozonized in pure methanol, a dimeric rather than a trimeric peroxide resulted. The syrupy liquid boiled at 120 °C and was obtained in 75% yield, on the basis of structure **13b**. Since the NMR spectrum presented only a weak band for an aldehyde proton, **13b** may be contaminated with its methanol hemiacetal or the dimeric equivalent of **14**. Anal. Calcd for $C_{18}H_{36}O_8$ (**13b**): C, 56.82; H, 9.54; O, 33.64; M_r, 380.5 Calcd for $C_{19}H_{40}O_9$ (methanol hemiacetal of **13b**): C, 55.32; H, 9.77; O, 34.91; M_r, 412.5. Found: C, 55.50; H, 9.13; O, 35.24 M_r (cryoscopic in naphthalene), 393.1.

The IR spectrum revealed bands at 3200 cm^{-1} (hydroxyl), 2920 and 2845 cm^{-1} (C–H), 1700–1725 cm^{-1} (carbonyl), 1430 cm^{-1} (CH_3), and 1165, 1180 and 1195 cm^{-1} (peroxy and ether bands). The NMR spectrum consisted of bands at δ 9.75 (weak triplet, aldehyde proton), δ 5.2 and 4.6–4.7 (multiplet, peroxy carbon protons), δ 3.4 and 3.45 (singlets, methoxy protons), δ 2.24–2.45 (relatively weak multiplet, methylene protons next to carbonyl), and δ 1.3–1.6 (multiplet, remaining methylene protons).

B. Cyclohexene (50 mmol), in 100 mL of dioxane plus 4 mL of methanol, was ozonized at 5 °C with an ozone–oxygen stream containing 50 mmol of ozone. The yield of syrupy liquid, based on structure **15b**, was 92–96%. Because of its molecular weight, elementary analyses and NMR spectrum, which showed only a weak aldehyde proton and methylene protons next to carbonyl bands, the material is thought to be a mixture of **15b**, **16a**, and, possibly, either **16b** or a small amount of a dimer analogous to **13b**. The slightly high oxygen and active oxygen contents could indicate a very small amount of material with a higher active oxygen content.

Anal. Calcd for $C_7H_{14}O_4$ (**15b**): C, 51.84; H, 8.70; O, 39.46; active oxygen, 9.87; M_r, 162.18. Calcd for $C_8H_{18}O_5$ (**16a**): C, 49.47; H, 9.34; O, 41.19; active oxygen, 8.24; M_r, 194.22. Calcd for $C_9H_{20}O_5$ (**16b**): C, 51.90; H, 9.68; O, 38.42; active oxygen, 7.68; M_r; 208.25. Calcd for $C_{14}H_{28}O_8$ (analogue of **13b**): C, 51.83; H, 8.70; O, 39.46; active oxygen, 9.86; M_r, 324.38. Found: C, 49.12; H, 8.20; O, 42.50; active oxygen, 10.48; M_r (cryoscopic in naphthalene) 208.85, 209.60.

Significant IR bands were found at 3400 and 3200 cm^{-1} (hydroxyl), 1720 cm^{-1} (carbonyl), 1195, 1105 and 1070 cm^{-1} (peroxy) and 1430 cm^{-1} (CH_3). The NMR spectrum had bands at δ 9.72 (weak triplet, aldehyde proton), δ 5.1–5.25 and 4.6–4.8 (multiplets, peroxy carbon protons), δ 3.65 and 3.45 (strong singlets, methoxy protons, first one twice as large as second one), δ 2.24–2.4 (moderately weak multiplet, methylene protons next to carbonyl), and δ 1.4–1.6 (multiplet, remaining methylene protons).

Ozonolyses in Acetic Acid. Fifty millimoles of cyclohexene in 100 mL of glacial acetic acid plus 10 mL of formic acid was reacted with 50 mmol of ozone in an ozone–oxygen stream at 10 °C. The solution was purged with nitrogen, after which it was heated to 110 °C while a stream of oxygen was passed into it. After about 8–10 h, the reaction solution was no longer peroxidic. Evaporation of the solvent left a white residue which, upon recrystallization from ethyl acetate, melted at 152 °C. The yield of adipic acid was 77%. Similarly, glutaric acid (mp 97 °C) was obtained from cyclopentene in 52% yield. Identifications were by comparison of melting points and IR and NMR spectra with those of authentic samples.

Acknowledgment. This work was supported by grant (F-042) from the Robert A. Welch Foundation, for which the authors are grateful. Dr. Habib acknowledges with gratitude a leave of absence from the National Research Center and the Egyptian Petroleum Research Institute, Cairo, Egypt.

Registry No. **2**, 60-29-7; **11**, 505-48-6; **12a**, 90460-81-4; **12b**, 90460-82-5; **13a**, 90460-83-6; **13b**, 90460-84-7; **15b**, 42324-19-6; **16a**, 90460-85-8; O_3, 10028-15-6; AcOEt, 141-78-6; MeOH, 67-56-1; CH_2Cl_2, 75-09-2; $MeCH(OMe)_2$, 534-15-6; HCO_2H, 64-18-6; cyclohexene, 110-83-8; cyclooctene, 931-88-4; cyclopentene, 142-29-0; adipic acid, 124-04-9; glutaric acid, 110-94-1; adipaldehyde, 1072-21-5; methyl 6-oxohexanoate, 6654-36-0; dimethyl adipate, 627-93-0; glutaraldehyde, 111-30-8; methyl 5-oxopentanoate, 6026-86-4; dimethyl glutarate, 1119-40-0; octanedial, 638-54-0; 8-oxooctanoic acid, 929-48-6; dimethyl octanedioate, 1732-09-8; dioxane, 123-91-1; glacial acetic acid, 64-19-7.