Synthesis of Pentaoxa[5]peristylanes

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The synthesis of alkyl-substituted pentaoxa[5]peristylanes has been accomplished by ozonolysis of 2,3-bis-*endo*-7-*anti*-triacylnorbornenes **6a**−**d** and by direct chemical transformation of the tetraacetal tetraoxa cages **11** and **12**. Various reaction conditions have been used to optimize the overall yield for the synthesis of methyl group substituted pentaoxa[5]peristylane **7d**. Ozonolysis of **6d** in $CDCl_3$ at −78 °C without reduction was performed to study the ozonolysis chemistry of the triacylnorbornenes **6a**−**d**. The synthesis of the parent (unsubstituted) compound **25** of pentaoxa[5]peristylane has been accomplished by a three-step efficient sequence with a maximum 45% overall yield via ozonolysis of the dihemiacetal **24**. The structure of pentaoxa[5]peristylanes was proven by X-ray analysis of the parent compound **25**. The syntheses of the triacetal tetraoxa cage **26**, a new type of oxa cage, and a new entry for the synthesis of the parent compound **33** of tetraacetal tetraoxa cages were also demonstrated.

Introduction

The synthesis and chemistry of polycyclic cage compounds have attracted considerable attention in recent years.[1] The vast majority of the work reported in this area has dealt with carbocyclic cage compounds, such as adamantane,[2] triprismane,[3] tetraprismane (cubane),[4] pentaprismane,[5] homopentaprismane,[6] hexaprismane,[7] heptacyclotetradecane (HCTD),[8] pagodane,[9] dodecahedrane,[10] and fullerene (C60).[11] On the other hand, the synthesis and chemistry of heterocyclic cage compounds have received less attention. However, there are some reports regarding the chemistry[12] and synthesis[13−18] of oxa cage compounds in the literature. This class of heterocyclic cages is synthesized by intramolecular alkene−oxirane ($2\sigma-2\pi$) photocycloaddition,[13] by transannular cyclization of suitable compounds,[14] by tandem cyclization,[15] by dehydration of diols having the proper stereochemistry,[16] by base-promoted rearrangement,[17] and by intramolecular etherification of the alkene bond with organoselenium reagents.[18]

We visualized that elaboration of oxa cages from carbocyclic cages might be achieved by replacing the skeletal carbon atoms with oxygen atoms at the proper positions and by extending the skeletal backbone. For instance, starting with homopentaprismane (**A**), one might be able to "create" the following three different types of oxa cage compounds, types **B**, **C**, and **D** (Scheme 1). Also, we can elaborate pentaoxa[5]peristylane **F** from [5]peristylane **E**. We viewed types **C**, **D**, and **F** oxa cages as cage backboned diacetal, tetraacetal, and pentaacetal crown ethers, respectively. Types **D** and **F** oxa cages, in particular, can be viewed as a class of cage-backboned coronands (crown ethers) containing a 2*n*-crown-*n* moiety in which the ligand oxygen atoms are separated by one

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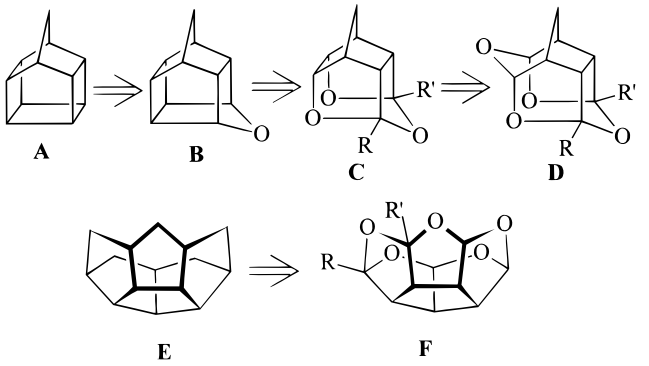
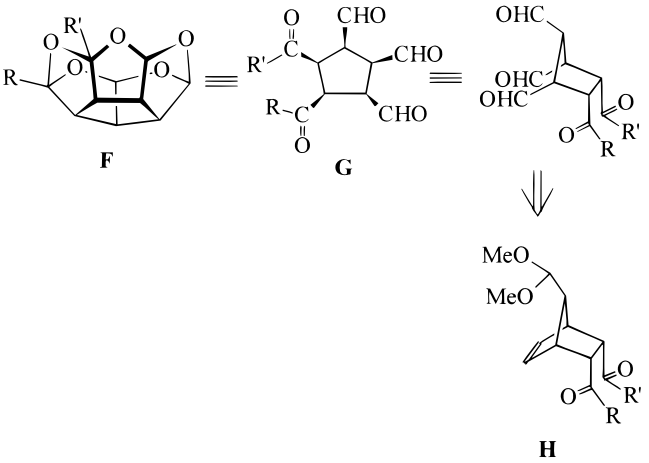
Scheme 1



Scheme 2



bridging carbon atom, whereas most known coronands are composed of repeating ethyleneoxy units to give the 3*n*-crown-*n* moiety. All three types of oxa cages, **C**, **D**, and **F**, might exhibit interesting cation-binding properties. Particularly, [5]peristylane[19] and pentaoxa[5]peristylane **F** (R = R′ = H) are a class of aesthetically pleasing and topologically novel molecular entities which possess bowl-shaped structures.

From the standpoint of retrosynthetic analysis, we realized that pentaoxa[5]peristylane **F** can be regarded as the cyclic acetal form of *all-cis* 1,2,3,4,5-pentacarbonylcyclopentane **G** (Scheme 2). To access **G**, we decided to utilize the rigid, stereochemically well-defined norbornene framework through strategic positioning of appropriate substituents that could serve as surrogates for the carbonyl functionality. Accordingly, we chose the norbornene derivatives **H** as the starting material for synthesizing the pentaoxa[5]peristylanes **F**.

The utility of ozonolysis in organic synthesis usually centers on the chemical transformation of an alkene bond to carbonyl groups or to an α-alkoxy hydroperoxide if an alcohol is present.[20] Recently, we utilized the ozonolysis reaction for the synthesis of a series of oxa cage compounds, such as diacetal trioxa cages,[21] triacetal trioxa cages,[22] tetraacetal tetraoxa cages,[23] and tetraacetal pentaoxa cages.[24] Later on, we investigated the chemical nature of the acetal group of tetraoxa cages and discovered a hydride rearrangement and a one-pot conversion from oxa cages to aza cages.[25] We also developed a method for the synthesis of diacetal trioxa cages[26] and dioxa cages[27] by iodine-induced cyclization reaction. As part of a program that involves the synthesis, chemistry, and applications of new heterocyclic cages, we report here the full details of the synthesis of alkyl-substituted pentaoxa[5]peristylanes[28] via the ozonolysis of 2,3-bis-*endo*-7-*anti*-triacylnorbornenes and via the chemical transformation from tetraoxa cages to pentaoxa[5]-peristylanes. We also wish to report the synthesis of the parent (unsubstituted) compound[29] of pentaoxa[5]peristylanes and the parent compound of tetraacetal tetraoxa cages via the ozonolysis of dihemiacetal derivatives of norbornene and to report the X-ray structure of pentaoxa-[5]peristylane **25**. Also, we wish to report the synthesis of triacetal tetraoxa cage **26**, a new type of oxa cage.

Results and Discussion

Synthesis of Pentaoxa[5]peristylanes and Conversion of Tetraoxa Cage to Pentaoxa Cage. Reaction of 5-trimethylsilylcyclopentadiene **1** with trimethyl orthoformate **2** in the presence of trimethylsilyl triflate (TMSOTf) in dichloromethane at −45 °C gave compound **3**,[30] which was used for the next reaction without purification. Diels−Alder reaction of compound **3** with *cis*-enediones **4a**−**d**[23,26] in dichloromethane at 0 °C for 72 h gave the *anti-endo* adducts **5a**−**d** in 70−75% yields. Treatment of **5a**−**d** with $Cu(BF_4)_2$ or methanesulfonic acid in dichloromethane at 25 °C gave the hydrolysis products **6a**−**d** in 75−80% yields. Ozonolysis of **6a**−**c** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide, gave the pentaoxa[5]peristylanes **7a**−**c** in 75−80% yields (Scheme 3). The amounts of the tetraoxa cages **8**, **9**, and **10** were too small to be isolated. Ozonolysis of **6d** under the same reaction conditions gave the tetraoxa cage compounds **11** (34%) and **12** (32%) and the pentaoxa[5]peristylane **7d** (20%). Tetraoxa cage **11** leaves one acetyl group intact, not participating the cyclization reaction, whereas tetraoxa cage **12** leaves one formyl group intact. Thus, the synthesis of alkyl-substituted pentaoxa[5]peristylanes was accomplished for the first time in our lab.[28]

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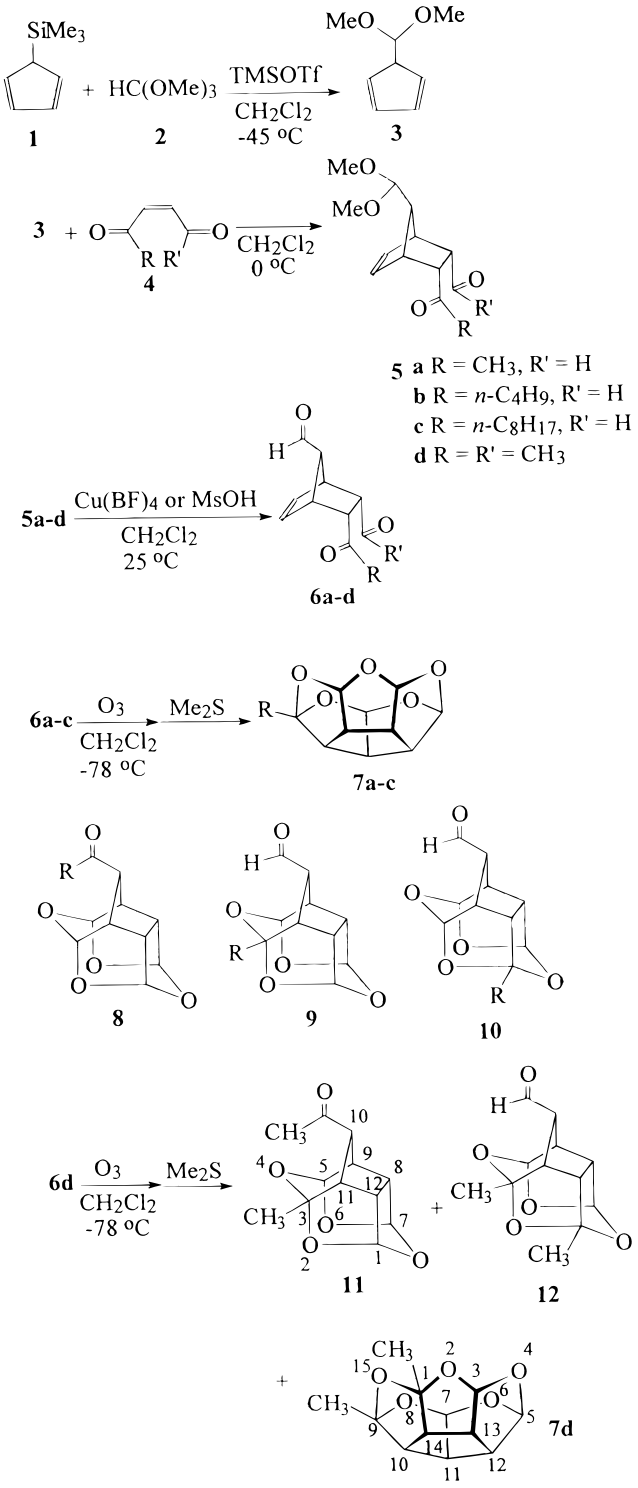
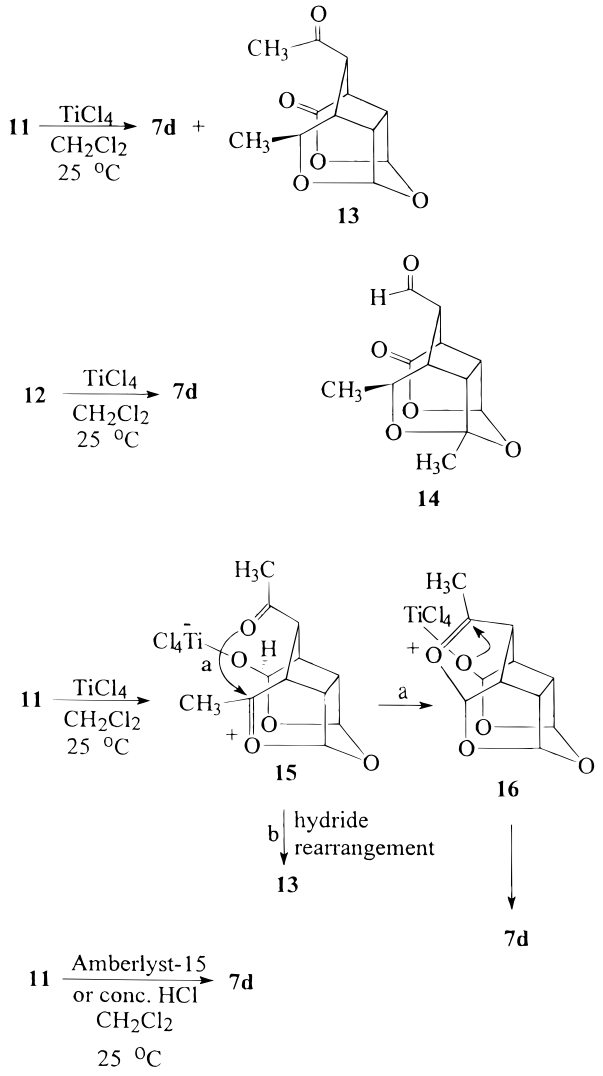
Scheme 3



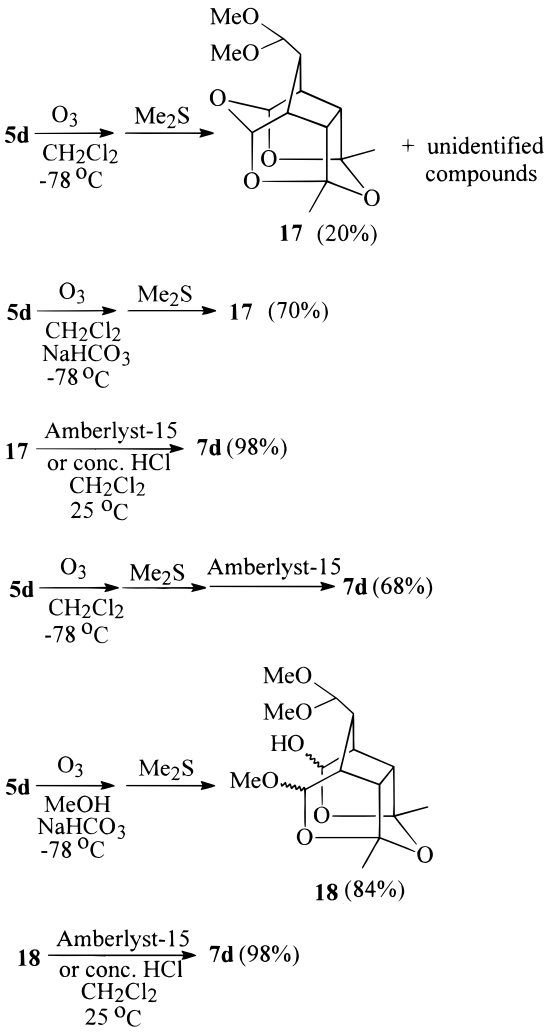
Scheme 4



We also performed the chemical transformations of tetraoxa cages **11** and **12** to pentaoxa[5]peristylane **7d**. Treatment of **11** with a catalytic amount of $TiCl_4$ in dichloromethane at 25 °C for 4 h gave the pentaoxa[5]-peristylane **7d** in 75% yield and the hydride rearrangement product **13** in 20% yield (Scheme 4). Reaction of **12** under the same reaction conditions gave **7d** in 90% yield. The amount of **14** was too small to be isolated. A mechanism was proposed for the conversion of **11** to **7d** and **13**. Coordination of $TiCl_4$ regioselectively to the O_4 oxygen atom of **11** followed by cleavage of the C_3-O_4 bond gives the oxonium ion **15**. Nucleophilic addition of the carbonyl group on the apical carbon to the oxonium ion gives the oxonium ion **16** (route a). Nucleophilic addition of the alkoxide ion to the oxonium ion gives the pentaoxa cage **7d**. On the other hand, hydride rearrangement[25] (route b) of **15** gives the product **13**. A similar mechanism can be applied for the conversion of **12** to **7d**. These results indicate that the nucleophilic addition of the formyl group on the apical carbon to the oxonium ion **15** may be faster than that of the acetyl group. Also, the nucleophilic addition of the acetyl group on the apical carbon to the oxonium ion **15** may be faster than the hydride rearrangement. Treatment of **11** and **12** with Amberlyst-15 or concentrated hydrochloric acid in dichloromethane at 25 °C gave the pentaoxa[5]peristylane **7d** in a quantitative yield. Thus, we have demonstrated for the first time the direct conversion of tetraacetal tetraoxa cage to pentaoxa[5]peristylane. Also, we have accomplished the synthesis of alkyl-substituted pentaoxa[5]-peristylanes in 35−45% overall yields, starting from compound **3**.

Optimization of the Overall Yield of 7d with Various Reaction Conditions. Ozonolysis of **5d** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide, gave compound **17** in 20% yield with several unidentified compounds. Ozonolysis of **5d** in dichloromethane at −78 °C in the presence of sodium

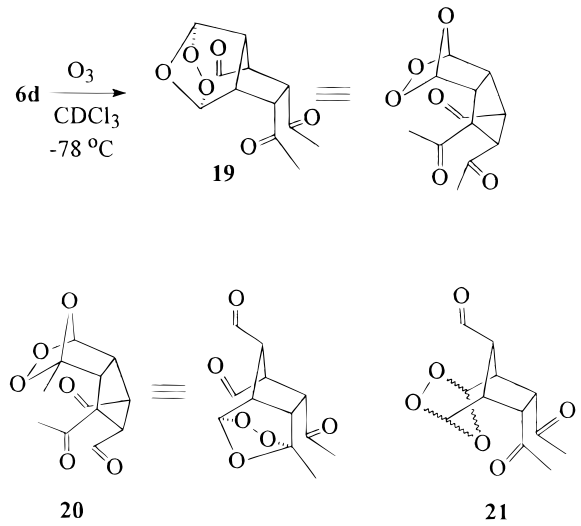
Scheme 5



bicarbonate, followed by reduction with dimethyl sulfide, gave **17** in 70% yield (Scheme 5). Treatment of **17** with Amberlyst-15 or concentrated hydrochloric acid in dichloromethane at 25 °C gave the pentaoxa[5]peristylane **7d** in a quantitative yield. Ozonolysis of **5d** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide and then treatment of the mixture with Amberlyst-15, gave the pentaoxa cage **7d** in 68% yield. Ozonolysis of **5d** in methanol at −78 °C in the presence of sodium bicarbonate, followed by reduction with dimethyl sulfide, gave compound **18** in 84% yield. The stereochemistry of the hydroxy and methoxy groups of **18** was not determined. Treatment of **18** with Amberlyst-15 or concentrated hydrochloric acid in dichloromethane at 25 °C gave the pentaoxa cage **7d** in a quantitative yield. Thus, we have optimized the overall yield of pentaoxa[5]peristylane **7d** up to 64%, starting from **3**, via compound **18**.

Ozonolysis Chemistry on Compound 6d. We also focused our attention on the ozonolysis chemistry to clarify the site selectivity of the final ozonide formation. Ozonolysis of **6d** in $CDCl_3$ at −78 °C gave the final ozonide **19** (>95%) (Scheme 6). The isomers **20** and **21**

Scheme 6



were obtained in a negligible amount. The ^1H and ^{13}C NMR spectra of **19** were taken at −30 °C right after the ozonation reaction without purification. The ^1H NMR spectrum of **19** revealed one singlet at δ 9.93 for the aldehyde proton, two singlets at δ 6.53 and 6.37 for the 1,2,4-trioxolane ring protons, and two singlets at δ 2.29 and 2.03 for the two methyl ketone protons. The ^{13}C NMR spectrum of **19** displayed two singlets at δ 205.81 and 204.60 for the two methyl ketone carbons, one peak at δ197.53 for the aldehyde carbon, and two peaks at δ 100.83 and 100.48 for the 1,2,4-trioxolane ring carbons. These results are consistent with our previous report[23d] in that it is the *anti* carbonyl group on the apical carbon rather than the *endo* carbonyl group that reacts intramolecularly with the carbonyl oxide group to form the final ozonide.

Synthesis and Structure of the Unsubstituted Pentaoxa[5]peristylane 25 and New Oxa Cage 26. In the course of synthesis of cage compounds, the synthesis of the parent (unsubstituted) compound is also important . Diels−Alder reaction of compound **3** with maleic anhydride in dichloromethane at 0 °C for 24 h gave the *endo* adduct **22** in 90% yield. Reaction of **22** with $LiAlH_4$ in dry THF at refluxing temperature gave the diol **23** in 70% yield. Swern oxidation of **23** in dichloromethane gave the dihemiacetal **24** in 80% yield, which is a mixture of stereoisomers. Ozonolysis of the crude product **24** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide, gave the parent pentaoxa-[5]peristylane **25** in a low yield (20%) with unidentified compounds. Ozonolysis of **24** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide and then treatment of the reaction mixture with Amberlyst-15 or concentrated HCl, gave **25** in 85% yield (Scheme 7). Reaction of furan with dimethyldioxirane[32] at −78 °C, followed by addition of compound **3** at 0 °C, gave the *endo* adduct **24** in 58% yield. Thus, the parent pentaoxa[5]-peristylane **25** was obtained in 45% overall yield by a three-step sequence, starting from compound **1**. This is the shortest and most efficient sequence for the synthesis of **25**.[33] Ozonolysis of the diol **23** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide and then treatment of the reaction mixture with Amberlyst-

(31) Ozonolysis of **6d** in dichloromethane at −78 °C followed by removal of the solvent at room temperature without reduction gave oligomeric or polymeric products which were not soluble in $CDCl_3$ for taking NMR spectra.

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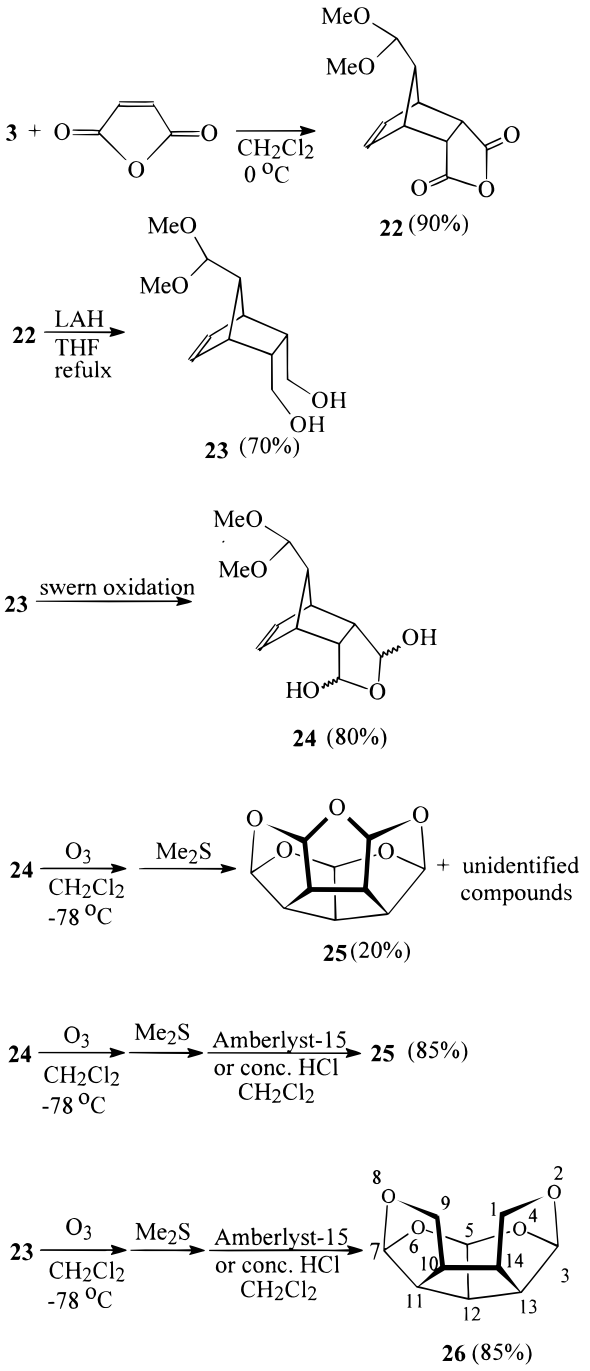
Scheme 7



15, gave the tetraoxa cage compound **26** in 85% yield. Tetraoxa cage **26** possesses a new type of skeleton.

The IR spectrum of **26** showed no hydroxyl and carbonyl absorptions. The ^{1}H NMR spectrum of **26** revealed one doublet at δ 5.84 for the two acetal protons on C-3 and C-7, one doublet at δ 5.70 for the acetal proton on C-5, and two doublets of doublets at δ 4.29 and 4.02 for the methylene protons on C-1 and C-9. The ^{13}C NMR spectrum of **26** displayed one peak at δ 112.18 for the acetal carbons C-3 and C-7, one peak at δ 111.50 for the acetal carbon C-5, and one peak at δ 70.53 for the secondary carbons C-1 and C-9. The high-resolution mass

(33) After we accomplished the synthesis of alkyl-substituted pentaoxa[5]peristylanes,[28] Prof. Mehta et al. reported the synthesis of **25** by a 10-step sequence in a 0.3% overall yield.[29]

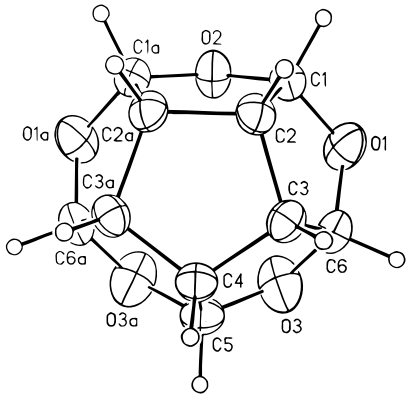


Figure 1. ORTEP diagram of **25**.

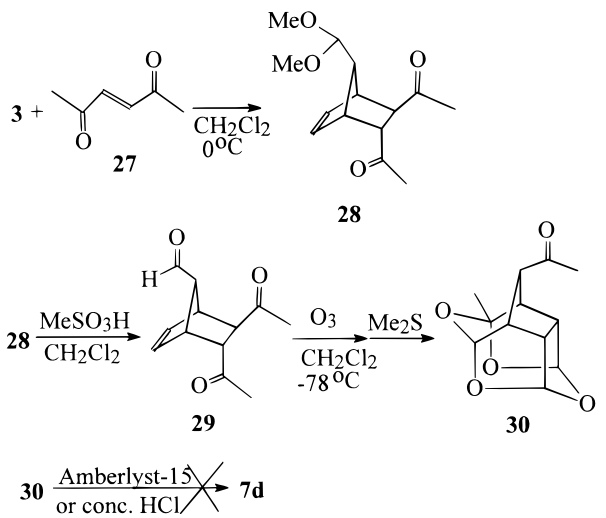
spectrum of **26** exhibited the correct value. The ^{1}H NMR spectrum of **25** revealed one broad singlet at δ 4.90 for the five equivalent acetal protons and another broad singlet at δ 2.76 for the five methine protons (with DMSO-d_6 as solvent). The ^{13}C NMR spectrum of **25** displayed one peak at δ 113.33 for the five acetal carbons and one peak at δ 57.45 for the five methine carbons. The structure of pentaoxa[5]peristylanes was also proven by X-ray analysis of the crystalline compound **25** (Figure 1).

Compound **25** crystallizes from dichloromethane−hexane as colorless needles with crystal dimensions 0.50 × 0.12 × 0.12 mm. The molecule crystallizes in an orthorhombic space group *Pnma*, with unit cell parameters a = 13.3576(6), b = 10.9486(5), and c = 5.5123(3) Å, V = 806.2(3) Å^3, Z = 4, with high crystal density D_c = 1.732 g/cm^3. Compound **25** does not possess the anticipated C_{5v} symmetry in the solid state but displays C_s symmetry in the crystal with the crystallographic mirror plane passing through O_2, C_4, and C_5. The distances from O_1 to C_{6a}, O_1 to O_{3a}, and O_2 to O_{3a} are 4.25, 3.88, and 3.39 Å, respectively, on the basis of calculations with Simens SHELXTL PLUS (VMS). These distances are greater than the summation of the diameter of sodium cation and the van der Waals radius of the carbon or oxygen atom. Therefore, we estimate that the cavity of pentaoxa[5]peristylanes is large enough for binding a sodium cation or lithium cation. In other words, we expect that pentaoxa[5]peristylanes may exhibit interesting cation-binding properties. A study on the applications of pentaoxa[5]peristylanes for their cation-binding properties is undertaken.

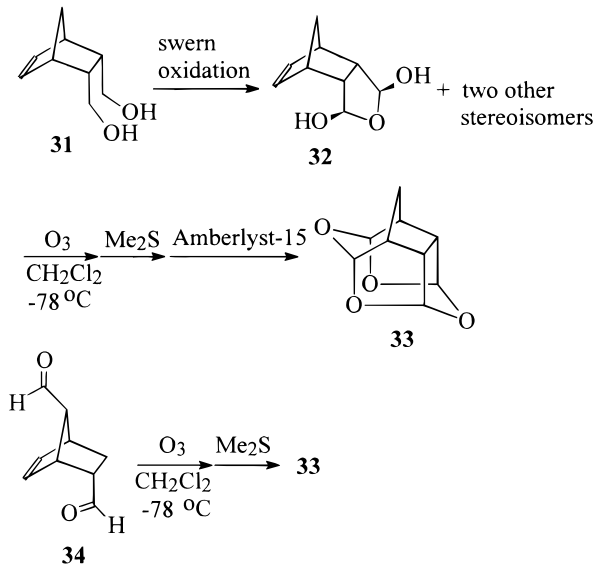
Synthesis of Other Oxa Cages. Diels−Alder reaction of compound **3** with *trans*-endione **27**[22] in dichloromethane at 0 °C for 72 h gave the *trans*-adduct **28** in 75% yield. Treatment of **28** with methanesulfonic acid in dichloromethane at 25 °C gave the hydrolysis product **29** in 80% yield. Ozonolysis of **29** in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide, gave the tetraacetal tetraoxa cage **30** in 90% yield (Scheme 8). Treatment of **30** with Amberlyst-15 or concentrated HCl in dichloromethane at 25 °C remained unchanged. No detectable amount of the pentaoxa[5]peristylane **7d** was obtained.

We have also utilized a sequence similar to that shown in Scheme 7 to synthesize the parent compound of tetraacetal tetraoxa cages. Reduction of cyclopentadiene−maleic anhydride adduct with $LiAlH_4$ in dry THF at refluxing temperature gave the diol **31**. Swern oxidation

Scheme 8



Scheme 9



of **31** in dichloromethane gave the dihemiacetal **32** as the major product and two other stereoisomers as the minor products. The stereochemistry of the hydroxy groups of **32** was determined on the basis of NOE experiments. Irradiating the alkene protons (δ 6.10) of **32** gives 3.8% enhancement for the hemiacetal proton absorptions and 4.0% enhancement for the bridgehead proton absorptions. Irradiating the hemiacetal protons (δ 4.97) of **32** gives 4.7% enhancement for the alkene proton absorptions and 4.8% enhancement for the bridgehead proton absorptions. Ozonolysis of the mixture of **32** and its stereoisomers in dichloromethane at −78 °C, followed by reduction with dimethyl sulfide and then treatment with Amberlyst-15, gave the parent compound **33** in 85% yield (Scheme 9), a new entry for the synthesis of **33**. The parent tetraoxa cage **33** was also obtained by ozonolysis of 2-*endo*-7-*anti*-diformylnorbornene **34**.[23d]

Conclusion

We have accomplished for the first time the synthesis of alkyl-substituted pentaoxa[5]peristylanes. Ozonolysis of **6a**−**c** in dichloromethane at −78 °C followed by reduction with Me_2S gave the pentaoxa[5]peristylanes **7a**−**c** in high yields. Ozonolysis of 7-*anti*-formyl-2,3-bis-*endo*-diacetylbicyclo[2.2.1]-5-heptene **6d** under the same reaction conditions gave the tetraoxa cages **11** and **12** and the pentaoxa[5]peristylane **7d**. The tetraoxa cages **11** and **12** can be converted into the pentaoxa[5]-peristylane **7d** by treatment with $TiCl_4$ or Amberlyst-15 or concentrated HCl in dichloromethane. Optimization of the overall yield of the pentaoxa cage **7d** was performed with various reaction procedures. We have also demonstrated that it is the *anti* carbonyl group on the apical carbon rather than the *endo* carbonyl group that reacts intramolecularly with the carbonyl oxide group to form the final ozonide, consistent with our previous report.[23d] The synthesis of the parent compound of pentaoxa[5]peristylanes was accomplished in a 45% overall yield by a three-step sequence. The structure of pentaoxa[5]peristylanes was proven by X-ray analysis of the parent compound **25**. The synthesis of a new type of oxa cage, **26**, was also accomplished. The synthesis of the parent compound **33** of tetraacetal tetraoxa cages via a new route was also performed.

Experimental Section

General. Melting points were determined in capillary tubes and are uncorrected. Infrared spectra were recorded in $CHCl_3$ solutions or as neat thin films between NaCl disks. ^{1}H NMR spectra were determined at 300 MHz, and ^{13}C NMR spectra were determined at 75 MHz on Fourier transform spectrometers. Chemical shifts are reported in ppm relative to TMS in the solvents specified. The multiplicities of ^{13}C signals were determined by DEPT techniques. High-resolution mass values were obtained with a high-resolution mass spectrometer at the Department of Chemistry, National Tsing Hua University. Elemental analyses were performed at the microanalysis laboratory of this department. X-ray analyses were carried out on a diffractometer at the Department of Chemistry, National Tsing Hua University. For thin-layer chromatography (TLC) analysis, precoated TLC plates (Kieselgel 60 F_{254}) were used, and column chromatography was done by using Kieselgel 60 (70−230 mesh) as the stationary phase. THF was distilled immediately prior to use from sodium benzophenone ketyl under nitrogen. CH_2Cl_2 was distilled from CaH_2 under nitrogen.

General Procedure for the Preparation of 2,3-Bis-*endo*-diacylnorbornenes 5a−**d**. To a solution of 5-trimethylsilylcyclopentadiene **1** (1.0 g, 7.3 mmol) in dichloromethane (30 mL) was added trimethyl orthoformate (0.85 g, 8.0 mmol) at 25 °C. The mixture was cooled to −40 °C, and a catalytic amount of TMSOTf (0.16 g, 0.73 mmol) was added at −40 °C. The reaction mixture was stirred at −40 °C for 0.5 h. The mixture was quenched by addition of a saturated $NaHCO_3$ aqueous solution. Extractive workup with dichloromethane followed by an ice−water wash, drying over K_2CO_3, and evaporating the solution at 0 °C afforded the crude product **3**,[30] which was kept at 0 °C without purification for the Diels−Alder reaction. To this crude product **3** in dichloromethane (30 mL) was added the *cis*-enedione **4d**[23] (0.89 g, 8.0 mmol) at 0 °C. The reaction mixture was stirred at 0 °C for 72 h. The solvent was evaporated, and the crude product was purified by column chromatography to give the *endo* adduct **5d** (1.0 g) in 55% overall yield. The same reaction conditions and procedure were applied to the preparation of **5b**−**d** in 70−75% yields.

2,3-Bis-*endo*-diacetyl-7-*anti*-dimethoxymethylbicyclo-[2.2.1]-5-heptene 5d: pale yellow oil liquid; IR (neat) 1710, 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.13 (brs, 2H), 4.22 (δ, J = 8.1 Hz, 1H), 3.42 (brs, 2H), 3.31 (s, 6H), 3.17 (brs, 2H), 2.05 (s, 6H), 2.00−1.97 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 205.99 (2CO), 132.07 (2CH), 102.99 (CH), 62.20 (CH), 57.45 (2CH), 53.90 ($2CH_3$), 47.89 (2CH), 29.86 ($2CH_3$); LRMS *m*/*z* (rel int) 252 (M^+, 10), 221 (100); HRMS (EI) calcd for

$C_{14}H_{20}O_4$ 252.1362, found 252.1375. Anal. Calcd for $C_{14}H_{20}O_4$: C, 66.63; H, 7.99. Found: C, 66.55; H, 7.94.

Hydrolysis of 5a−d. To a solution of **5d** (0.50 g, 2.00 mmol) in dichloromethane (30 mL) was added methanesulfonic acid ($MeSO_3H$) (0.19 g, 2.00 mmol) at 25 °C. The reaction mixture was stirred at room temperature for 15 min. After addition of saturated $NaHCO_3$ (20 mL) and extraction with CH_2Cl_2, the organic layer was washed with brine, dried over $MgSO_4$, and evaporated, and the residue was purified by column chromatography to give **6d** (0.33 g, 80%). The same reaction conditions and procedure were applied for the preparation of **6a−c** in 80−85% yields.

2-*endo*-7-*anti*-Diformyl-3-*endo*-acetylnorbornene 6a: pale yellow oil liquid; IR (neat) 2820, 2720, 1710 cm $^{-1}$; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.61 (d, J = 2.1 Hz, 1H), 9.52 (d, J = 2.4 Hz, 1H), 6.44 (dd, J = 6.0, 3.0 Hz, 1H), 6.10 (dd, J = 6.0, 3.0 Hz, 1H), 3.81−3.77 (m, 1H), 3.69 (brs, 1H), 3.58 (brs, 1H), 3.14−3.09 (m, 1H), 2.47 (d, J = 1.5 Hz, 1H), 2.21 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 205.20 (CO), 202.32 (CHO), 200.19 (CHO), 134.98 (CH), 131.78 (CH), 69.72 (CH), 59.05 (CH), 55.35 (CH), 48.27 (CH), 46.44 (CH), 28.75 (CH_3); LRMS m/z (rel int) 192 (M^+, 12), 191 (58), 190 (63), 163 (100); HRMS calcd for $C_{11}H_{12}O_3$ 192.0786, founf 192.0790. Anal. Calcd for $C_{11}H_{12}O_3$: C, 65.95; H, 10.07. Found: C, 65.87; H, 10.01.

2,3-Bis-*endo*-diacetyl-7-*anti*-formylnorbornene 6d: pale yellow oil liquid; IR (neat) 2820, 2720, 1710 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.60 (d, J = 2.1 Hz, 1H), 6.23 (brs, 2H), 3.54 (brs, 2H), 3.32 (brs, 2H), 2.39 (d, J = 2.1 Hz, 1H), 2.09 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 205.11 (2CO), 203.13 (CHO), 132.76 (2CH), 69.02 (CH), 56.74 (2CH), 47.91 (2CH), 29.93 ($2CH_3$); LRMS m/z (rel int) 266 (M^+, 15), 205 (45), 177 (100); HRMS (EI) calcd for $C_{12}H_{14}O_3$ 206.0943, found 206.0955. Anal. Calcd for $C_{12}H_{14}O_3$: C, 71.14; H, 8.54. Found: C, 71.22; H, 8.59.

General Procedure for the Ozonolysis of 6a−c. Formation of the Pentaoxa[5]peristylanes 7a−c. A solution of **6a** (0.50 g, 2.78 mmol) in dichloromethane (30 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution was added dimethyl sulfide (0.30 g, 4.86 mmol) at −78 °C. Then, the reaction mixture was stirred at room temperature for 5 h. The solvent was evaporated, and the crude product was purified by column chromatography to give the pentaoxa[5]peristylane **7a** (0.48 g) (78%).

1-Methyl-2,4,6,8,15-pentaoxahexacyclo[7.5.1.0^{3,13}.0^{5,12}.0^{7,11}.0^{10,14}]pentadecane 7a: white solid; mp 254−255 °C; IR ($CHCl_3$) 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.90 (d, J = 6.0 Hz, 2H), 5.87 (d, J = 5.4 Hz, 2H), 3.69−3.64 (m, 3H), 3.35−3.32 (m, 2H), 1.52 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 123.57 (C), 113.49 (2CH), 112.79 (2CH), 59.92 (CH), 58.74 (2CH), 58.24 (2CH), 39.42 (CH_3); LRMS m/z (rel int) 224 (M^+, 8), 209 (100); HRMS (EI) calcd for $C_{11}H_{12}O_4$ 224.0685, found 224.0692. Anal. Calcd for $C_{11}H_{12}O_4$: C, 63.44; H, 5.81. Found: C, 63.58; H, 5.87.

Ozonolysis of 6d. Formation of the Tetraacetal Tetraoxa Cages 11 and 12 and the Pentaoxa[5]peristylane 7d. A solution of **6d** (0.50 g, 2.43 mmol) in dichloromethane (30 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution was added dimethyl sulfide (0.30 g, 4.86 mmol) at −78 °C. Then, the reaction mixture was stirred at room temperature for 5 h. The solvent was evaporated, and the crude product was purified by column chromatography to give the tetraacetal tetraoxa cages **11** (0.208 g) (36%) and **12** (0.185 g) (32%) and the pentaoxa[5]peristylane **7d** (0.115 g) (20%).

3-Methyl-10-*syn*-acetyl-2,4,6,13-tetraoxapentacyclo[5.5.1.0^{3,11}.0^{5,9}.0^{8,12}]tridecane 11: white solid; mp 183−184 °C; IR ($CHCl_3$) 1710, 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.85 (d, J = 5.1 Hz, 1H), 5.79 (d, J = 5.4 Hz, 1H), 5.69 (d, J = 4.5 Hz, 1H), 3.54−3.36 (m, 2H), 3.17−3.10 (m, 3H), 2.27 (s, 3H), 1.48 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 204.83 (CO), 108.98 (C), 108.95 (CH), 107.90 (CH), 101.44 (CH), 56.84 (CH), 53.90 (CH), 51.94 (CH), 50.59 (CH), 45.56 (CH), 29.07 (CH_3), 27.01 (CH_3); LRMs m/z (rel int) 238 (M^+, 17), 223 (56), 195 (100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0849. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.48; H, 5.93. Found: C, 60.59; H, 5.97.

1,3-Dimethyl-10-*syn*-formyl-2,4,6,13-tetraoxapentacyclo[5.5.1.0^{3,11}.0^{5,9}.0^{8,12}]tridecane 12: white solid; mp 187−188 °C; IR (neat) 1725, 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.96 (s, 1H), 5.85 (d, J = 5.1 Hz, 1H), 5.68 (d, J = 6.3 Hz, 1H), 3.56−3.48 (m, 1H), 3.24−3.16 (m, 3H), 3.03−3.00 (m, 1H), 1.56 (s, 3H), 1.48 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 199.20 (CHO), 116.36 (C), 108.93 (CH), 107.92 (C), 101.06 (CH), 57.43 (CH), 56.04 (CH), 53.01 (CH), 50.95 (CH), 45.11 (CH), 27.48 (CH_3), 25.06 (CH_3); LRMS m/z (rel int) 238 (M^+, 5), 195 (100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0820. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.48; H, 5.93. Found: C, 60.41; H, 5.88.

1,9-Dimethyl-2,4,6,8,15-pentaoxahexacyclo[7.5.1.0^{3,13}.0^{5,12}.0^{7,11}.0^{10,14}]pentadecane 7d: white solid; mp 235−236 °C; IR ($CHCl_3$) 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.90 (d, J = 6.0 Hz, 1H), 5.85 (d, J = 5.4 Hz, 2H), 3.68−3.65 (m, 3H), 3.39−3.35 (m, 2H), 1.51 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 120.30 (2C), 113.33 (CH), 112.46 (2CH), 62.72 (2CH), 58.91 (2CH), 58.53 (CH), 26.94 ($2CH_3$); LRMS m/z (rel int) 238 (M^+, 14), 223 (100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0845. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.48; H, 5.93. Found: C, 60.60; H, 5.99.

Reaction of 11 with Catalytic $TiCl_4$ in CH_2Cl_2. To a solution of **11** (0.24 g, 1.00 mmol) in dichloromethane (50 mL) was added a catalytic amount of $TiCl_4$ (0.010 g, 0.005 mmol) at room temperature. The reaction mixture was stirred at 25 °C for 4 h. The reaction mixture was quenched by addition of water (30 mL) and extracted with dichloromethane. The organic layer was washed with brine, dried over $MgSO_4$, and evaporated, and the residue was purified by column chromatography to give the pentaoxa[5]peristylane **7d** (0.18 g) in 75% yield and the hydride rearrangement product **13** (0.048 g) in 20% yield.

Spectral data for 13: white waxy solid; mp 143−145 °C; IR ($CHCl_3$) 2980, 1770, 1715, 1250, 1070 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.07 (d, J = 6.3 Hz, 1H), 5.96 (d, J = 6.0 Hz, 1H), 3.92−3.50 (m, 5H), 2.47 (dd, J = 9.0, 9.0 Hz, 1H), 2.29 (s, 3H), 1.39 (d, J = 6.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 205.90 (CO), 177.90 (CO), 111.12 (CH), 106.57 (CH), 78.43 (CH), 60.83 (CH), 56.08 (CH), 55.26 (CH), 50.49 (CH), 48.62 (CH), 27.67 (CH_3), 19.46 (CH_3); LRMS m/z (rel int) 238 (M^+, 34), 195(100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0835. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.48; H, 5.93. Found: C, 60.59; H, 5.98.

Conversion of 12 to 7a. The same reaction conditions and prodecure as for the reaction of **11** with $TiCl_4$ in CH_2Cl_2 were applied for the conversion of **12** to give **7d** in 90% yield. The amount of the hydride rearrangement product **14** was too small to be isolated.

Ozonolysis of 5d. Formation of Compound 17. Method 1. A solution of **5d** (0.50 g, 1.98 mmol) in dichloromethane (80 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution was added dimethyl sulfide (0.60 g, 9.9 mmol) at −78 °C. The reaction mixture was stirred at room temperature for 6 h. The solvent was evaporated, and the crude product was purified by column chromatography to give compound **17** (0.11 g, 20%) with several unidentified compounds. **Method 2.** A solution of **5d** (0.50 g, 1.98 mmol) in dichloromethane (80 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution were added solid $NaHCO_3$ (2.5 g) and dimethyl sulfide (0.60 g, 9.9 mmol) at −78 °C. The reaction mixture was stirred at room temperature for 6 h. The solvent was evaporated, and the crude product was purified by column chromatography to give compound **17** (0.39 g, 70%).

Spectral data for 17: white waxy solid; mp 67−68 °C; IR ($CHCl_3$) 2980, 2880, 1050 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.53 (d, J = 5.7 Hz, 2H), 4.83 (d, J = 9.6 Hz, 1H), 3.37 (s, 6H), 3.16−3.13 (m, 2H), 2.92−2.86 (m, 2H), 2.50−2.46 (m, 1H), 1.69 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 117.15 (2C), 102.55 (CH), 101.45 (2CH), 56.95 (2CH), 53.90 ($2CH_3$), 46.42 (2CH),

46.39 (CH), 25.07 ($2CH_3$); LRMS *m/z* (rel int) 284 (M^+, 11), 253 (100); HRMS (EI) calcd for $C_{14}H_{20}O_6$ 284.1260, found 284.1268. Anal. Calcd for $C_{14}H_{20}O_6$: C, 59.13; H, 7.09. Found: C, 59.25; H, 7.20.

Ozonolysis of 5d in Methanol. Formation of Compound 18. A solution of **5d** (0.50 g, 1.98 mmol) in methanol (80 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution were added dimethyl sulfide (0.60 g, 9.9 mmol) and solid $NaHCO_3$ (2.5 g,) at −78 °C. The reaction mixture was stirred at room temperature for 6 h. The solvent was evaporated, and the crude product was purified by column chromatography to give compound **18** (0.53 g, 84%).

Spectral data for 18: pale yellow oil liquid; IR (neat) 3450, 2960, 1050 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.67(d, J = 2.7 Hz, 1H), 5.19 (s, 1H), 4.75 (d, J = 9.0 Hz, 1H), 3.42 (s, 3H), 3.38 (s, 3H), 3.35 (s, 3H), 3.23−3.12 (m, 2H), 2.77−2.75 (m, 2H), 2.64−2.60 (m, 1H), 1.74 (brs, 1H), 1.61 (s, 3H), 1.53 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 117.68 (C), 116.49 (C), 105.76 (CH), 102.71 (CH), 99.69 (CH), 59.53 (CH), 58.02 (CH), 55.00 (CH_3), 54.10 (CH), 53.93 (CH_3), 52.67 (CH_3), 52.52 (CH), 48.54 (CH), 26.51 (CH_3), 26.42 (CH_3); LRMS *m/z* (rel int) 316 (M^+, 11), 75 (100); HRMS (EI) calcd for $C_{15}H_{24}O_7$ 316.1522, found 316.1530.

Ozonolysis of 6d in $CDCl_3$. Formation of the Final Ozonide 19. A solution of **6d** (0.010 g, 0.048 mmol) in $CDCl_3$ (1 mL) was cooled to −78 °C, and ozone was bubbled through it at − 78 °C until the solution turned light blue to give the final ozonide **19** (>95%). This solution was bubbled with N_2 to get rid of excess ozone at −78 °C. The ^1H and ^{13}C NMR spectra of **19** were taken at −30 °C right after the ozonation reaction without purification.

Spectral data for 19: ^1H NMR (300 MHz, $CDCl_3$) δ 9.93 (s, 1H), 6.53 (s, 1H), 6.37 (s, 1H), 3.69 (dd, J = 6.9, 6.9 Hz, 1H), 3.1−3.00 (m, 2H), 2.92−2.87 (m, 2H), 2.29 (s, 3H), 2.03 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 205.81 (CO), 204.60 (CO), 197.53 (CHO), 100.83 (CH), 100.48 (CH), 55.37 (CH), 55.09 (CH), 54.80 (CH), 45.26 (CH), 44.19 (CH), 29.98 (CH_3), 29.39 (CH_3).

Preparation of Compound 22. To a solution of 5-trimethylsilylcyclopentadiene **1** (0.50 g, 3.7 mmol) in dichloromethane (25 mL) was added trimethyl orthoformate (0.43 g, 4.0 mmol) at 25 °C. The mixture was cooled to −40 °C, and a catalytic amount of TMSOTf (0.12 g, 0.55 mmol) was added at −40 °C. The reaction mixture was stirred at −40 °C for 30 min. The mixture was quenched by addition of a saturated $NaHCO_3$ aqueous solution. Extractive workup with dichloromethane followed by an ice−water wash, drying over K_2CO_3, and evaporation of the solvent at 0 °C afforded the crude product **3**. To the crude product **3** in dichloromethane (25 mL) was added maleic anhydride (0.40 g, 4.1 mmol) at 0 °C. The reaction mixture was stirred at 0 °C for 18 h. The solvent was evaporated, and the crude product was purified by column chromatography to give the *endo* adduct **22** (0.64 g) in 73% overall yield.

Spectral data for 22: white solid; mp 93−94 °C; IR ($CHCl_3$) 1865, 1780, 1100 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.35 (brs, 2H), 4.26 (d, J = 7.8 Hz, 1H), 3.70−3.67 (m, 2H), 3.55−3.52 (m, 2H), 3.38 (s, 6H), 2.30−2.27 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 170.67 (2CO), 133.23 (2CH), 102.03 (CH), 66.89 (2CH), 53.81 ($2CH_3$), 47.16 (CH), 46.76 (2CH); LRMS *m/z* (rel int) 238 (M^+, 11), 207 (100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0828.

Reduction of 22 with $LiAlH_4$. To a solution of compound **22** (0.50 g, 2.10 mmol) in dry THF (30 mL) was added $LiAlH_4$ (0.21 g, 6.30 mmol) at 25 °C. The reaction mixture was refluxed for 12 h. After cooling, solid potassium sodium tartrate (3.0 g) was added. To this reaction mixture was then dropwise added saturated potassium sodium tartrate (20 mL) at 0 °C. The reaction mixture was filtered through Celite. The filtrate was extracted with ether. The combined organic layer was washed with brine, dried over $MgSO_4$, and evaporated, and the residue was purified by column chromatography to give the diol **23** (0.335 g) in 70% yield.

Spectral data for 23: white solid; mp 112−114 °C; IR ($CHCl_3$) 3600−3300, 1050 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.98 (brs, 2H), 4.22 (d, J = 8.4 Hz, 1H), 4.13 (brs, 2H), 3.62−3.56 (m, 2H), 3.43−3.35 (m, 2H), 3.31 (s, 6H), 2.80 (brs, 2H), 2.60−2.56 (m, 2H), 2.08−2.05 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 132.39 (2CH), 102.73 (CH), 63.48 (CH), 62.55 ($2CH_2$), 53.17 ($2CH_3$), 47.75 (2CH), 45.56 (2CH); LRMS *m/z* (rel int) 228 (M^+, 1), 210 (100); HRMS (EI) calcd for $C_{12}H_{20}O_4$ 228.1362, found 228.1368.

Swern Oxidation of Compound 23. A mixture of DMSO (2.5 mL, 35 mmol) and CH_2Cl_2 (6 mL) was added to a solution of oxalyl chloride (2.6 g, 20 mmol) in CH_2Cl_2 (20 mL) at −55 °C. After the mixture was stirred for 30 min, a solution of **23** (0.68 g, 3.0 mmol) in CH_2Cl_2 (13 mL) and DMSO (12 mL) was added at −55 °C. The solution was stirred at −55 °C for 2 h. Triethylamine (9.3 mL, 49 mmol) was then added, and the reaction mixture was allowed to warm to 25 °C for 30 min. Water (25 mL) was then added, and the CH_2Cl_2 layer was separated. Concentrated HCl was added to the aqueous part, followed by extraction of the aqueous solution with CH_2Cl_2. The combined organic solutions were washed once with 1 N HCl and once with a saturated NaCl solution. The organic layer was dried over $MgSO_4$ and evaporated to give the dihemiacetal **24** (0.58 g) (80%), which is a mixture of stereoisomers. The crude product **24** was run for the next ozonolysis reaction without purification.

Ozonolysis of 24. Formation of Pentaoxa[5]peristylane 25. A solution of **24** (0.48 g, 2.00 mmol) in dichloromethane (40 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution was added dimethyl sulfide (0.25 g, 4.00 mmol) at −78 °C. The reaction mixture was stirred at room temperature for 6 h. The solvent was evaporated, and the crude product was purified by column chromatography to give the parent pentaoxa-[5]peristylane **25** (0.084 g) in 20% yield with unidentified compounds.

2,4,6,8,15-Pentaoxahexacyclo[7.5.1.$0^{3,13}$.$0^{5,12}$.$0^{7,11}$.$0^{10,14}$]-pentadecane 25: white solid; mp >230 °C (dec); IR ($CHCl_3$) 1070 cm^{-1}; ^1H NMR (300 MHz, CD_3SOCD_3) δ 4.90 (brs, 5H), 2.76 (brs, 5H); ^{13}C NMR (75 MHz, CD_3SOCD_3, DEPT) δ 113.33 (5CH), 57.45 (5CH); LRMS *m/z* (rel int) 210 (M^+, 1), 182 (22), 79 (100); HRMS (EI) calcd for $C_{10}H_{10}O_5$ 210.0528, found 210.0536. Anal. Calcd for $C_{10}H_{10}O_5$: C, 57.13; H, 4.80. Found: C, 57.02; H, 4.70.

Ozonolysis of 24 Followed by Treatment with Amberlyst-15. Efficient Synthesis of Pentaoxa[5]peristylane 25. A solution of **24** (0.48 g, 2.00 mmol) in dichloromethane (40 mL) was cooled to −78 °C, and ozone was bubbled through it at −78 °C until the solution turned light blue. To this solution was added dimethyl sulfide (0.25 g, 4.00 mmol) at −78 °C. After 5 min of stirring, Amberlyst-15 (1.00 g) was added to the solution. Then, the reaction mixture was stirred at room temperature for 24 h. After filtration of Amberlyst-15, the solvent was evaporated, and the crude product was purified by column chromatography to give pentaoxa[5]peristylane **25** (0.36 g) in 85% yield.

Ozonolysis of 23 Followed by Treatment with Amberlyst-15. Synthesis of New Tetraoxa Cage Compound 26. The same reaction conditions and procedure as for the efficient synthesis of pentaoxa[5]peristylane **25** were applied for the synthesis of the new-type tetraoxa cage **26** in 85% yield: white solid; mp 151−153 °C; IR ($CHCl_3$) 1070 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.84 (d, J = 6.0 Hz, 2H), 5.70 (d, J = 6.0 Hz, 1H), 4.29 (dd, J = 9.0, 4.8 Hz, 2H), 4.02 (dd, J = 9.0, 7.5 Hz, 2H), 3.56−3.47 (m, 2H), 3.30−3.20 (m,1H), 3.10−3.00 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 112.18 (2CH), 111.50 (CH), 70.53 ($2CH_2$), 59.34 (2CH), 52.93 (CH), 47.37 (2CH); LRMS *m/z* (rel int) 196 (M^+, 8), 150 (62), 111 (100); HRMS (EI) calcd for $C_{10}H_{12}O_4$ 196.0736, found 196.0748. Anal. Calcd for $C_{10}H_{12}O_4$: C, 61.20; H, 6.17. Found: C, 61.33; H, 6.23.

Preparation of Compound 28. The same reaction conditions and procedure as for the preparation of compounds **5a**−**d** were applied for the preparation of compound **28**. In this case,

a Diels−Alder reaction of crude compound **3** with (3*E*)-3-hexene-2,5-dione **27** in dichloromethane was applied.

Spectral data for 28: pale yellow oil; IR (neat) 1710, 1380, 1050 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.13 (dd, J = 6.0, 3.0 Hz, 1H), 5.85 (dd, J = 6.0, 3.0 Hz, 1H), 4.16 (d, J = 8.1 Hz, 1H), 3.40−3.37 (m, 1H), 3.24 (brs, 1H), 3.22 (s, 3H), 3.14 (s, 3H), 2.95 (brs, 1H), 2.86 (d, J = 4.5 Hz, 1H), 2.21−2.18 (m, 1H), 2.17 (s, 3H), 2.08 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 208.02 (CO), 206.30 (CO), 135.29 (CH), 131.27 (CH), 101.73 (CH), 60.30 (CH), 55.14 (CH), 53.30 (CH_3), 53.16 (CH_3), 51.64 (CH), 47.59 (CH), 46.95 (CH), 29.44 (CH_3), 28.51 (CH_3); LRMS *m*/*z* (rel int) 252 (M^+, 8), 224 (100); HRMS (EI) calcd for $C_{14}H_{20}O_4$ 252.1362, found 252.1371.

Preparation of Compound 29. The same reaction conditions and procedure as for the preparation of compounds **6a**−**d** were applied for the preparation of **29**.

Spectral data for 29: pale yellow oil; IR (neat) 2820, 2720, 1720, 1710 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.56 (d, J = 1.5 Hz, 1H), 6.28 (dd, J = 6.0, 3.0 Hz, 1H), 6.03 (dd, J = 6.0, 3.0 Hz, 1H), 3.67 (brs, 1H), 3.48−3.44 (m, 1H), 3.42 (brs, 1H), 3.06−3.04 (m, 1H), 2.67 (d, J = 1.5 Hz, 1H), 2.26 (s, 3H), 2.17 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 207.97 (CO), 205.70 (CO), 202.17 (CHO), 135.86 (CH), 132.45 (CH), 68.04 (CH), 54.80 (CH), 53.02 (CH), 47.43 (CH), 46.47 (CH), 29.71 (CH_3), 28.66 (CH_3); LRMS *m*/*z* (rel int) 206 (M^+, 5), 175 (100); HRMS (EI) calcd for $C_{12}H_{14}O_3$ 206.0943, found 206.0950.

Ozonolysis of 29. Formation of Tetraoxa Cage 30. The same reaction conditions and procedure as for the ozonolysis of **6a**−**d** were applied for the ozonolysis of **29** to give tetraoxa cage **30** in 90% yield.

3-Methyl-10-*anti*-acetyl-2,4,6,13-tetraoxapentacyclo-[5.5.1.$0^{3,11}$.$0^{5,9}$.$0^{8,12}$]tridecane 30: white solid; mp 183−184 °C; IR ($CHCl_3$) 1710, 1050 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.80 (d, J = 5.4 Hz, 1H), 5.76 (d, J = 5.4 Hz, 1H), 5.56 (d, J = 6.3 Hz, 1H), 3.51−3.42 (m, 2H), 3.13 (brs, 1H), 3.04−2.99 (m, 1H), 2.83−2.80 (m, 1H), 2.30 (s, 3H), 1.48 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 206.94 (CO), 109.77 (C), 109.36 (CH), 108.69 (CH), 102.78 (CH), 56.22 (CH), 53.30 (CH), 52.02 (CH), 51.53 (CH), 47.08 (CH), 27.95 (CH_3), 25.94 (CH_3); LRMS *m*/*z* (rel int) 238 (M^+, 13), 190 (100); HRMS (EI) calcd for $C_{12}H_{14}O_5$ 238.0841, found 238.0833. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.48; H, 5.93. Found: C, 60.61; H, 9.99.

Swern Oxidation of Compound 31. The same reaction conditions and procedure as for the Swern oxidation of compound **23** were applied for the oxidation of **31** to give the dihemiacetal **32** as the major product and the other two stereoisomers as the minor products. The stereochemistry of the hydroxy groups of **32** was determined on the basis of NOE experiments.

3*β*,5*β*-Dihydroxy-4-oxatricyclo[5.2.1.$0^{2,6}$]-8-decene 32: pale yellow oil liquid: IR (neat) 3500−3300, 1050 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.10 (brs, 2H), 4.97 (brs, 2H), 3.96 (brs, 2H), 3.05 (brs, 2H), 2.99 (brs, 2H), 1.45−1.33 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT) δ 134.40 (2CH), 102.20 (2CH), 54.83 (2CH), 51.30 (CH_2), 44.80 (2CH); LRMS *m*/*z* (rel int) 168 (M^+, 3), 151 (100).

Ozonolysis of 32 Followed by Treatment with Amberlyst-15. A New Entry for the Synthesis of Tetraoxa Cage 33. The same reaction conditions and prodecure as for the ozonolysis of **24** followed by treatment with Amberlyst-15 were applied for the ozonolysis of **32** to give the parent tetraoxa cage **33** in 85% yield. The parent tetraoxa cage **33** was also synthesized by ozonolysis of 2-*endo*-7-*anti*-diformylnorbornene **34**.[23d]

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Supporting Information Available: ^1H and ^{13}C NMR spectral data of compounds **5a**−**c**, **6b**,**c**, and **7b**,**c** and the X-ray data for compounds **25**. This material is available free of charge via the Internet at http://pubs.acs.org.

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