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Ring opening of epoxides with $NaHSO_4$: isolation of β-hydroxy sulfate esters and an effective synthesis for *trans*-diols

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ABSTRACT

Sodium hydrogen sulfate ($NaHSO_4$) was observed to be highly effective as a reagent or catalyst in the ring-opening reactions of epoxides under mild conditions. Reaction of epoxides with $NaHSO_4$ gave isolable β-hydroxy sulfate esters and vicinal diols. Experimenting with different epoxides, the study investigated the scope of the ring-opening reaction.

1. Introduction

Epoxides are versatile organic tools as both building blocks and synthetic intermediates. For instance, the ring opening of epoxides with carbon and heteroatomic nucleophiles provides β-substituted alcohols.[1] One of the most important ring-opening reactions is the conversion of epoxides to *trans*-1,2-diols (or *vic*-diols).[2] This functionality is usually a fundamental structural component for cyclitols, potential glycosidase inhibitors, which are receiving considerable attention as chemotherapeutic applications against diabetes, cancer, and viral infections.[3] *myo*-Inositol (**1**) derivatives play a central role in the cellular signal of various glycosidase enzymes (Fig. 1).[4] Several multiply sulfated compounds have been found in biologically active compounds and marine organisms.[5] For instance, sulfated sterols have exhibited effects such as anti-HIV, antiviral activity, and inhibition of protein tyrosine kinases.[6] Compound **2** isolated from *Stilopus australis* is the first sterol with a 5-pregnen skeleton (Fig. 1).[7]

Carbohydrate sulfates play an essential role in cellular communication.[8] Moreover, sulfate functionality comprises intermediates in organic synthesis as powerful alkylating agents or hydroxyl protecting groups.[9] Despite the growing importance of sulfate monoesters in biochemistry, the number of synthesis methods is limited. Classical methods for sulfate synthesis include the esterification of the parent alcohols with H_2SO_4 or cholorosulfonic acid.[10] The most commonly used sulfating agents are complexes of SO_3 with pyridine, tertiary amine, or amides.[11]

Magnesium hydrogen sulfate ($Mg(HSO_4)_2$)[12] and tetrabutylammonium bisulfate (Bu_4NHSO_4)[13] are effective catalysts for the hydrolysis of epoxides and aziridines under mild conditions. Silica-supported sodium hydrogen sulfate ($NaHSO_4 \cdot SiO_2$) efficiently catalyzes various reactions.[14] In continuation of our work on the epoxides, we also noticed that the epoxides underwent the ring-opening reaction with sodium hydrogen sulfate. Herein, we report our results on the ring opening of various epoxides with $NaHSO_4$ under mild reaction conditions.

2. Results and discussions

Initially, we investigated the reaction of cyclohexene-epoxide (**3**) and sodium bisulfate at room temperature in methylene chloride. The heterogeneous reaction of epoxide with $NaHSO_4$ in equivalent amounts gave a mixture of β-hydroxy sulfate ester **4** and epoxide **3** (Scheme 1). When the reaction was repeated with 2 equiv of $NaHSO_4$ under the same conditions, sulfate ester **4** was obtained as the single reaction product characterized by ^1H and ^{13}C NMR spectroscopy. The NMR spectra of the product confirmed the assumption that the presence of protons and carbons connected the bisulfate (ddd at δ=4.46 ppm, J=9.0, 5.7, 3.7 Hz; δ=91.7 ppm) and the alkoxy (a multiplet at δ=4.04 ppm; δ=74.2 ppm) groups.

To add new members to these molecules potentially important for biological processes, we undertook the synthesis of several β-hydroxy sulfate ester analogs. We modulated the ring size and skeleton structure of molecules containing an epoxide. In a similar manner, the concerned sulfate esters **5**–**7** were synthesized with

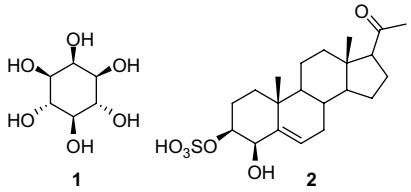

Figure 1. Samples for cyclitol and sulfate monoester.

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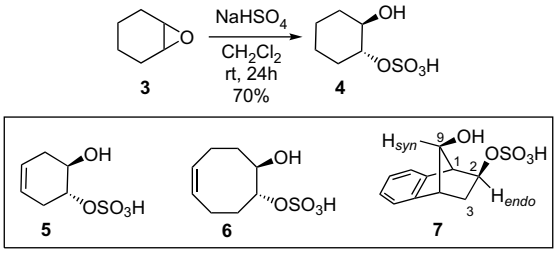
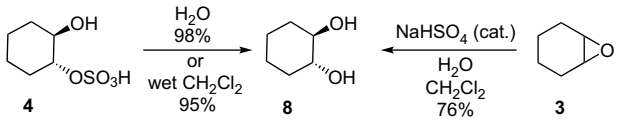


Scheme 1. Ring opening of epoxides with $NaHSO_4$: obtained hydroxy sulfate ester.

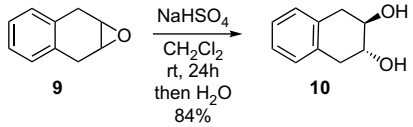
the appropriate epoxides using the same strategy (Scheme 1). The regiochemical formation of the opening products **4**–**6** could be understood on the basis of the usual stereoelectronic factors that favor a trans-diaxial opening mode. However, sulfate ester **7** is a Wagner–Meerwein-type product. The formation of **7** may well proceed via a non-classic carbocation intermediate.[2c] It is not possible to explain the product by the classic addition of hydrogen sulfate. The configurations of hydroxyl and sulfate in **7** were determined from the coupling constants of the relevant protons. The long-range coupling constant (J=1.5 Hz) between 7*syn*-H and 2*endo*-H in molecule **7** (**M** or **W** orientation) confirms the *exo* position of the sulfate. The large coupling constants (J=12.7 Hz) for the geminal 3 and 3′ protons are in agreement with the proposed structures.

We observed that these sulfate esters were unstable in workup conditions and purification steps. Therefore, we turned our attention to the hydrolysis of the hydrogen sulfate group. 2-Hydroxycyclohexyl hydrogen sulfate (**4**) selected as a test molecule was treated with water or wet CH_2Cl_2. After workup, *trans*-cyclohexane-1,2-diol (**8**)[15] was obtained as the sole product (Scheme 2). Due to the instability of the sulfate esters toward water, we also investigated the catalytic activity of $NaHSO_4$ for the ring-opening reaction of epoxide **3** in water medium. Reaction of **3** was carried out in wet CH_2Cl_2 in the presence of catalytic $NaHSO_4$ (0.10 mmol) and it gave *trans*-diol **8** as the sole product.



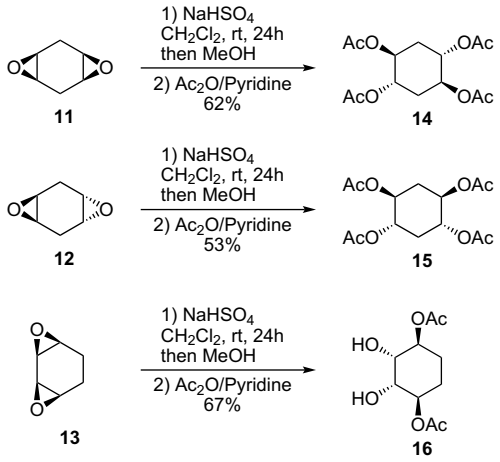
Scheme 2. Hydrolysis of sulfate ester **4** and epoxide **3**.

Additionally, the ring opening of 1,2,3,4-tetrahydronaphthalene-2,3-epoxide (**9**) with 2 equiv of $NaHSO_4$ was performed and a mixture of the diol and mono-sulfate ester was obtained. The concerned sulfate ester was attempted to be purified by crystallization. Yet, the desired mono-sulfate ester could not be isolated. Therefore, the reaction mixture was hydrolyzed to yield the diol **10**[16] with water (Scheme 3).



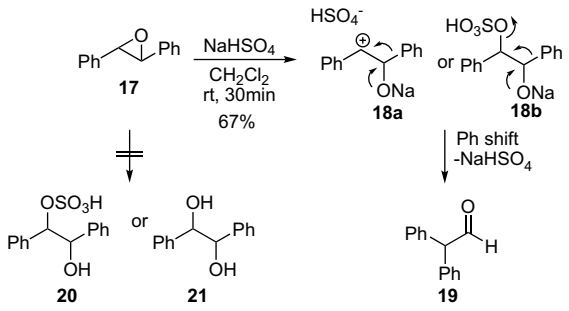
Scheme 3.

The observed results encouraged us to examine the ring-opening reactions of bisepoxides with sodium hydrogen sulfate, for which *syn*- and *anti*-bisepoxides **11**–**13** were selected (Scheme 4). Thus, the ring-opening reaction of *syn*-bisepoxide **11** was carried out with the excess of $NaHSO_4$. Due to the solubility problem, the reaction mixture was solved with methanol, which hydrolyzes the formed di-sulfate ester to the corresponding tetrole, and then filtrated over filter paper. The crude product was characterized by being acetylated with acetic anhydride–pyridine. Since bisepoxide **11** has two epoxide units, two trans-hydroxylation products (or hydroxyl sulfate ester) can be expected. The ^1H and ^{13}C NMR spectra of the acetylation product yielded only one hydroxylation product **14**,[17] instead of two symmetrical products contrary to our expectations. We assumed that the steric hindrance role of the first added sulfate group was effective in the observed regioselectivity. The other bisepoxides **12** and **13** were also transformed into the corresponding products **15** and **16**[18] under similar reaction conditions (Scheme 4). The molecule obtained from **13** is a half-acetylation product.



Scheme 4. Ring opening of *syn*- and *anti*-bisepoxides **11**–**13** and obtained products **14**–**16**.

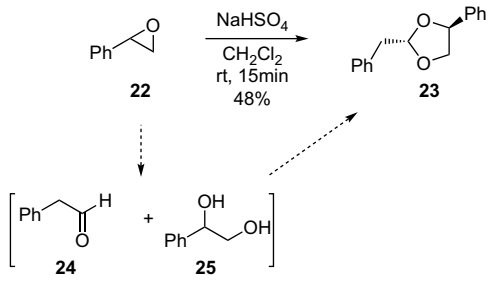
After the successful formation of the mono-sulfate esters and diols from the rigid carbocyclic mono- or bisepoxides and epoxide in a bicyclic framework, we further investigated the ring-opening activity of sodium hydrogen sulfate toward benzylic epoxides such as stilbene oxide and styrene oxide. If this trend continues, the formation of sulfate ester or diol can be expected to occur. Therefore, *trans*-stilbene oxide (**17**) was firstly treated with an equivalent amount of $NaHSO_4$ in methylene chloride at room temperature. Following the chromatography on silica gel, 2,2-diphenylacetaldehyde (**19**),[19] a pinacol-type rearrangement product, was obtained as the single reaction product, instead of sulfate ester **20** or diol **21**, the possible expected ring-opening products (Scheme 5). As can be understood, the formation of this product involves the formation of a carbenium ion intermediate **18a** or sodium alcoholate **18b** that subsequently rearranges through a 1,2-phenyl shift to produce the carbonyl compound. The driving force behind the rearrangement of benzylic epoxide to pinacol product might be the formation of



Scheme 5.

a more stable benzylic carbocation in which the positive charge can be delocalized on the phenyl.

Finally, we studied the reaction of styrene oxide (**22**) with $NaHSO_4$, which was performed by treating epoxide **22** with excess $NaHSO_4$ in methylene chloride for 15 min (Scheme 6). Surprisingly, chromatography of the crude product provided 1,3-dioxolane derivative **23**, which is known in the literature and whose constitution was elucidated by NMR spectroscopy.[20] We assume that the 1,3-dioxolane derivative **23** is formed by the acetalization of the initially formed 2-phenylacetaldehyde (**24**) and 1-phenylethane-1,2-diol (**25**) under the given reaction conditions. Two possible approaches can be postulated for the outcome of this final experiment. Firstly, epoxide **22** hydrolyzes to give its parent diole **25**, which undergoes the pinacol rearrangement product **24** and then, aldehyde **24** is caught with diol **25** to give dioxolane **23**. Secondly, the epoxide gives both hydrolysis and semi-pinacol rearrangement reactions, which undergoes acetal as in situ.



Scheme 6.

3. Conclusion

In conclusion, we have described sodium hydrogen sulfate as a highly effective reagent for ring-opening reactions of epoxides. This unknown behavior of $NaHSO_4$ toward monocarbocyclic epoxides provides a facile and convenient route for the synthesis of isolable β-hydroxy sulfate esters or *trans*-1,2-diols. Furthermore, the ring-opening reactions of the epoxide with a bicyclic skeleton and the benzylic epoxides with $NaHSO_4$ are exposed to Wagner–Meerwein and pinacol rearrangement. Using epoxides and sodium hydrogen sulfate, the present study not only includes advantages such as experimental convenience and mild conditions, but it also creates opportunities for the synthesis of potentially important molecules for biological processes such as sulfate esters and cyclitols.

4. Experimental section

4.1. General methods

Melting points were determined on Buchi 539 capillary melting apparatus. Infrared spectra were recorded on a Mattson 1000 FT-IR spectrophotometer. ^{1}H NMR and ^{13}C NMR spectra were recorded on 200 (50) and 400 (100) MHz Varian spectrometer and are reported in δ units with $SiMe_4$ as internal standard. Elemental analyses were carried out on a Leco CHNS-932 instrument.

*4.1.1. trans-(1R(S),2R(S))-2-Hydroxycyclohexyl hydrogen sulfate (**4**)*

To a solution of cyclohexene-epoxide (**3**) (250 mg, 2.6 mmol) in 10 mL of CH_2Cl_2 was added 615 mg $NaHSO_4$ (5.12 mmol) at room temperature. The reaction was completed in 24 h as verified by TLC. Then, the reaction mixture was filtered over filter paper and the solvent was concentrated under reduced pressure. The crude product **4** (450 mg, 90%) was recrystallized from CH_2Cl_2/hexane as white crystals (350 mg, 70%, mp 194–195 °C). ^{1}H NMR (200 MHz, $CDCl_3$) δ 4.46 (ddd, J=9.0, 5.8, 3.7 Hz, $CHOSO_3H$, 1H), 4.26 (m, OH, 1H), 3.57–3.52 (m, CHOH, 1H), 2.33–2.30 (m, CH_2, 1H), 2.10–2.03 (m, CH_2, 1H), 1.80–1.69 (m, CH_2, 2H), 1.41–1.25 (m, CH_2, 4H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 91.7, 74.2, 35.4, 33.1, 26.0, 25.5; IR (CH_2Cl_2, cm^{-1}) 3391, 2936, 2862, 1453, 1392, 1191, 1075, 992, 910. Anal. Calcd for $C_6H_{12}O_5S$: C, 36.73; H, 6.16; S, 16.34. Found: C, 36.92; H, 6.13; S, 16.47.

*4.1.2. trans-(1R(S),6R(S))-6-Hydroxycyclohex-3-enyl hydrogen sulfate (**5**)*

Product **5** was obtained from 1,4-cyclohexadiene-epoxide (150 mg, 1.56 mmol) and $NaHSO_4$ (375 mg, 3.12 mmol) as described for the preparation of **4** in 24 h. The residue (290 mg) was crystallized from CH_2Cl_2/hexane: white crystals **5** (225 mg, 74%, mp 126–127 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.56–5.51 (m, =CH, 2H), 4.80 (ddd, J=14.8, 9.5, 6.2 Hz, $CHOSO_3H$, 1H), 3.99 (ddd, J=15.0, 9.6, 6.3 Hz, CHOH, 1H), 2.87–2.81 (m, CH_2, 1H), 2.63–2.57 (m, CH_2, 1H), 2.43–2.35 (m, CH_2, 1H), 2.21–2.07 (m, CH_2 and OH, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 124.5, 123.5, 86.2, 69.1, 34.1, 31.7; IR (CH_2Cl_2, cm^{-1}) 3256, 2928, 1399, 1195, 1067, 996, 969, 894. Anal. Calcd for $C_6H_{10}O_5S$: C, 37.11; H, 5.19; S, 16.51. Found: C, 37.35; H, 5.05; S, 16.30.

*4.1.3. trans-(1R(S),8R(S),Z)-8-Hydroxycyclooct-4-enyl hydrogen sulfate (**6**)*

Product **6** was obtained from 1,5-cyclooctadiene-epoxide (300 mg, 2.41 mmol) and $NaHSO_4$ (580 mg, 4.82 mmol) as described for the preparation of **4** in 24 h. The residue (510 mg) was crystallized from CH_2Cl_2/hexane: white crystals **6** (380 mg, 70%, mp 115–116 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.62–5.56 (m, =CH, 2H), 4.89–4.84 (m, $CHOSO_3H$, 1H), 4.04 (ddd, J=12.5, 8.5, 3.7 Hz, CHOH, 1H), 3.31 (m, OH, 2H), 2.52–2.36 (m, CH_2, 2H), 2.25–2.16 (m, CH_2, 4H), 2.15–2.00 (m, CH_2, 1H), 1.78–1.71 (m, CH_2, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 129.0,128.5, 91.3, 72.1, 31.9, 30.1, 23.3, 23.2; IR (CH_2Cl_2, cm^{-1}) 3405, 2936, 1723, 1187, 1058, 890, 734. Anal. Calcd for $C_8H_{14}O_5S$: C, 43.23; H, 6.35; S, 14.43. Found: C, 42.99; H, 6.23; S, 14.30.

*4.1.4. 9(R(S))-Hydroxy-1,2,3,4-tetrahydro-1,4-methanonaphthalen-2(R(S))-yl sulfate (**7**)*

Product **7** was obtained from benzonorbornadiene-epoxide (110 mg, 0.69 mmol) and $NaHSO_4$ (167 mg, 1.39 mmol) as described for the preparation of **4** in 24 h. The residue (120 mg) was crystallized from CH_2Cl_2/hexane: yellow crystals **7** (127 mg, 83%, mp 186–187 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, J=7.0 Hz, C_6H_4, 1H), 7.26–7.17 (m, C_6H_4, 3H), 5.01 (ddd, J=3.9, 3.2, 1.5 Hz, $CHOSO_3H$, 1H), 4.39 (m, CH, 1H), 4.10–4.09 (m, CHOH, 1H), 3.78–3.77 (m, CH, 1H), 2.74 (dd, J=12.7, 3.9 Hz, A part of AX system, CH_2, 1H), 1.58 (m, OH, 1H), 1.55 (ddd, J=12.7, 3.2, 1.5 Hz, X part of AX system, CH_2, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.9, 135.9, 129.0, 127.6, 124.4, 120.8, 84.4, 74.2, 56.0, 43.1, 36.0; IR (CH_2Cl_2, cm^{-1}) 3410, 2924, 2853, 1720, 1465, 1332, 1210, 1188, 1078, 1015, 750. Anal. Calcd for $C_{11}H_{12}O_5S$: C, 51.55; H, 4.72; S, 12.51. Found: C, 51.75; H, 4.70; S, 12.38.

*4.1.5. Hydrolysis of **4** to trans-(1R(S),2R(S))-cyclohexane-1,2-diol (**8**)*

(A) *trans*-(1*R*(*S*),2*R*(*S*))-2-Hydroxycyclohexyl hydrogen sulfate (**4**) (100 mg, 0.51 mmol) and 10 mL of water were stirred for 5 min at room temperature. Water was evaporated at 60 °C under reduced pressure. The residue was dissolved in 30 mL of CH_2Cl_2 and then dried (Na_2SO_4). Diol **8** crystallized from CH_2Cl_2/hexane: white solid (58 mg, 98%, mp 107–108 °C, lit.[15a] mp 144–145 °C, lit.[15d] mp 107.5–108.5 °C).

(B) *trans*-(1*R*(*S*),2*R*(*S*))-2-Hydroxycyclohexyl hydrogen sulfate (**4**) (100 mg, 0.51 mmol) and 2 mL of CH_2Cl_2 and 20 mL of water

were stirred for 30 min at room temperature. The solvent was evaporated under reduced pressure. The residue was dissolved in 30 mL of CH_2Cl_2 and then dried (Na_2SO_4). Diol **8** was obtained as white solid (56 mg, 95%).

(C) A solution of cyclohexene-epoxide (**3**) (100 mg, 1.02 mmol) and 13 mg $NaHSO_4$ (0.10 mmol) in 2 mL of CH_2Cl_2 and 20 mL of water was stirred for 24 h at room temperature. Then, the reaction mixture was filtered over filter paper and the solvent was concentrated under reduced pressure. The crude product **8** (110 mg, 93%) was dissolved in 30 mL of CH_2Cl_2 and then dried (Na_2SO_4). Diol **8** was obtained as white solid (90 mg, 76%). ^{1}H NMR (200 MHz, $CDCl_3$) δ 3.34 (m, CHOH, 2H), 3.24 (m, OH, 2H), 1.98–1.86 (m, CH_2, 2H), 1.71–1.69 (m, CH_2, 2H), 1.26–1.24 (m, CH_2, 4H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 77.8, 34.9, 25.3; IR (CH_2Cl_2, cm^{-1}) 3290, 2859, 1446, 1352, 1254, 1210, 1073, 1044, 928, 857. Anal. Calcd for $C_6H_{12}O_2$: C, 62.04; H, 10.41. Found: C, 61.88; H, 10.32.

4.1.6. *trans-(2R(S),3R(S))-1,2,3,4-Tetrahydronaphthalene-2,3-diol (**10**)*

To a solution of 1,2,3,4-tetrahydronaphthalene-2,3-epoxide (**9**) (80 mg, 0.55 mmol) in 10 mL of CH_2Cl_2 was added 264 mg $NaHSO_4$ (2.18 mmol) at room temperature. The mixture was stirred for 24 h and 2 mL of water was added to the mixture. Then, the reaction mixture was filtered over filter paper, the solvent was dried (Na_2SO_4), and concentrated under reduced pressure. The crude product **10** (75 mg, 84%) was recrystallized from CH_2Cl_2/hexane as white crystals (45 mg, 50%, mp 161–162 °C, lit.[16] mp 157–159 °C). ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.18–7.10 (m, AA′BB′ system, C_6H_4, 4H), 3.94–3.83 (m, CHOH, 2H), 3.18 (ddd, J=5.5, 3.8, 1.7 Hz, A part of AB system, CH_2, 2H), 2.95–2.75 (m, B part of AB system, CH_2 and OH, 4H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 135.8, 130.8, 128.3, 74.3, 38.8; IR (CH_2Cl_2, cm^{-1}) 3368, 2925, 1721, 1493, 1172, 1064, 745. Anal. Calcd for $C_{10}H_{12}O_2$: C, 73.15; H, 7.37. Found: C, 73.40; H, 7.30.

4.1.7. *trans,trans-(1S(R),2S(R),4S(R),5S(R))-Cyclohexane-1,2,4,5-tetrayl tetra acetate (**14**)*

To a stirred solution of *syn*-bisepoxide **11** (140 mg, 1.25 mmol) in a CH_2Cl_2 (10 mL) was added 900 mg $NaHSO_4$ (7.50 mmol) at room temperature. After the mixture was stirred for 24 h, 15 mL of methanol was added, the reaction mixture was filtered over filter paper, and the solvent was concentrated under reduced pressure. Then, the crude product (170 mg) was acetylated in pyridine (1.00 g) and Ac_2O (0.50 g) at 1 day. Then, the mixture was cooled to 0 °C and poured into a cold solution (1%, 100 mL) of HCl. The mixture was extracted with CH_2Cl_2 (3×50 mL). The combined organic layer was washed with $NaHCO_3$ (5%, 100 mL) and water (100 mL), and then dried over Na_2SO_4. After the solvent was evaporated, tetra acetate **14** was recrystallized from CH_2Cl_2/hexane as pale yellow crystals (245 mg, 62%, mp 147–148 °C, lit.[17] mp 144–145 °C). The yield of **14** was calculated as a total according to *syn*-bisepoxide **11**. ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.08–5.04 (m, OCH, 4H), 2.11–2.01 (m, CH_2, 4H), 2.06 (s, OAc, 12H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 171.6, 71.2, 32.2, 22.9; IR (CH_2Cl_2, cm^{-1}) 2966, 1741, 1441, 1370, 1233, 1182, 1030, 974, 934. Anal. Calcd for $C_{14}H_{20}O_8$: C, 53.16; H, 6.37. Found: C, 53.01; H, 6.15.

4.1.8. *trans,trans-(1R(S),2R(S),4S(R),5S(R))-Cyclohexane-1,2,4,5-tetrayl tetra acetate (**15**)*

To a stirred solution of *anti*-bisepoxide **12** (185 mg, 1.65 mmol) in CH_2Cl_2 (10 mL) was added 1190 mg $NaHSO_4$ (9.91 mmol) at room temperature. After the mixture was stirred for 24 h, 15 mL of methanol was added, the reaction mixture was filtered over filter paper, and the solvent was concentrated under reduced pressure. Then, the crude product (200 mg) was acetylated in pyridine (1.50 g) and Ac_2O (0.60 g) at 1 day. Then, the mixture was cooled to 0 °C and poured into a cold solution (1%, 100 mL) of HCl. The mixture was extracted with CH_2Cl_2 (3×50 mL). The combined organic layer was washed with $NaHCO_3$ (5%, 100 mL) and water (100 mL), and then dried over Na_2SO_4. After the solvent was evaporated, tetra acetate **15** was recrystallized from CH_2Cl_2/hexane as white crystals (275 mg, 53%, mp 138–139 °C). The yield of **15** was calculated as a total according to *anti*-bisepoxide **12**. ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.96–4.92 (m, OCH, 4H), 2.38 (dt, J=12.5, 4.2 Hz, A part of AX system, CH_2, 2H), 2.02 (s, OAc, 12H), 1.57 (br d, J=12.5 Hz, X part of AX system, CH_2, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.1, 70.4, 32.0, 21.1; IR (CH_2Cl_2, cm^{-1}) 1727, 1373, 1235, 1059, 919, 749. Anal. Calcd for $C_{14}H_{20}O_8$: C, 53.16; H, 6.37. Found: C, 53.34; H, 6.32.

4.1.9. *trans,trans-(1R(S),2R(S),3S(R),4S(R))-2,3-Dihydroxy-cyclohexane-1,4-diyl diacetate (**16**)*

To a stirred solution of *syn*-bisepoxide **23** (185 mg, 1.65 mmol) in CH_2Cl_2 (10 mL) was added 1190 mg $NaHSO_4$ (9.91 mmol) at room temperature. After the mixture was stirred for 24 h, 15 mL of methanol was added, the reaction mixture was filtered over filter paper, and the solvent was concentrated under reduced pressure. Then, the crude product (215 mg) was acetylated in pyridine (1.50 g) and Ac_2O (0.60 g) at 1 day. Then, the mixture was cooled to 0 °C and poured into a cold solution (1%, 100 mL) of HCl. The mixture was extracted with CH_2Cl_2 (3×50 mL). The combined organic layer was washed with $NaHCO_3$ (5%, 100 mL) and water (100 mL), and then dried over Na_2SO_4. After the solvent was evaporated, tetra acetate **16** was recrystallized from CH_2Cl_2/hexane as pale yellow crystals (256 mg, 67%, mp 114–115 °C, lit.[18] mp 115–116 °C). The yield of **16** was calculated as a total according to *anti*-bisepoxide **13**. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.25 (br d, J=5.9 Hz, OCH, 2H), 3.45–3.43 (m, CHOH, 2H), 2.07 (s, OAc, 6H), 1.80–1.71 (m, CH_2, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 76.5, 71.6, 24.0, 21.3; IR (CH_2Cl_2, cm^{-1}) 3522, 2925, 2846, 1747, 1599, 1459, 1432, 1371, 1245, 1172, 1125, 1056. Anal. Calcd for $C_{10}H_{16}O_6$: C, 51.72; H, 6.94. Found: C, 52.01; H, 7.00.

4.1.10. *2,2-Diphenylacetaldehyde (**19**)*

A solution of *trans*-stilbene oxide (**17**) (280 mg, 1.42 mmol) and $NaHSO_4$ (171 mg, 1.42 mmol) in 10 mL of CH_2Cl_2 was stirred at room temperature for 30 min. Then, the reaction mixture was filtered over filter paper and the solvent was concentrated under reduced pressure. The residue (275 mg) was submitted to column chromatography on silica gel (25 g) eluting with ethyl acetate/hexane (2%). Elution gave 2,2-diphenylacetaldehyde (**19**) as colorless liquid (188 mg, 67%). ^{1}H NMR (200 MHz, $CDCl_3$) δ 9.87 (d, J=2.5 Hz, CHO, 1H), 7.43–7.22 (m, C_6H_5, 10H), 4.91 (d, J=2.5 Hz, CH, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 200.4, 138.4, 131.1, 131.0, 129.6, 66.1; IR (CH_2Cl_2, cm^{-1}) 3061, 3029, 2896, 2721, 1954, 1885, 1809, 1724, 1657, 1599, 1494, 1451, 1389, 1279, 1177, 1079, 950. Anal. Calcd for $C_{14}H_{12}O$: C, 85.68; H, 6.16. Found: C, 85.35; H, 6.10.

4.1.11. *trans-(2S(R),4S(R))-2-Benzyl-4-phenyl-1,3-dioxolane (**23**)*

A solution of styrene oxide (**22**) (150 mg, 1.25 mmol) and $NaHSO_4$ (300 mg, 2.50 mmol) in 10 mL of CH_2Cl_2 was stirred at room temperature for 15 min. Then, the reaction mixture was filtered over filter paper and the solvent was concentrated under reduced pressure. The residue (210 mg) was subjected to column chromatography on silica gel (25 g) eluting with ethyl acetate/hexane (2%). Elution gave *trans*-(2*S*(*R*),4*S*(*R*))-2-benzyl-4-phenyl-1,3-dioxolane (**23**) as colorless liquid (140 mg, 48%, lit.[20a] mp 42 °C, lit.[20d] mp 33–34 °C). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36–7.25 (m, C_6H_5, 10H), 5.30 (t, J=4.6 Hz, OCH, 1H), 5.01 (t, J=6.8 Hz, OCH, 1H), 4.17 (dd, J=7.7, 6.8 Hz, A part of AX system, CH_2, 1H), 3.69 (dd, J=7.7, 6.8 Hz, X part of AX system, CH_2, 1H), 3.15 (dd, J=13.9, 4.6 Hz, A part

of AB system, CH_2, 1H), 3.11 (dd, J=13.9, 4.6 Hz, B part of AB system, CH_2, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.6, 136.2, 130.2, 128.7, 128.6, 128.4, 126.6, 126.6, 105.6, 78.7, 72.2, 41.0; IR (CH_2Cl_2, cm^{-1}) 2924, 1495, 1455, 1134, 1080, 1028, 754, 698. Anal. Calcd for $C_{16}H_{16}O_2$: C, 79.97; H, 6.71. Found: C, 79.69; H, 6.51.

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Supplementary data

Supplementary data includes experimental procedures and ^1H and ^{13}C NMR spectra of compounds. Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.11.092.

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