New approach to cyclic sulfites and sulfates through reactions of sulfur oxychlorides with glycidols

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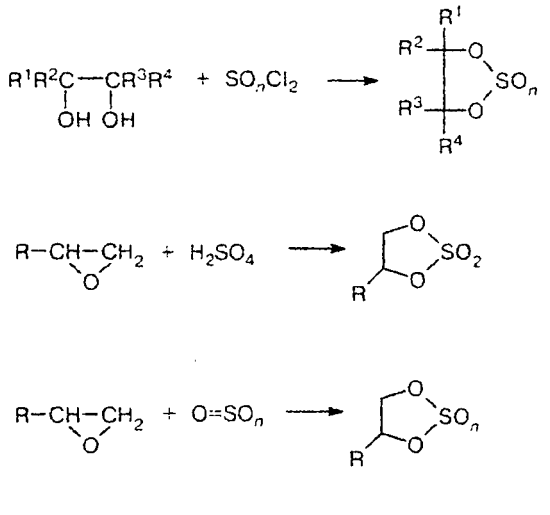
Reactions of 2,3-epoxyalcohols (glycidols) with thionyl chloride or sulfuryl chloride afford cyclic sulfites or sulfates, respectively. These reactions yield predominantly 4-chloroalkyl-1,3,2-dioxathiolane oxides. The configuration of the C(4) atom in the latter compounds exactly corresponds to that of the C(2) atom of the parent glycidol, whereas the configuration of the exocyclic atom is almost completely reversed with respect to that of the C(3) atom of the precursor.

Key words: epoxyalcohols, thionyl chloride, sulfuryl chloride, cyclic sulfites, cyclic sulfates, stereochemistry.

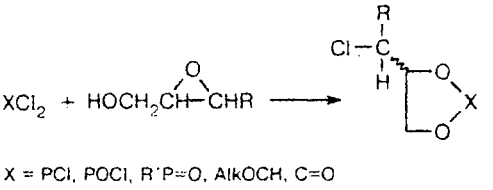
Organic cyclic esters of sulfurous and sulfuric acids, *viz.*, cyclic sulfites and sulfates (CSS), have been known over more than six decades.[1] However, it was not until 1988 that these compounds were found[2] to act as epoxides, and yet to be more active. Beginning with that study, the chemistry of cyclic sulfites and sulfates has been extensively investigated. Examples of the use of these compounds as key intermediates in the synthesis of biologically active compounds were reported in hundreds of publications. Three reviews[3] were partially or completely devoted to the chemistry of CSS. However, procedures for the synthesis of the dioxathiolane ring (Scheme 1) are restricted to reactions of diols with sulfur oxychlorides and reactions of epoxides with derivatives of sulfuric acid or sulfur oxides.[3]

Previously, we have found[4] that the reactions of activated geminal dichlorides with 2,3-epoxypropan-1-ols (glycidols) afford 1,3,2-dioxacarbo- or 1,3,2-dioxaheterocyclanes (Scheme 2).

Scheme 1



Scheme 2



In this work, we consider the regio- and stereochemistry of the reactions of sulfur oxychlorides SO_nCl_2 (n = 1 or 2) with glycidols (for a preliminary communication, see Ref. 5).

The reaction of thionyl chloride with an excess of racemic glycidol **1** in the presence of two equivalents of triethylamine afforded a mixture of diastereoisomeric diglycidyl sulfites **2** as the major products (Scheme 3). In this case, the ratio between two achiral *meso* products, (*R,r,S*)-**2** and (*R,s,S*)-**2**, and racemic chiral sulfite *rac*-**2** was ~1 : 1 : 2 (according to the data of ^{13}C NMR spectroscopy).

Chiral sulfites **2** are characterized by the absence of symmetry elements. As a consequence, the structurally identical glycidyl fragments in the molecule (*R,R*)-**2** or (*S,S*)-**2** are in diastereotopic relation with respect to one another and are manifested as individual signals in the

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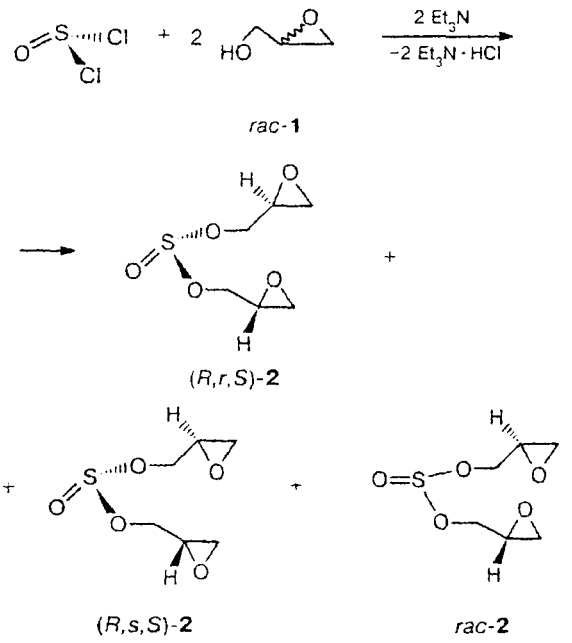
Scheme 3



magnetic resonance spectra. From this viewpoint, the ^{13}C NMR spectrum of the $SOCH_2$ fragment is most descriptive. Figure 1 shows this spectrum for a mixture of diastereomeric sulfites **2** prepared from racemic glycidol and (*S*)-glycidol. First, based on the change in the ratio between signals on going from racemic glycidol **1** to scalemic glycidol, the pair of high-field signals was unambiguously assigned to the chiral diastereomer (*rac*-**2** in Fig. 1, *a* and predominantly (*R,R*)-**2** in Fig. 1, *b*). Second, the fact that one of the *meso* isomers (see Fig. 1, *b*) substantially prevails is indicative of the different rates of replacement of the enantiotopic chlorine atoms in $SOCl_2$ by the oxygen atom of the OH group of scalemic glycidol.

Scalemic glycidol was prepared by enantioselective Sharpless epoxidation of allyl alcohol. The NMR spectra of a mixture of diastereomers **2** (see, in particular, Fig. 1, *b*) can be used for determining the enantiomeric composition of the starting glycidol (*S*)-**1**. According to the Horeau equation, the enantiomeric excess (*ee*) of the starting glycidol $[(K - 1)/(K + 2)]^{1/2} = 89.3\%$, where $K = Q_1/Q_2$ and Q_1 and Q_2 designate the overall integral intensities of the chiral product (62.38 and 62.46, $I_{over} = 210.2$) and of both *meso* forms (62.63 and 62.78, $I_{over} = 16.4$), respectively.[6] For the same specimen of (*S*)-**1**, the enantiomeric excess determined independently by chromatography was 90.0%. Therefore, the results of the two methods are in satisfactory agreement.

In the presence of an excess of glycidol, nucleophilic replacement at the sulfur atom of thionyl chloride proceeds more readily with the participation of the oxygen atom of the OH group of epoxyalcohol. If glycidol *rac*-**1** and $SOCl_2$ are taken in an equimolar ratio and the

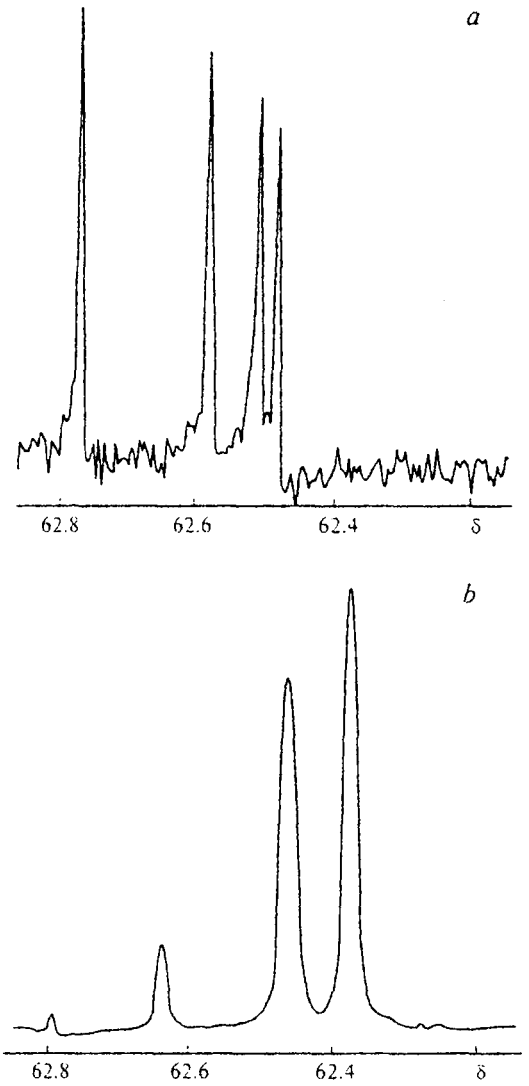
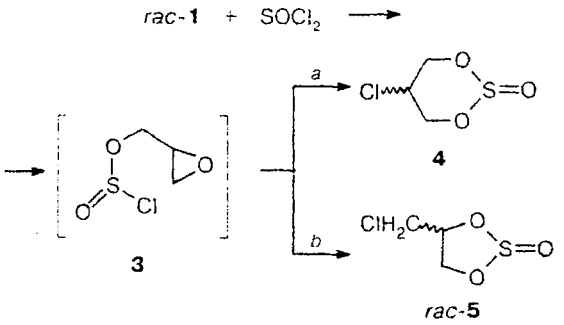


Fig. 1. ^{13}C NMR spectrum of the $SOCH_2$ fragment for a mixture of diglycidyl sulfites **2** prepared from racemic (*a*) and scalemic (*b*) (*S*)-glycidols.

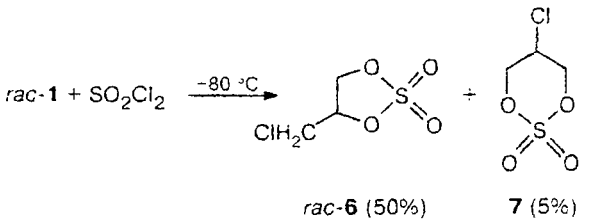
reaction is carried out in the presence of one equivalent of Et_3N or in the absence of a base, unstable monoglycidyl chlorosulfite **3** formed at the first stage is stabilized through intramolecular ring opening of the oxirane fragment. This process can afford both six- and five-membered dioxathiocyclanes (**4** and **5**, respectively; Scheme 4).

In the case of single fractionation, the total yield of a mixture of cyclic sulfites reached 90%. In the ^{13}C NMR spectrum of this mixture, the major signals (96—98% of the overall integral intensity) belong to racemic *cis*- and *trans*-4-chloromethyl-2-oxo-1,3,2-dioxathiolanes (Table 1), the *cis*-**5** : *trans*-**5** ratio being approximately 1.0 : 1.4. The substantially less intense signals (the overall intensity is 2—4%) at δ_C 46.92 and 51.64 (CHCl) and

Scheme 4



Scheme 5



at δ_C 60.87 and 60.20 (OCH_2) correspond to *cis*- and *trans*-5-chloro-2-oxo-1,3,2-dioxathianes, respectively (*cis*-**4** : *trans*-**4** ≈ 3 : 1). The assignment of the signals in the spectra was made based on the results of studies performed previously[7–10] in which the NMR spectra of dioxathianes and 1,3,2-dioxathiolanes were examined, in particular, the δ_C values for racemic sulfites **4** and **5** were reported.[8,10] The published values virtually coincide with those for the specimens of these compounds prepared in this work.

After second distillation, the mixture of sulfites **5** became virtually free of an admixture of isomers **4** (initially insignificant) and, consequently, the reaction of glycidol with $SOCl_2$ is an efficient procedure for the preparation of 4-chloromethyl-substituted five-membered cyclic sulfites.

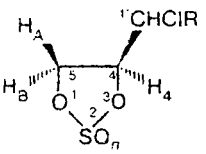
We failed to prepare diglycidyl sulfate by varying the conditions of the reaction of glycidol *rac*-**1** with sulfuryl chloride. However, the reaction of equimolar amounts of *rac*-**1** with SO_2Cl_2 at a temperature below −70 °C in the absence of a base afforded 4-chloromethyl-2,2-dioxo-1,3,2-dioxathiolane (**6**) in 50% yield (Scheme 5). The ^{13}C NMR spectrum of the product has signals of compound **6** (see Table 1) along with signals at δ_C 46.74 (CH_2Cl) and 76.38 (OCH_2) belonging to 5-chloro-2,2-dioxo-1,3,2-dioxathiane (**7**), which formed in 8–10% yield with respect to thiolane **6**.

It should be noted that direct sulfation of organic substrates with sulfuryl chloride does not generally afford cyclic sulfates.[3] The standard procedure for the preparation of these compounds involves oxidation of the corresponding sulfites. With the aim of isolating sulfate **6** of higher purity, we oxidized a mixture of diastereomeric sulfites **5** with $KMnO_4$ in a two-phase CH_2Cl_2–H_2O system. The two-step synthesis of product **6** from glycidol **1** and $SOCl_2$ can be performed as a one-pot procedure without intermediate isolation of sulfites.

Dioxathiolanes **5** and **6** are synthetic equivalents of epichlorohydrin (**8**), which is a widely used epoxide. It is unlikely that compounds **5** and **6** in racemic form are economically competitive with epichlorohydrin. However, the situation can reverse on going to scalemic reagents. The available approaches to the synthesis of scalemic epichlorohydrin (see the review [11] surveying the syntheses of scalemic C_3-epoxides and their precursors) are based either on the use of natural compounds as the starting compounds to form epichlorohydrin adopting only one of the two possible configuration[12] or on bioengineering procedures using living organisms. At the same time, scalemic glycidols, including the simplest compound **1**, are among the most inexpensive and readily accessible chiral building blocks due to the widely accepted enantioselective Sharpless epoxidation.[13] To our knowledge, scalemic cyclic sulfites and sulfates (**5** and **6**, respectively) have not been described previously.

The reaction of $SOCl_2$ with glycidol (*S*)-**1** proceeded analogously to the above reaction with *rac*-**1**, which

Table 1. Parameters of the ^1H and ^{13}C NMR spectra of selected cyclic sulfites and sulfates

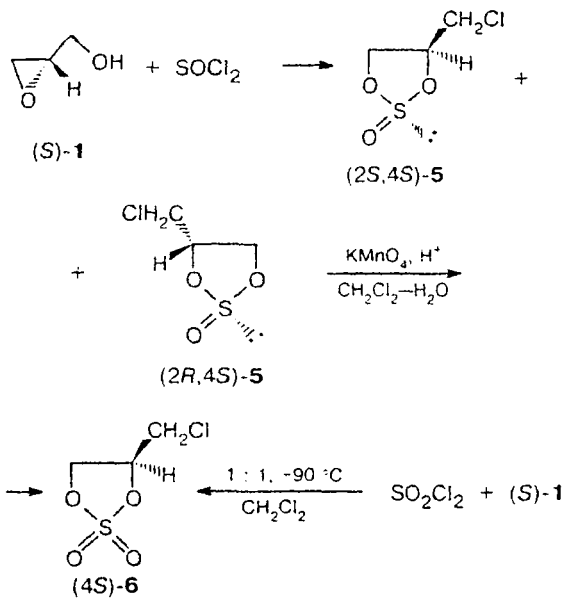


Compound	Configuration	δ_C			δ_H					$J_{H(4),H(5A)}$; $J_{H(4),H(5B)}$; $J_{H(5A),H(5B)}$; $J_{H(4),H(1')}$/Hz
		C(4)	C(5)	C(1′)	HC(4)	$H_AC(5)$	$H_BC(5)$	HC(1′)	Ph	
trans-**5**	(2*R*,4*S*)	78.83	68.94	42.56	5.09	4.66	4.32	3.62	—	5.6; 6.4; −9.0; 5.4
cis-**5**	(2*S*,4*S*)	80.93	68.98	43.35	4.73	4.47	4.55	3.81	—	7.5; 6.4; −8.7; 5.3
6	(4*S*)	79.50	70.25	41.46	5.15	4.85	4.65	3.84	—	6.8; 6.6; −8.9; 5.8
10	(2*S*,4*S*,1′*R*)	83.77	70.90	62.85	5.06	4.80	4.70	4.85	7.38	—; —; —; 5.3
11	(2*R*,4*S*,1′*R*)	81.55	69.21	60.82	5.22	4.80	4.57	4.77	7.34	7.8; 6.4; −8.6; 5.1
12	(2*S*,4*S*,1′*S*)	82.23	68.21	60.75	5.17	4.47	4.12	4.79	7.26	5.2; 6.2; −8.5; 6.0
13	(4*S*,1′*R*)	81.54	70.69	59.98	5.10	4.76	4.87	5.07	7.44	7.5; 6.6; −9.3; 5.9

made it possible to isolate a mixture of diastereomeric chloromethyl sulfites **5** in ~85% yield. When performing chromatographic analysis of the mixture, we failed to achieve separation of the enantiomers of *cis*-**5** sufficient for the quantitative determination of their ratio. For *trans*-**5**, this separation was performed and the *ee* value (89.3%) was virtually equal to that for the initial glycidol. It is beyond reason to believe that the enantiomeric purity of the enantiomer of *cis*-**5** differs from that of *trans*-**5**, and it can be assumed that the chiral center of the initial glycidol remains unaffected in this reaction path and retains its configuration in the final products, *viz.*, in (2*S*,4*S*)-**5** and (2*R*,4*S*)-**5**.

Scalemic sulfate (4*S*)-**6** was prepared both by direct sulfation of glycidol (*S*)-**1** with sulfuryl chloride and by oxidation of a mixture of isomers of (4*S*)-**5** (Scheme 6).

Scheme 6



An insignificant difference in the specific optical rotation observed for specimens of (4*S*)-**6** is attributable to the presence of an admixture of achiral dioxathiane **7** in the sulfate prepared according to the first procedure.

To examine the stereochemistry of the replacement in the oxirane ring, we carried out the reaction of $SOCl_2$ with (2*S*,3*S*)-3-phenyl-2,3-epoxypropan-1-ol (**9**), which was readily prepared by enantioselective epoxidation of cinnamic alcohol followed by recrystallization of the product.[14,15]

Single distillation of the products obtained in the reaction of equimolar amounts of $SOCl_2$ and epoxyalcohol **9** afforded a mixture of isomeric sulfites (~55%). According to the data of TLC and NMR spectroscopy, the mixture contained three products (**10**, **11**, and **12**; the yields were 45, 52, and 3%, respectively), each being isolated by column chromatography. Based on this fact and taking into account the data of NMR spectroscopy

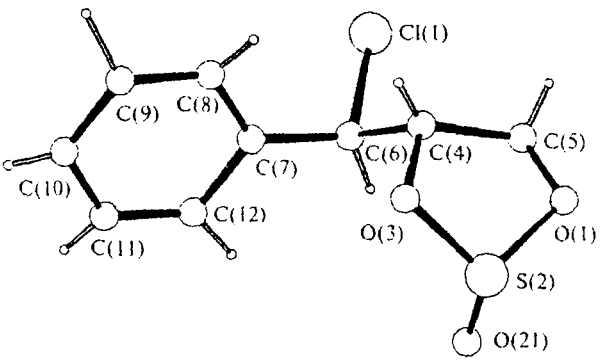


Fig. 2. Molecular structure of compound **10** in the crystal.

(see Table 1), crystalline cyclic sulfite, characterized by the minimum retention time, was identified as (2*S*,4*S*)-4-[1-chloro-(1*R*)-1-phenylmethyl]-2-oxo-1,3,2-dioxathiolane (**10**) by analogy with the adduct of (*S*)-glycidol, *viz.*, (2*S*,4*S*)-**5**. This assignment and the absolute configuration of the chiral centers were confirmed by the results of X-ray diffraction analysis (Fig. 2, Table 2).

Oxidation of a mixture of sulfites **10**—**12** with $KMnO_4$ in an acidic medium gave rise to a single product in 50% yield (the minor components were lost in the course of treatment). This signifies that cyclic sulfites **10** and **11** dominant in the reaction mixture differ only by the configuration of the sulfur atom, and the final sulfate **13** has the structure of (4*S*)-4-[1-chloro-(1*R*)-1-phenylmethyl]-2,2-dioxo-1,3,2-dioxathiolane, which was also confirmed by the data of X-ray diffraction analysis (Fig. 3, see Table 2).

Minor sulfite **12** was identified based on the following data. In the ^{13}C NMR spectra of **12**, the signal of CH_2O is observed at δ_C 68.21, which is characteristic of five-membered sulfites (the ^{13}C NMR spectra of six-membered sulfites have these signals at δ_C 55—65). Based on this fact as well as on the general similarity of the spectra of sulfites **5**, **10**, and **11** (see Table 1), the structure of substituted 1,3,2-dioxathiolane was assigned to product **12**. The relative configurations of the substituents in this ring can be determined from the chemi-

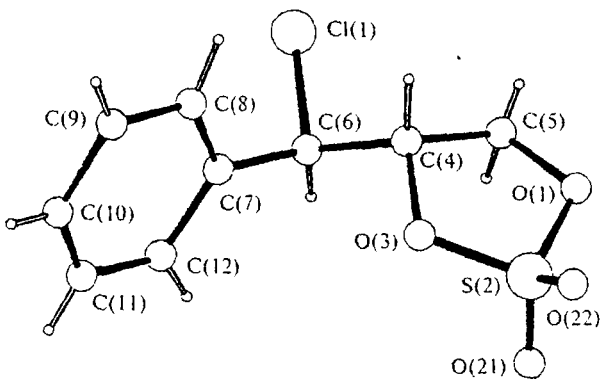


Fig. 3. Molecular structure of compound **13** in the crystal.

Table 2. Principal bond lengths (d), bond angles (ω), and torsion angles (τ) in molecules **10** and **13**

Bond	d/Å		Bond	d/Å	
	10	**13**		**10**	**13**
Cl(11)—C(6)	1.829(7)	1.814(6)	C(4)—C(6)	1.50(1)	1.499(8)
S(2)—O(1)	1.617(6)	1.507(4)	C(6)—C(7)	1.47(1)	1.489(7)
S(2)—O(3)	1.592(6)	1.548(4)	C(7)—C(8)	1.39(1)	1.374(7)
S(2)—O(21)	1.440(6)	1.340(5)	C(7)—C(12)	1.41(1)	1.385(7)
S(2)—O(22)	—	1.385(5)	C(8)—C(9)	1.33(1)	1.346(7)
O(1)—C(5)	1.40(1)	1.444(8)	C(9)—C(10)	1.39(1)	1.381(8)
O(3)—C(4)	1.462(9)	1.445(7)	C(10)—C(11)	1.38(1)	1.335(8)
C(4)—C(5)	1.50(1)	1.513(7)	C(11)—C(12)	1.30(1)	1.357(7)

Angle	ω/deg		Angle	ω/deg	
	10	**13**		**10**	**13**
O(1)—S(2)—O(3)	92.6(3)	98.3(2)	O(3)—C(4)—C(5)	104.6(6)	104.1(4)
O(1)—S(2)—O(21)	107.7(4)	113.6(3)	O(3)—C(4)—C(6)	109.0(6)	106.2(4)
O(1)—S(2)—O(22)		109.8(4)	C(5)—C(4)—C(6)	115.7(6)	115.7(5)
O(3)—S(2)—O(21)	106.6(3)	109.5(3)	O(1)—C(5)—C(4)	108.0(7)	103.7(4)
O(3)—S(2)—O(22)		110.7(3)	C(12)—C(6)—C(4)	103.9(5)	105.4(4)
O(21)—S(2)—O(22)		113.9(4)	C(12)—C(6)—C(7)	109.3(5)	111.3(4)
S(2)—O(1)—C(5)	109.8(5)	111.1(4)	C(4)—C(6)—C(7)	116.9(6)	115.0(5)
S(2)—O(3)—C(4)	112.5(5)	112.5(3)			

Angle	τ/deg		Angle	τ/deg	
	10	**13**		**10**	**13**
O(1)—S(2)—O(3)—C(4)	27.7(5)	4.7(4)	O(3)—C(4)—C(6)—C(11)	173.3(5)	−178.7(3)
S(2)—O(3)—C(4)—C(5)	−13.1(7)	14.3(5)	O(3)—C(4)—C(6)—C(7)	52.8(8)	58.3(5)
O(3)—C(4)—C(5)—O(1)	−11.2(8)	−28.1(5)	C(5)—C(4)—C(6)—C(11)	−69.2(7)	−63.7(5)
C(4)—C(5)—O(1)—S(2)	31.1(7)	33.7(5)	C(5)—C(4)—C(6)—C(7)	170.3(6)	173.2(4)
O(3)—S(2)—O(1)—C(5)	−34.7(6)	−23.8(4)			

cal shift of H(C(4)). Thus, the downfield shift of its signal was generally accounted[16] for by the anisotropic effect of the S=O bond, which is significant only in the case of the *trans* isomer. Hence, a *trans* structure can be assigned to sulfite **12**. Taking into account that the configuration at the C(4) atom is retained upon formation of five-membered sulfites in the reaction under consideration, (2*R*,4*S*)-4-[1-chloro-(1*S*)-1-phenylmethyl]-2-oxo-1,3,2-dioxathiolane is the only possible structure for compound **12**.

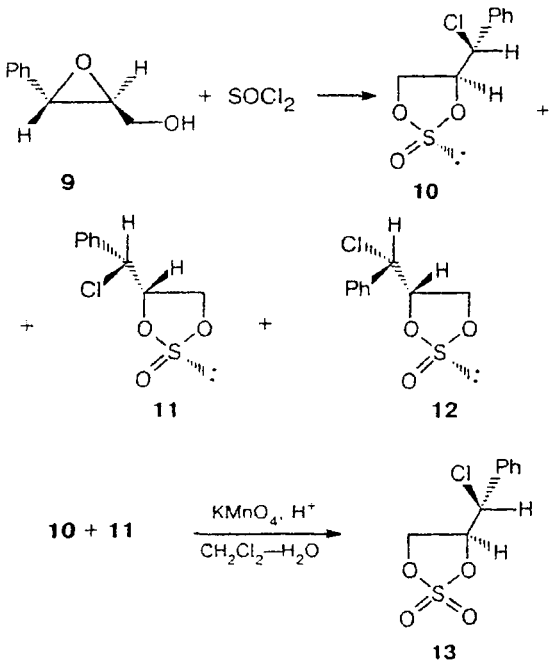
The substantial upfield shift of the signal for the H_B(C(5)) atom (see Table 1) is indirect evidence in favor of the inversion of the configuration of the exocyclic carbon atom in molecule **12**. The results of calculations by molecular mechanics (MM+, the HyperChem program package) for both (4*S*,1′*R*)-isomers of **10** and **11** in the case of rotation about the C(4)—C(1′) bond demonstrated that the major conformer is that in which the Cl—C—C—O dihedral angle (τ) is equal to ~180° and the phenyl group is remote from the CH_2—O fragment (as can be seen from Figs. 2 and 3 and Table 2, these conformers of **10** and **13** are observed in the crystals). For the (2*R*,4*S*,1′*S*)-isomer, the situation is radically different. Thus the conformer with τ = 59° becomes preferential, and next are the conformers with τ = −53° (E_{rel} = 0.97 kcal mol^{-1}) and τ = 175° (E_{rel} = 1.33 kcal mol^{-1}). The characteristic feature of the major conformer with τ = 59° is that the H_B(C(5)) atom in the *trans* position with respect to the CHClPh substituent is located in the *shielding* region of the aromatic fragment (the calculated distance between the H_B(C(5)) atom and the center of the benzene ring is ~3.5 Å).

Hence, the formation of the major products can be described by Scheme 7.

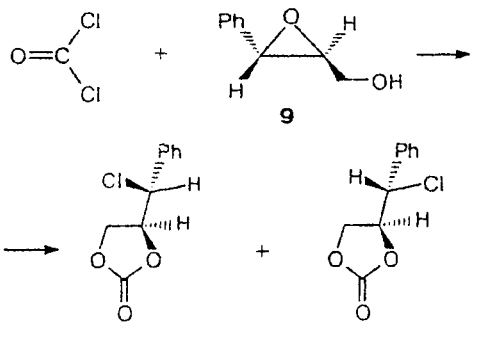
In molecules **10**, **11**, and **13**, the C(1′) atom has an inverted configuration compared to that of the C(3) atom in the starting glycidol **9**. In product **12**, the configurations of the C(1′) and C(3) atoms remain unchanged. Previously, we have observed the retention of the configuration of the terminal atom of the starting glycidol (~15% of the portion of the inverted product) in the minor final product of the reaction of glycidol **9** with phosgene (Scheme 8).[4d]

Evidently, the higher stereoselectivity observed in the analogous reaction with thionyl chloride ((**10**+**11**) : **12** ≈ 17 : 1) is associated with the higher stability (the lower reactivity) of an intermediate of type **3**. The lifetime of the latter is large enough for diglycidyl derivatives of **2** to be formed, whereas the analogous monoglycidyl deriva-

Scheme 7



Scheme 8



tive of phosgene, *viz.*, chloroformate, undergoes cyclization to give chloromethyldioxolanone even in the presence of an excess of glycidol.[4d]

Apparently, sulfuryl chloride is even more active in analogous reactions. This is evidenced by the fact that diglycidyl sulfate cannot be prepared by the direct reaction of compound **1** with SO_2Cl_2 and the formation of five-membered sulfate **6** is accompanied by the formation of a noticeable amount (~10%) of six-membered sulfate **7**, *i.e.*, the regioselectivity of this process is lower than that of the above reaction with $SOCl_2$. Undoubtedly, the stereoselectivity of the reaction of SO_2Cl_2 with glycidol **9** should be substantially poorer. For these reasons, we did not perform direct sulfation of epoxyalcohol **9** with sulfuryl chloride.

To summarize, we developed a new procedure for the preparation of cyclic sulfites and sulfates, which are synthetic equivalents of epoxides, particularly, of epichlorohydrin. The procedure involves the direct reaction of 2,3-epoxypropan-1-ols with thionyl chloride or sulfuryl chloride. The important characteristic feature of the procedure is that the absolute configuration of the C(2) atom of the starting epoxyalcohol is retained in the final heterocycle (the C(4) atom). The reactions of $SOCl_2$ with glycidols bearing also a chiral center at the C(3) atom proceed stereoselectively to form predominantly products with the inverted configuration of this center, which appeared to be exocyclic in the final product.

Experimental

The IR spectra were recorded on a UR-20 spectrometer in Nujol mulls. The NMR spectra were obtained on Varian Gemini-200 (199.8 MHz for ^1H) and Bruker MSL-400 (100.6 MHz for ^{13}C) instruments with Me_4Si as the internal standard. The optical rotation was measured on a Polamat A polarimeter. The enantiomeric composition was determined by GLC (a Biokhrom-1 chromatograph, a Supelco-β-Dex-120 column, 30 m × 0.25 mm). TLC was carried out on Silufol plates.

Diglycidyl sulfites (2). A solution of $SOCl_2$ (6.58 g, 55.0 mmol) in Et_2O (15 mL) was added with stirring to a solution of glycidol *rac*-**1** (8.20 g, 110.0 mmol) and Et_3N (11.18 g, 110.0 mmol) in anhydrous Et_2O (20 mL) cooled to −70 °C over 30 min. The temperature of the reaction mixture was warmed to −20 °C. Then the mixture was refluxed for 5 min and cooled. The precipitate of $Et_3N \cdot HCl$ was filtered off and washed with Et_2O (15 mL). The filtrate was concentrated under atmospheric pressure and then under reduced pressure. The residue was distilled *in vacuo* and the fraction with the boiling point of 145—147 °C (1.0 Torr) was collected, n_D^{20} 1.4720. A mixture of diastereomers of diglycidyl sulfite **2** was obtained in a yield of 3.20 g (30%). IR (film), ν/cm^{-1}: 3070, 3010 (C—H of epoxide); 1221 (S=O); 980, 950, 910, 860, 845 (C—O, S—O). ^1H NMR ($CDCl_3$), δ: 2.43—2.47, 2.60—2.64 (both m, CH_2 of epoxide); 2.96—3.04 (m, CH of epoxide); 3.55—3.70, 4.05—4.17 (both m, OCH_2). ^{13}C NMR ($CDCl_3$), δ: 44.16, 44.19, 44.22, 44.22 (OCH_2); 49.15, 49.16, 49.17, 49.19 (CH of epoxide); 62.42, 62.52, 62.59, 62.78 (CH_2 of epoxide).

Analogously, the reaction of glycidol (*S*)-**1** (*ee* 90.0%, 1.32 g, 17.8 mmol), $SOCl_2$ (1.06 g, 8.9 mmol), and Et_3N (1.93 g, 19.0 mmol) afforded a mixture (0.60 g, 35%) containing more than 90% of sulfite (*R,R*)-**2**, b.p. 104—106 °C (0.01 Torr), n_D^{20} 1.4735, $[\alpha]_D^{20}$ −25.6 (*c* 3.8, CH_2Cl_2). The ^1H NMR spectrum is virtually identical to that given above. ^{13}C NMR ($CDCl_3$), δ: 43.92, 43.97 (CH_2 of epoxide); 48.95, 48.99 (CH of epoxide); 62.38, 62.46, 62.63, 62.78 ($SOCH_2$).

4-Chloromethyl-2-oxo-1,3,2-dioxathiolanes (5). A solution of glycidol *rac*-**1** (7.47 g, 0.1 mol) and Et_3N (10.9 g, 0.1 mol) in benzene (20 mL) was added dropwise to a stirred solution of $SOCl_2$ (12.0 g, 0.1 mol) in dry benzene (15 mL) at 10 °C. The reaction mixture was heated to 80 °C and cooled to −20 °C. The precipitate that formed was filtered off and washed on a filter with benzene (30 mL). The solvent was distilled off under reduced pressure. The residue was twice distilled *in vacuo*. A mixture of *cis*- and *trans*-racemic sulfites **5** was isolated in a yield of 13.0 g (86%), b.p. 68—69 °C (1.0 Torr), n_D^{20} 1.4839 (lit. data[9]: for a mixture of isomers of **5** prepared from racemic 3-chloropropane-1,2-diol, b.p. 95 °C (12 Torr), n_D^{25} 1.4808). IR (film), ν/cm^{-1}: 1210 (S=O); 1030, 960, 850 (C—O, S—O).

Analogously, the addition of a solution of glycidol (*S*)-**1** (3.52 g, 47.6 mmol) in CH_2Cl_2 (10 mL) to a solution of $SOCl_2$ (5.66 g, 47.6 mmol) in CH_2Cl_2 (15 mL) at 0 °C followed by refluxing of the reaction mixture for 30 min gave rise to a mixture of sulfites (2*S*,4*S*)-**5** and (2*R*,4*S*)-**5** in a ratio of 1.00 : 1.14 in 84% total yield, b.p. 94—96 °C (1.0 Torr), n_D^{20} 1.4831, $[\alpha]_D^{22}$ +24.8 (*c* 2.4, CH_2Cl_2). Chromatography (silica gel L (μ 40/100), a 220×20 mm column, a 8 : 5 petroleum ether—Et_2O mixture) of the mixture (0.53 g) afforded the isomers (2*S*,4*S*)-**5** (R_f 0.31, $[\alpha]_D^{20}$ −6.3 (*c* 0.64, CH_2Cl_2)) and (2*R*,4*S*)-**5** (R_f 0.27, $[\alpha]_D^{20}$ +58.2 (*c* 0.3, CH_2Cl_2)) in yields of 80 and 200 mg, respectively.

4-Chloromethyl-2,2-dioxo-1,3,2-dioxathiolane (6). ***A.*** A solution of glycidol *rac*-**1** (2.22 g, 29.9 mmol) in CH_2Cl_2 (5 mL) was added to a stirred solution of SO_2Cl_2 (4.0 g, 29.6 mmol) in dry CH_2Cl_2 (25 mL) under nitrogen at −90 °C for 15 min. The temperature was slowly increased to −40 °C. The reaction mixture was stirred for 2 h and warmed to −20 °C. The solvent was removed *in vacuo* and the residue was distilled *in vacuo*. Sulfate **6** was obtained in a yield of 3.01 g (59%), b.p. 86—88 °C (0.07 Torr), n_D^{20} 1.4640. IR (film), ν/cm^{-1}: 1400, 1220 (SO_2); 1040, 1000, 870, 830 (C—O, S—O).

Analogously, sulfate (4*S*)-**6** was obtained from SO_2Cl_2 (3.10 g, 23.0 mmol) and glycidol (*S*)-**1** (1.70 g, 23.3 mmol) in a yield of 1.95 g (49%), b.p. 80—82 °C (0.05 Torr), n_D^{20} 1.4650, $[\alpha]_D^{20}$ −1.8 (*c* 5.3, CH_2Cl_2).

B. A solution of H_2SO_4 (12.50 g) in water (100 mL) cooled to 0 °C was added to a solution of a mixture of sulfites **5** (6.75 g, 43 mmol) in CH_2Cl_2 (25 mL) placed into an ice bath. Then $KMnO_4$ was added portionwise with intense stirring until the solution developed a steady pink color; $KMnO_4$ was consumed in a total amount of 7.50 g (47.4 mmol). Then solid $Na_2S_2O_5$ was added portionwise until the brown precipitate was completely dissolved. The organic layer was separated and washed with water. The aqueous layer was extracted with CH_2Cl_2 and the combined organic extracts were dried over $MgSO_4$. After removal of CH_2Cl_2, the residue was distilled. Sulfate **6** was obtained in a yield of 3.0 g (35%), b.p. 80—82 °C (0.05 Torr), n_D^{20} 1.4635.

Analogously, sulfate (4*S*)-**6** was obtained from sulfite (4*S*)-**5** (1.88 g), H_2SO_4 (3.48 g), and $KMnO_4$ (2.09 g) in a yield of 0.51 g (25%), b.p. 105 °C (1 Torr), n_D^{20} 1.4650, $[\alpha]_D^{22}$ −2.0 (*c* 3.43, CH_2Cl_2).

(2*S*,3*S*)-2,3-Epoxy-3-phenylpropan-1-ol (9) was prepared from cinnamic alcohol according to a procedure reported previously[14]; b.p. 51 °C, $[\alpha]_D^{25}$ −50.5 (*c* 1.5, $CHCl_3$) (lit. data[15]: m.p. 50—51 °C, $[\alpha]_D^{20}$ −50.4 (*c* 2.4, $CHCl_3$)).

The reaction of (2*S*,3*S*)-2,3-epoxy-3-phenylpropan-1-ol (9) with $SOCl_2$. A mixture of epoxyalcohol **9** (4.24 g, 30.0 mmol) in anhydrous CH_2Cl_2 (10 mL) was added to a solution of $SOCl_2$ (3.36 g, 30.0 mmol) in dry CH_2Cl_2 (30 mL) with cooling to 0 °C over 30 min. The reaction mixture was stirred at −20 °C for 24 h. The course of the reaction was monitored by TLC. After completion of the reaction, the solvent was removed *in vacuo* and the residue was purified by distillation. A mixture of dioxathiolanes **10**—**12** was isolated as a viscous oil in a yield of 3.55 g (54%), b.p. 110 °C (0.028 Torr). IR, ν/cm^{-1}: 3100, 3070 (C_{Ar}—H); 1587, 1505 (Ph); 1212, 1198 (S=O); 1040, 1010, 998, 960 (C—O, S—O). Found (%): C, 46.67; H, 3.62; Cl, 14.82; S, 13.50. $C_9H_9ClO_3S$. Calculated (%): C, 46.45; H, 3.87; Cl, 15.27; S, 13.76.

A mixture of diastereomers **10**—**12** (0.70 g) was chromatographed (silica gel (μ 40/100), 220×20 mm column, a 10 : 1 heptane—Et_2O mixture as the eluent) to obtain **(2*S*,4*S*)-4-[1-chloro-(1*R*)-1-phenylmethyl]-2-oxo-1,3,2-dioxathiolane (10)** in a yield of 0.20 g (R_f 0.52, a 2 : 1 heptane—Et_2O mixture as the eluent), m.p. 59.5 °C, $[\alpha]_D^{20}$ +51.3 (*c* 0.54, CH_2Cl_2); ^{13}C NMR, signals of the phenyl fragment (CCl_4), δ: 127.61 (*o*-CH); 128.38 (*m*-CH); 128.78 (*p*-CH); 136.93 (*i*-C); **(2*R*,4*S*)-4-[1-chloro-(1*R*)-1-phenylmethyl]-2-oxo-1,3,2-dioxathiolane (11)** in a yield of 0.23 g (a viscous oil, R_f 0.35, a 2 : 1 heptane—Et_2O mixture as the eluent), $[\alpha]_D^{20}$ −30.4 (*c* 0.55, CH_2Cl_2); ^{13}C NMR, signals of the phenyl fragment (CCl_4), δ: 127.49 (*o*-CH); 128.56 (*m*-CH); 128.94 (*p*-CH); 136.27 (*i*-C); and **(2*R*,4*S*)-4-[1-chloro-(1*S*)-1-phenylmethyl]-2-oxo-1,3,2-dioxathiolane (12)** in a yield of 0.02 g (R_f 0.20, a 2 : 1 heptane—Et_2O mixture as the eluent), $[\alpha]_D^{20}$ +98.1 (*c* 0.25, CH_2Cl_2); ^{13}C NMR, signals of the phenyl fragment (CCl_4), δ: 127.63 (*o*-CH); 128.58 (*m*-CH); 129.03 (*p*-CH); 135.67 (*i*-C).

(4*S*)-4-[1-Chloro-(1*R*)-1-phenylmethyl]-2,2-dioxo-1,3,2-dioxathiolane (13). A solution of 98% H_2SO_4 (1.5 g) in water (22 mL) was added to a solution of a mixture of sulfites **10**—**12** (2.18 g, 8 mmol) in CH_2Cl_2 (5.5 mL) at 0 °C. Then $KMnO_4$ (1.64 g, 10 mmol) was added portionwise with stirring. After completion of the reaction, $Na_2S_2O_5$ was added until the brown precipitate was completely dissolved. The organic layer was separated and washed with water, the aqueous layer was extracted with CH_2Cl_2, and the combined organic extracts were dried over $MgSO_4$. After removal of the solvent *in vacuo*, the solid residue was purified by recrystallization from Et_2O. Sulfate **13** was obtained in a yield of 1.18 g (50%), m.p. 103—105 °C, $[\alpha]_D^{20}$ −25.5 (*c* 1.1, CH_2Cl_2). Found (%): C, 43.55; H, 3.33; Cl, 14.52; S, 12.46. $C_9H_9ClO_4S$. Calculated (%): C, 43.46; H, 3.65; Cl, 14.25; S, 12.89. ^{13}C NMR, signals of the aromatic fragment ($CDCl_3$), δ: 127.56 (*o*-CH); 128.98 (*m*-CH); 129.72 (*p*-CH); 134.84 (*i*-C). IR, ν/cm^{-1}: 3070 (C_{Ar}—H); 1590 (Ph); 1211, 1199 (S=O); 1018, 975 (C—O, S—O).

X-ray diffraction study of crystals of compounds 10 and 13. Crystals of sulfite **10** ($C_9H_9O_3Cl_1S_1$) are orthorhombic. At 20 °C, a = 6.007(9) Å, b = 10.218(5) Å, c = 16.87(2) Å, V = 1036(2) Å^3, Z = 4, d_{calc} = 1.49 g cm^{-3}, space group $P2_12_12_1$.

Crystals of sulfate **13** ($C_9H_9O_4Cl_1S_1$) are monoclinic. At 20 °C, a = 5.9388(9) Å, b = 7.226(2) Å, c = 12.391(2) Å, β = 91.12(2)°, V = 531.6(2) Å^3, Z = 2, d_{calc} = 1.55 g cm^{-3}, space group $P2_1$.

The unit cell parameters and the intensities of 3068 (**10**) and 1965 (**13**) reflections (of which 1812 (**10**) and 1157 (**13**) reflections were with $I \geq 3\sigma$) were measured on an automated four-circle Enraf-Nonius CAD-4 diffractometer (Mo-Kα radiation, graphite monochromator, ω/2θ scanning technique, θ ≤ 26°) at 20 °C. Intensities of three check reflections showed no decrease in the course of X-ray data collection. Absorption was ignored (μ(Mo) = 5.37 (**10**) and 5.35 cm^{-1} (**13**)).

The structures were solved by the direct method using the SIR program[17] and refined first isotropically and then anisotropically. All hydrogen atoms were revealed from the difference electron density syntheses and refined isotropically at the final stage. With the aim of establishing the absolute structures (and, consequently, the absolute configurations of molecules **10** and **13**), the "direct" and inverted models were refined. The values of the R factors for the "direct" structures were as follows: R = 0.05733, R_w = 0.07156 for the structure of **10** and R = 0.04878, R_w = 0.05387 for the structure of **13**. The values of the R factors for the inverted structures were as follows: R = 0.05780, R_w = 0.07183 (**10**) and R = 0.04890, R_w = 0.05405 (**13**). A total of 163 (**10**) and 171 (**13**) parameters were refined using 1345 (**10**) and 1174 (**13**) reflections. According to the Hamilton test,[18] the "direct" structures correspond to the absolute structures with the probability of 95%. The final values of the R factors were as follows: R = 0.057, R_w = 0.072 based on

1345 reflections (**10**) and $R = 0.049$, $R_w = 0.054$ based on 1174 (**13**) reflections with $F^2 \geq 3\sigma$. All calculations were carried out on an AlphaStation 200 computer using the MOLEN program package.[19] The figures were drawn and the intermolecular contacts in the crystals were analyzed using the PLATON program.[20] The atomic coordinates were deposited with the Cambridge Structural Database. The molecular structures of compounds **10** and **13** are shown in Figs. 2 and 3, respectively. Their principal geometric parameters are given in Table 2.

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