An Unprecedented Co^{II}-Tetraphenylporphyrin-Catalyzed Decomposition of Bicyclic Endoperoxides: A New Approach to Substituted Furofuran Systems

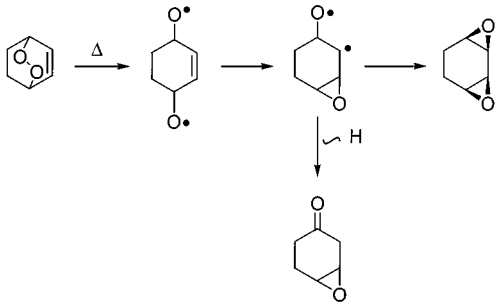
Mehmet Emin Sengul,[b] Nermin Simsek,[a] and Metin Balci*[a]

Keywords: Endoperoxides / Cycloheptatriene / Dichloroketene / Singlet oxygen / Cobalt / Porphyrins / Furofurans

Co^{II}-tetraphenylporphyrin-catalyzed decomposition of bicyclic endoperoxides **4** and **5** with a strained double bond moiety has been studied. Compounds **4** and **5** have been synthesized by photooxygenation of **3** which itself was obtained by dichloroketene addition to cycloheptatriene, followed by removal of the chlorine atoms. An unusual decomposition mode of **4** promoted by Co^{II}-TPP resulted in the formation of **8** and **9** which are important building blocks in furofuran systems.

Introduction

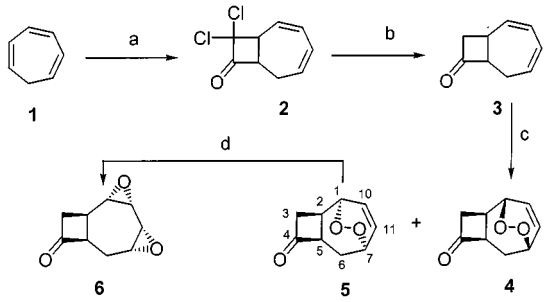
Unsaturated bicyclic endoperoxides have proven extremely useful in synthesis as they are readily convertible into a variety of stereospecifically oxygenated compounds.[1] One of the common reactions of unsaturated bicyclic endoperoxides is the thermal cleavage of the weak oxygen–oxygen bond followed by addition of the oxygen radicals to the adjacent double bond to give diepoxides with a *syn* configuration.[2] However, decomposition of some bicyclic endoperoxides containing a strained C=C double bond is always accompanied by side reactions. Carless et al.[3] have shown that β,γ-epoxy ketones are often formed as major products from the thermolysis or photolysis of unsaturated bicyclic endoperoxides (Scheme 1).



Scheme 1. Thermal decomposition of bicyclic endoperoxides

Foote et al.[4] have reported that unsaturated bicyclic endoperoxides can be conveniently converted into the corresponding diepoxides by using cobalt(II) tetraphenylporphyrin (CoTPP). We have successfully applied this reaction to some unsaturated bicyclic endoperoxides with strained and perturbed diene moieties, and shown that the side reactions can be completely suppressed.[5] In connection with our work on the synthesis of tropon derivatives we were interested in the synthesis of ketone **3**. In this paper, we describe the preparation of **3**, its photooxygenation, an unusual CoTPP-catalyzed rearrangement of the formed bicyclic endoperoxide **4** and transformation of the aldehyde **8**.

The ketene cycloaddition reaction[6] is a powerful tool for the functionalization of unsaturated hydrocarbons. Surprisingly, the addition of dichloroketene to cycloheptatriene is has not yet been reported in the literature. When trichloroacetyl chloride is treated with activated zinc[7] in the presence of cycloheptatriene, a high yield of adduct **2** (78%) is obtained (Scheme 2). NMR spectroscopic studies indicated that the dichloroketene adds to the terminal double bond of cycloheptatriene in a regiospecific manner to form **2**. The regioselectivity of this reaction is determined by the fact that the larger lobe of the HOMO of the olefin overlaps with the larger lobe of the LUMO of the ketene. Finally, the correct constitution of **2** was determined by removal of the chlorine atoms with Zn–Cu in acetic acid. The resulting hydrocarbon **3** was characterized by NMR spectroscopy.



Scheme 2. Synthesis of the endoperoxides **4** and **5**: a) Cl_3CCOCl/Zn, $POCl_3$/Ether, (78%); b) CH_3COOH/Zn, 70 °C, (65%); c) tetraphenylporphyrin, O_2, hν, $CHCl_3$/CCl_4, (30 and 25%); d) CoTPP, $CHCl_3$, room temp., quantitative

Tetraphenylporphyrin-sensitized photooxygenation of the cyclohepta-1,3-diene unit of **3** at room temperature resulted in the formation of the bicyclic endoperoxides **4** and **5** (Scheme 2). After chromatography on silica gel **4** and **5** were isolated with 25% and 30% yields, respectively. Structural assignments were obtained from their ^1H and ^{13}C NMR spectra. The stereochemistry of the endoperoxides **4** and **5** has been confirmed by differential ^1H NMR NOE

[a] Department of Chemistry, Atatürk University, 25240 Erzurum, Turkey
[b] Department of Chemistry, Middle East Technical University, 06531 Ankara, Turkey
Fax: (internat.) + 90-312/210-1280
E-mail: mbalci@metu.edu.tr

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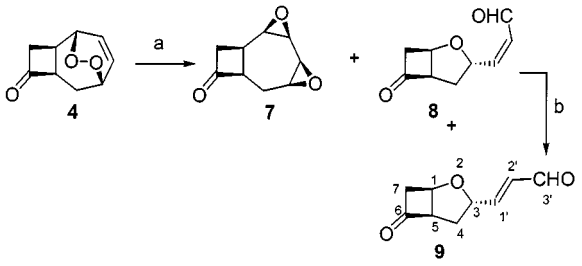
measurements. Irradiation at the resonance of the olefinic proton in **5** (δ = 6.55) induces an enhancement of one of the bridgehead protons and the *endo*-cyclobutane proton that indicates clearly the *trans* orientation of the cyclobutanone ring with respect to the peroxide linkage. An AM1 geometry optimization[8] carried out on the starting ketone **3** further indicates that the cyclobutanone ring does not exert any steric effect, which can be clearly seen in the ratio of the formed peroxides. Reaction of the *trans*-endoperoxide **5** with CoTPP produced a single product in nearly quantitative yield (Scheme 2). This compound was identified as the bis(epoxide) **6** by spectroscopic methods.

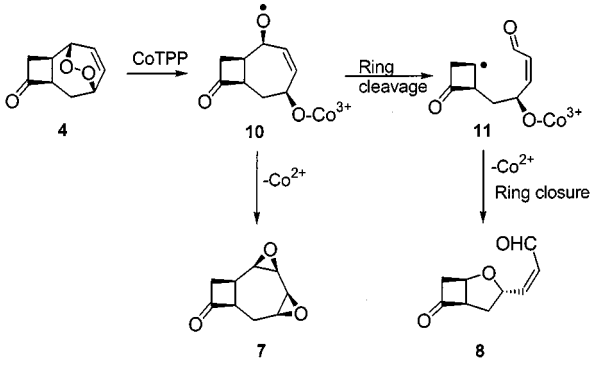
However, when the *cis*-endoperoxide **4** was subjected to CoTPP reaction under the same reaction conditions, a mixture consisting of the expected bis(epoxide) **7** (70%) and an isomeric mixture of aldehydes **8** and **9** (30%, in a ratio of 9:1) was obtained (Scheme 3). We assume that **8** is a primary product and **9** is a secondary product which is formed after isomerization of **8** under the given reaction conditions. Furthermore, we noticed that the ratio of **9** was increased during silica gel column chromatography. Therefore, the aldehyde mixture was further reacted with triphenylphosphane[9] in CH_2Cl_2. This quantitatively converted the *Z*-aldehyde **8**[10] into the more stable *E*-aldehyde **9**. The structure of **9** was determined by extensive double resonance experiments and NOE measurements. The measured vicinal coupling constant of 15.7 Hz indicates clearly the *trans*-configuration at the C=C double bond. Irradiation (NOE measurements) of the allylic proton resonance H-3 (δ = 5.03) induces an enhancement of the resonances of H-4 protons and of the low-field olefinic proton H-1′. The fact that the cyclobutanone protons H-1 and -H-5 did not show any effect confirms the configuration of **9**.



Scheme 3. Reaction of the endoperoxide **4** with CoTPP: a) CoTPP, $CHCl_3$, 0 °C; b) PPh_3, CH_2Cl_2, room temp., quantitative

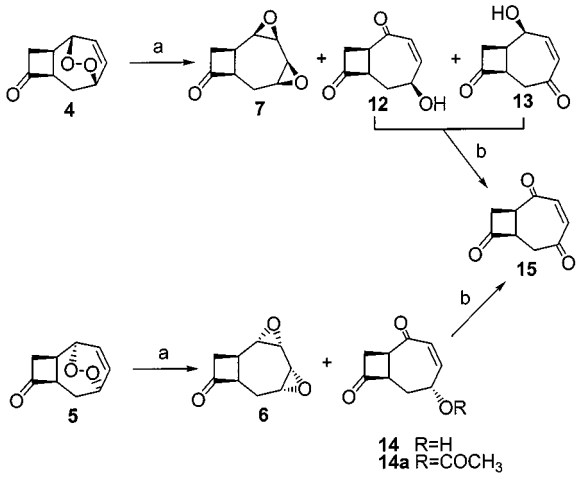
For the product distribution in the CoTPP-catalyzed reactions of **4** and **5** we assume that the conformational factors in the seven-membered-ring play an important role. The decomposition reaction of **4** probably goes through two different channels, leading to diepoxide **7** and open-chain aldehyde **8**, via the intermediates **10** and **11**, as shown in Scheme 4. This type of rearrangement of a bicyclic endoperoxide is unprecedented.

In order to test the thermal behavior of these endoperoxides, and to see whether they will undergo similar rearrangements upon thermolysis, as in the case of CoTPP-catalyzed reaction, we submitted endoperoxides **4** and **5** to thermolysis in a sealed tube.



Scheme 4. Formation of aldehyde **8**

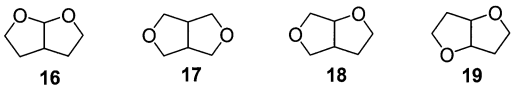
The thermal stability of the endoperoxides was quite high and heating at 195 °C in toluene for three days was needed in order to react them completely. The major products of the thermolysis were the expected bis(epoxides) **6** and **7** (Scheme 5).[11] The structures were established by comparison of the physical data of the bis(epoxides) with those obtained by CoTPP-catalyzed rearrangement of **4** and **5**. In the case of **4** we isolated a mixture consisting of the α,β-unsaturated hydroxy ketones **12** and **13** in 20% yield, together with the major product bis(epoxide) **7**. The bis(epoxide) **7** has been separated from the mixture of **12** and **13** by column chromatography. All attempts to separate the hydroxy ketone mixture **12** and **13** failed. For the structural characterization we oxidized this mixture with CrO_3 in acetic acid and isolated the interesting triketone **15** in 65% yield. On the other hand, thermolysis of **5** also provided the hydroxy ketone **14** as a side product in 27%, which was converted into triketone **15** upon oxidation. In both cases we were not able to detect any trace of **8** or any product related to **8**. At this stage we conclude that thermolysis and CoTPP-catalyzed rearrangement of these endoperoxides **4** and **5** follow completely different routes.



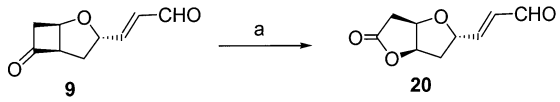
Scheme 5. Thermolysis of the endoperoxides **4** and **5**: a) 195 °C, toluene, 3 days; b) CrO_3, CH_3COOH, 24 h

The bicyclic ketone **9** is an important building block for the synthesis of furofuran systems, which possess important biological activities. In particular, the attachment of a func-

tional group, such as an unsaturated aldehyde group to a tetrahydrofuran ring, gives further opportunities to introduce additional functionality.



The perhydro-furo[2,3b]- and perhydro[3,4c]furan moieties (**16** and **17**) are a subunit of interest as they are encountered in various natural products such as clerodin, azadirachtin, aflatoxin B_2, and sesamin. These have attracted intense attention because of their potent antifeedant activity against various insects and larvae.[12] Those moieties are presumed to be responsible for at least part of the biological activity. The synthesis of such buildings blocks (**16**) has been described in the last two decades by different groups.[13] The furofuran systems were mainly synthesized by Baeyer-Villiger oxidation of the corresponding cyclic ketones,[14,15] which were obtained through the classical intermolecular cycloaddition of dichloroketene with the corresponding dihydrofuran followed by removal of the chlorine atoms. The bicyclic ketoaldehyde **9** might be an important precursor for the synthesis of the substituted furofuran system **19**. For this reason we treated **9** with *m*-chloroperbenzoic acid and obtained the lactone **20** in 65% yield where incorporation of an oxygen atom was regiospecific (Scheme 6).



Scheme 6. Baeyer-Villiger oxidation of ketone **9**: a) *m*-CPBA, $NaHCO_3$, CH_2Cl_2 12 h, 65%

In summary, we have found a new cleavage mode of the bicyclic endoperoxides upon treatment with CoTPP; the system undergoes C–C cleavage following the initial breaking of the oxygen–oxygen linkage. Furthermore, we assume that conformational factors determine the mode of the cleavage. The facile preparation of the starting material **4** and **5** suggest that the chemistry of **4** should find application in the synthesis of the substituted furofuran systems **19**. Currently, we are trying to introduce suitable substituents in **3** which can eventually change the distribution of the formed endoperoxides of type **4** and **5** and increase the yield of the Co-TPP catalyzed rearrangement.

Experimental Section

General: Melting points were determined with a Thomas-Hoover capillary melting point apparatus and were not corrected. – IR: Perkin–Elmer 377 Infrared recording spectrophotometer. – NMR: Varian Gemini 200 at 200 MHz (^{1}H). Data are reported in δ units with TMS as internal standard. All column chromatography was performed on silica gel (60-mesh, Merck) and Florisil 0.150–0.250 mm (60–100 mesh, ASTM). All substances reported in this paper are in their racemic form.

[1*S*(*R*),7*R*(*S*)]-9,9-Dichlorobicyclo[5.2.0]nona-2,4-dien-8-one (2): A 1-L three-necked flask equipped with a condenser, addition funnel, and N_2 inlet was charged with cycloheptatriene (25 g, 0.27 mol), Zn–Cu (52.7 g, 0.81 mol) and anhydrous diethyl ether (300 mL). The suspension was stirred under N_2 and a solution of trichloroacetyl chloride (58.9 g, 0.324 mol) and phosphoryltrichloride (distilled from potassium carbonate, 49.7 g, 0.324 mol) in diethyl ether (100 mL) was added dropwise over 3 h. When the addition of the solution was complete, the mixture was refluxed with stirring for 24 h. The reaction mixture was then filtered through a pad of celite and the unreacted zinc was washed with 100 mL of diethyl ether. The ethereal solution was washed with saturated $NaHCO_3$, water and dried with $MgSO_4$. The solvent was then removed in vacuo. The residue was chromatographed through a silica gel column (50 g) eluting with ethyl acetate/hexane (1:9) to give dichloroketone **2** (44.0 g, 0.216 mol, 78%) as a pale yellow oil. IR (neat): $\tilde{\nu}$ = 3055, 3010, 3000, 2927, 1829, 1472 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 5.7–6.3 (m, 4 H, 2,3,4,5-H), 4.0 (ddd, *J* = 11.3, 8.7 and 5.2 Hz, 1 H, 7-H), 3.65 (dd, *J* = 11.3 and 3.4 Hz, 1 H, 1-H), 2.1–2.7 (m, 2 H, 6-H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 197.84 (C-8), 133.47, 131.03, 130.72, 130.67 (C-2,3,4,5), 79.26 (C-9), 68.05, 53.24 (C-1,7), 29.75 (C-6) – $C_9H_8Cl_2O$ (203.1): calcd. C 53.23, H 3.97; found C 53.12, H 3.91.

[1*S*(*R*)7*R*(*S*)]-Bicyclo[5.2.0]nona-2,4-dien-8-one (3): To a vigorously stirring suspension of Zn (14.86 g, 0.23 mol) in 150 mL glacial acetic acid at room temperature, was added dropwise a solution of dichloroketone **2** (22.65 g, 0.11 mol) in 50 mL of acetic acid. After addition was complete, the temperature was raised to and maintained at 70 °C for 20 h. The reaction mixture was cooled and treated with diethyl ether, and the zinc residue was filtered. The ethereal layer was washed three times with water and a saturated solution of sodium carbonate to remove acetic acid and dried with $MgSO_4$. The solvent was removed in an evaporator. Chromatography of the residue on 50 g of silica gel eluting with ethyl acetate/hexane (1:9) afforded ketone **3** (9.5 g, 0.07 mol, 65%) as a colorless liquid. IR (neat): $\tilde{\nu}$ = 3033, 2993, 3000, 2990, 1783, 1750, 1472, 1140 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 5.60–6.25 (m, 4 H, 2,3,4,5-H), 3.70 (m, 1 H, 7-H), 2.9–3.6 (m, 3 H, 1,9-H), 2.35 (m, 2 H, 6-H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 212.4 (C-8), 137.8, 134.1, 130.87, 128.5 (C-2,3,4,5), 73.5 (C-7), 56.7 (C-9), 30.9 (C-1), 28.8 (C-6). – $C_9H_{10}O$ (134.2): calcd. C 80.56, H 7.51; found C 80.26, H 7.39.

Photooxygenation of [1*S*(*R*),7*R*(*S*)]-Bicyclo[5.2.0]nona-2,4-dien-8-one (3): To a stirred solution of ketone **3** (5.0 g, 0.03 mol) in 200 mL of $CHCl_3/CCl_4$ (1:1) mixture was added tetraphenylporphyrin (TPP) (30 mg). The resulting mixture was irradiated with a projection lamp (150 Watt) while oxygen was being passed through the solution and the mixture was stirred for 10 h at room temperature. Evaporation of the solvent (30 °C, 20 Torr) and chromatography of the residue on a silica gel column (130 g) eluting with ethyl acetate (1:3) gave as the first fraction endoperoxide [1*R*(*S*),2*S*(*R*),5*S*(*R*),7*S*(*R*)]-8,9-dioxatricyclo[5.2.2.0^{2,5}]undec-10-en-4-one (**5**) as colorless crystals (1.86 g, 30%). – M.p. 75–77 °C from ethyl acetate/*n*-hexane (1:1). – IR (neat): $\tilde{\nu}$ = 3106, 3004, 2978, 2850, 1778, 1446, 1344, 1293 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 6.55 (dd, A-part of AB-system, *J* = 9.4, and 6.6 Hz, 1 H, 10-H or 11-H), 6.35 (dd, B-part of AB-system, *J* = 9.4, and 4.9 Hz, 1 H, 10-H or 11-H), 4.9 (m, 1 H, 1-H) 4.7 (m, 1 H, 7-H), 3.50 (m, 1 H, 5-H), 3.0–3.20 (m, 2 H, 2,3$_{exo}$-H), 2.1–2.4 (m, 3 H, 3$_{endo}$,6,6′-H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 210.5 (C-4), 135.0, 129.3 (C-10,11), 80.2, 78.5 (C-1,7), 58.6, 49.0, 34.4, 32.4 (C-2,3,5,6). – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 65.18, H 5.98.

As the second fraction we isolated [1*S*(*R*),2*S*(*R*),5*S*(*R*),7*R*(*S*)]-8,9-dioxatricyclo-[5.2.2.0^{2,5}]undec-10-en-4-one **(4)** also as colorless crystals (1.55 g, 25%). – M.p. 148–150 °C from ethyl acetate/*n*-hexane (1:1). – IR (neat): $\tilde{\nu}$ = 3106, 2978, 2953, 2902, 1780, 1446, 1395, 1344 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 6.55 (ddd, A-part of AB-system, *J* = 9.3, 4.8, and 1.2 Hz, 1 H, 10-H or 11-H), 6.45 (ddd, B-part of AB-system, *J* = 9.3, 4.6 and 2.6 Hz, 1 H, 10-H or 11-H), 4.75 (m, 1H, 1-H), 4.60 (m, 1 H, 7-H) 3.60 (br. t, 1 H, 5-H), 3.26 (ddd, A-part of AB-system, *J* = 17.2, 9.4, and 2.6, Hz, 1 H, 3-H), 3.06 (ddd, B-part of AB-system, *J* = 17.2, 4.1, and 1.7 Hz, 1 H, 3′-H), 2.82 (m, 1 H, 2-H), 2.57 (dd, A-part of AB-system, *J* = 14.3, 6.1 Hz, 1 H, 6-H), 1.77 (ddd, B-part of AB-system, *J* = 14.3, 9.8, and 1.2 Hz, 1 H, 6′-H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 210.5 (C-4), 133.3, 131.5 (C-10,11), 80.0, 77.3 (C-1,7), 58.2, 51.0, 33.6, 31.3 (C-2,3,5,6). – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 65.29, H 6.18.

[1*S*(*R*),2*R*(*S*),4*R*(*S*),5*S*(*R*),7*S*(*R*),9*S*(*R*)]-3,6-Dioxatetracyclo-[7.2.0.0^{2,4}.0^{5,7}]undecan-10-one (6): To a magnetically stirred solution of endoperoxide **5** (200 mg, 1.2 mmol) in 5 mL of $CHCl_3$ was added a solution of cobalt-*meso*-tetraphenylporphyrin (20 mg) in portions. The mixture was stirred for 30 min. at room temperature. The solvent was then evaporated. The reaction mixture was submitted to silica gel (20 g) column chromatography. Eluting with ethyl acetate/*n*-hexane afforded the bis(epoxide) **6** as colorless crystals (190 mg, 95%). – M.p. 54–56 °C from ethyl acetate/*n*-hexane (1:1). – IR (neat): $\tilde{\nu}$ = 3004, 2953, 1778, 1395 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.7–3.5 (m, 8 H), 2.15 (m, 2 H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 211.0, 62.5, 60.6, 54.9, 54.3, 52.6, 51.6, 28.3, 25.0. – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 64.88, H 6.00.

CoTPP-Catalyzed Reaction of (4): To a magnetically stirred solution of endoperoxide **4** (200 mg, 1.2 mmol) in 5 mL of $CHCl_3$ was added a solution of cobalt-*meso*-tetraphenylporphyrin (20 mg) in portions. The mixture was stirred for 30 min. at room temperature. To this solution was added slowly triphenylphosphane (66 mg, 0.25 mmol) and the mixture stirred for an additional 2 h. Chromatography on silica gel (130 g) eluting with ethyl acetate/*n*-hexane afforded as the first fraction 40 mg (isolated yield, 20%) (*E*)-3-[1*S*(*R*),3*R*(*S*),5*S*(*R*)]-6-oxo-2-oxabicyclo[3.2.0]hept-3-ylprop-2-enal (**9**) as a pale yellow liquid. – IR (neat): $\tilde{\nu}$ = 2990, 2945, 1791, 1702 1450, 1391 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 9.57 (d, *J* = 7.8 Hz, 1 H, 3′-H), 6.81 (dd, A-part of AB-system, *J* = 15.7, 4.8, Hz, 1 H, 1′-H), 6.32 (ddd, B-part of AB-system, *J* = 15.7, 7.8, 1.5 Hz, 1 H, 2′H), 5.09 (dt, *J* = 5.8, 2.6 Hz, 1 H, 3-H), 4.82 (m, 1 H, 1-H), 3.96 (m, 1 H, 5-H), 3.40 (dt, A-part of AB-system, *J* = 19.1, 5.8 Hz, 2 H, 7-H), 3.03 (dt, B-part of AB-system, *J* = 19.1, 2.5 Hz, 1 H, 7-H), 2.49 (ddd, A-part of AB-system, *J* = 12.8, 6.0, 0.8 Hz, 1 H, 4-H), 1.78 (dt, B-part of AB-system, *J* = 12.8, 10.0 Hz, 1 H, 4-H); ^{13}C NMR (50 MHz, $CDCl_3$): δ 210.9, 194.9, 155.0, 133.6, 79.6, 72.7, 67.6, 55.5, 36.6, 32.8. – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 64.75, H 5.96.

As the second fraction we isolated 125 mg (62%, isolated yield) of **[1*S*(*R*),2*R*(*S*),4*R*(*S*),5*S*(*R*),7*S*(*R*),9*R*(*S*)]-3,6-dioxatetracyclo-[7.2.0.0^{2,4}.0^{5,7}]undecan-10-one (7):** M.p. 107–108 °C from ethyl acetate/*n*-hexane (2:1). – IR (neat): $\tilde{\nu}$ = 3029, 2957, 1780, 1295 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.9–3.6 (m, 8 H), 2.18 (m, 2 H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 209.7, 60.6, 60.3, 55.4, 55.2, 52.0, 51.4, 27.1, 26.0. – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 65.23, H 6.16.

Thermolysis of (5) to [1*S*(*R*),5*R*(*S*),7*S*(*R*)]-5-Hydroxybicyclo-[5.2.0]non-3-ene-2,8-dione (14): A solution of endoperoxide **5** (400 mg, 2.4 mmol) in toluene (15 mL) was placed into a glass tube, sealed under vacuum and heated at 195 °C for three days. After cooling to room temperature the solvent was removed by evaporation. Column chromatography of the residue on silica gel (50 g, ethyl acetate/*n*-hexane, 1:1) afforded bis(epoxide) **6** (230 mg, 57%) as the first fraction. The second fraction afforded hydroxy-enone **14** (102 mg, 25.5%). as colorless crystals. – M.p. 111–113 °C from ethyl acetate/*n*-hexane. – IR (neat): $\tilde{\nu}$ = 3463, 2978, 2977, 1778, 1676, 1395, 1293 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 6.9 (dd, A-part of AB-system, *J* = 12.4, 2.6 Hz, 1 H, 4-H), 6.05 (dd, B-part of AB-system, *J* = 12.4, 0.9 Hz, 1 H, 3-H), 4.65 (dt, *J* = 10.6, 2.5 Hz, 1 H, 5-H), 2.6–3.6 (m, 7 H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 208.2 (C-8), 199.3 (C-2), 154.7 (C-4), 132.9 (C-3), 74.0 (C-5), 56.5, 50.3, 42.4, 37.6. – $C_9H_{10}O_3$ (166.2): calcd. C 65.05, H 6.07; found C 64.71, H 6.15.

[1*S*(*R*),3*R*(*S*),7*S*(*R*)]-6,9-Dioxobicyclo[5.2.0]non-4-en-3-yl Acetate (14a): To a magnetically stirred solution of **14** (30 mg, 0.18 mmol) in 2 mL of pyridine was added Ac_2O (27 mg, 0.27 mmol). The reaction mixture was stirred at room temperature for 6 h. The mixture was then cooled to 0 °C, 2 mL of 1 N HCl solution added, and the resulting mixture extracted with diethyl ether. The combined organic extracts were washed with $NaHCO_3$ solution and water and then dried with $MgSO_4$. The solvent was evaporated and the residue purified by column chromatography (10 g silica gel, eluting with ethyl acetate/*n*-hexane, 1:3), to afford colorless crystals (35 mg, 95%). – IR (neat): $\tilde{\nu}$ = 2957, 2923, 1804, 1778, 1676, 1395, 1268 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 6.55 (dd, A-part of AB-system, *J* = 12.4, 3.1 Hz, 1 H, 4-H), 6.08 (dd, B-part of AB-system, *J* = 12.4, 12.4, 1.6 Hz, 1 H, 5-H), 5.75 (dt, *J* = 10.9, 2.8 Hz, 1 H, 3-H), 2.8–3.6 (m, 6 H), 2.1 (s, 3 H, CH_3). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 207.1, 198.7, 172.4, 150.1, 133.8, 75.38, 56.5, 50.27, 42.2, 35.2, 22.9. – $C_{11}H_{12}O_4$ (208.2): calcd. C 63.45, H 5.81; found C 63.62, H 5.74.

Oxidation of (14) to [1*S*(*R*),7*S*(*R*)]-Bicyclo[5.2.0]non-3-ene-2,5,8-trione (15): To a magnetically stirred solution of **14** (70 mg, 0.42 mmol) in 5 mL of acetic acid was added CrO_3 (100 mg, 1.0 mmol) at room temperature. The reaction mixture was stirred at room temperature for 24 h. To the reaction mixture was added 50 mL ether and the organic layer was extracted with water, $NaHCO_3$ solution and then water again, and dried with $MgSO_4$. The solvent was evaporated and the residue was purified by column chromatography (30 g silica gel, eluting with chloroform/*n*-hexane, 1:1), to afford pale yellow crystals (45 mg, 65%). M.p. 94–96 °C from chloroform/*n*-hexane (3:1). – IR (KBr): $\tilde{\nu}$ = 3055, 2927, 1804, 1676, 1446 cm^{-1}. – ^{1}H NMR (200 MHz, $CDCl_3$): δ = 6.85 (d, A-part of AB-system, *J* = 12.9 Hz, 1 H, 3-H), 6.45 (dd, B-part of AB-system, *J* = 12.9, 12.4, 1.6 Hz, 1 H, 4-H), 3.5–3.9 (m, 3 H, 1,9-H), 3.2–3.3 (m, 1 H, 7-H), 2.7–2.9 (m, 2 H, 6-H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 204.6, 200.1, 197.6, 142.4, 138.6, 57.6, 46.7, 44.2, 43.1. – $C_9H_8O_3$ (164.0): calcd. C 65.85, H 4.91; found C 65.72, H 5.01.

Thermolysis of (4): A solution of endoperoxide **4** (200 mg, 1.2 mmol) in 15 mL of toluene was placed into a glass tube, sealed under vacuum, and heated at 195 °C for three days. After cooling to room temperature the solvent was removed by evaporation. Column chromatography of the residue on silica gel (50 g, ethyl acetate/*n*-hexane, 1:1) afforded bis(epoxide) **7** (152 mg, 77%) as the first fraction. Second fraction afforded a 40 mg (20%) mixture consisting of [1*S*(*R*),5*S*(*R*),7*S*(*R*)]-5-hydroxybicyclo[5.2.0]non-3-ene-2,8-dione (**12**) and [1*S*(*R*),6*R*(*S*),7*S*(*R*)]-6-hydroxybicyclo-[5.2.0]non-4-ene-3,9-dione (**13**) hydroxy-enone. The mixture of (**12**) and (**13**) was submitted to CrO_3 oxidation as reported for (**14**). The triketone (**15**) was obtained in 56% yield.

Synthesis of (*E*)-3-[(2*R*(*S*),3a*R*(*S*),6a*R*(*S*)]-5-Oxohexahydrofuro[3,2-*b*]furan-2-ylprop-2-enal (20): To a solution of the aldehyde (**9**) (90 mg, 0.54 mmol) in 20 mL of CH_2Cl_2 was added $NaHCO_3$ (67 mg, 0.79 mmol) and *m*-chloroperbenzoic acid (93 mg, 0.59 mmol) at room temperature. The resulting mixture was stirred for 1 h at room temperature. The organic layer was washed three times with $Na_2S_2O_3$ solution, with saturated $NaHCO_3$ solution and then with water. The separated organic phase was dried and concentrated. Purification of the residue by chromatography on silica gel elution with chloroform/*n*-hexane (1:3) gave **20** as a pale yellow oil (63 mg, 65%). – IR (neat): $\tilde{\nu}$ = 3005, 2950, 2923, 1783, 1740, 1688, 1395, 1268 cm^{-1}. – ^1H NMR (200 MHz, $CDCl_3$): δ = 9.57 (d, *J* = 7.7 Hz, 1 H, 1′-H), 6.74 (dd, A-part of AB-system, *J* = 15.8, 4.5 Hz, 1 H, 3′-H), 6.33 (ddd, *J* = 15.8, 7.7, 4.5 Hz, 1 H, 2′-H), 5.18 (t, *J* = 4.9 Hz, 1 H, 2-H), 4.75–4.93 (h, 2 H, 3_a,6_a-H), 2.78, (m, 2 H, 3-H), 2.63 (m, 1 H), 1.92 (ddd, *J* = 14.5, 10.0, 4.9 Hz, 1 H). – ^{13}C NMR (50 MHz, $CDCl_3$): δ = 194.8, 177.0, 155.0, 133.6, 86.0, 80.7, 78.82, 40.9, 38.5. – $C_9H_{10}O_4$ (182.2): calcd. C 59.34, H 5.53; found C 59.21, H 5.34.

Acknowledgments

The authors are indebted to the Department of Chemistry (Atatürk University) for the financial support of this work and the State Planning Organization of Turkey (DPT) for purchasing a 200 MHz spectrometer (Atatürk University).

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Received July 5, 1999
[O99397]