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Multinuclear Magnetic Resonance Study of Oxaziridines

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NMR data (^{13}C, ^{15}N, ^{17}O) for the three ring atoms of various oxaziridines are compared. Their significance for the prediction of the enantioselectivity of the oxidation of sulphides by chiral oxaziridines is discussed.

KEY WORDS Oxaziridines Multinuclear (^{13}C, ^{15}N, ^{17}O) magnetic resonance Enantioselective oxidations

INTRODUCTION

Oxaziridines, discovered[1] only in 1956, are a class of compounds which has recently received attention as potential anti-tumour agents[2] and analogues of penicillin.[3] They have found widespread use as reagents in synthetic organic chemistry for aminations[4] and oxidations.[5] Of particular interest are chiral oxaziridines, which may perform asymmetric oxidations, e.g. of carbanions[6–11] or sulphides.[11–14] Although successful oxaziridines have been developed for these purposes, there is still room for improving the chemo- and enantioselectivity. In this respect, it would be useful to have some correlation between the selectivity of the oxaziridines in a given reaction and easily accessible physical parameters. To see if NMR data can provide such a measure for selectivity, a multinuclear (^{13}C, ^{15}N, ^{17}O) magnetic resonance study of some oxaziridines was performed.

The crucial step which determines the enantioselectivity in oxidations of sulphides to sulphoxides by chiral oxaziridines is the transfer of the oxygen atom to the substrate. It has been demonstrated that the approach of a sulphide to the reagent is such that an enantiotopic lone electron pair of the sulphur lies in the plane of the oxaziridine ring, and the orientation of the small and the large group at sulphur (and, thus, the enantioselectivity) is determined mainly by the steric interaction of these groups with the sterically more or less demanding regions in the vicinity of the oxygen atom.[14–19] Hence the enantioselectivity is due to steric shielding of the oxygen by its environment and its geometric fit to the sulphide. NMR data should be able to give some insight into the accessibility of the oxygen by analysing the steric and electronic influences on the NMR parameters of the three atoms which form the oxaziridine ring.

SYNTHESIS AND STRUCTURAL CHARACTERIZATION OF THE OXAZIRIDINES

All the oxaziridines studied were prepared by oxidation of the corresponding imines with peracetic acid, 3-chloroperbenzoic acid (MCPBA), magnesium perphthalate or oxone ($KHSO_5$). In cases where isomeric oxaziridines can be formed, the structures were determined by ^1H and ^{13}C NMR if no unequivocal assignments exist in the literature. Tables 1 and 2 give the ^1H and ^{13}C NMR data for new compounds and for those where these data have not been adequately described. Figure 1 shows the structures of the oxaziridines used.

The assignment of ^1H and ^{13}C NMR signals in oxaziridine **1** is based on COSY and CH correlation and follows rational arguments for the chemical shifts of *cis–trans* isomers.[31] The inversion barrier at nitrogen is high enough to allow isolation and NMR studies of diastereoisomers (*cis–trans* isomers) of N-alkyl- and *N*-aryloxaziridines, without noticeable interconversion.[32] For *N*-sulphonyloxaziridines, where only one isomer is formed during oxidation, a lower inversion barrier has been found,[33,34] which accounts for the exclusive observation of the thermodynamically more stable diastereoisomer.[35,36] The assignment of *trans* or *cis* to the isomers is unequivocal for **8**, where an x-ray analysis exists,[37] and for **5** and **6** the assignment is based on a comparison of the ^1H NMR spectra of both isomers by analogy with **7** and **8**.[35,36] The relative amounts of *trans* and *cis* isomers strongly depend on the reaction conditions[38] and on the oxidant; e.g. a *ca.* 1 : 1 ratio was obtained in the synthesis of **4** (*trans* isomer) with MCPBA,[38] whereas we obtained 9 : 1 with oxone.

An x-ray structure of the sulphonyloxaziridine **10**, together with the ^1H NMR spectra, gives a sound basis

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Table 1. ^{1}H NMR spectra of new or incompletely described oxaziridines[a,b]

No.	R^2	R^1	R^3
1	0.90 (tr, 3H, 7.5 Hz); 1.52 (m, 1H)	0.75 (tr, 3H, 7.5 Hz); 1.21 (m, 1H) 1.66 (m, 2H)	1.05 (m), 1.61 (m) (CH_2); 1.07 (m), 1.59 (m) (CH_2); 1.04 (m), 1.44 (m) (CH_2); 1.14 (m), 1.33 (m) (CH_2); 1.30 (m), 1.72 (m) (CH_2); 2.15 (m) (CH)
2	3.53 (d, 6.3 Hz)	0.65 (d, 3H, 6.9 Hz); 0.86 (d, 3H, 6.8 Hz); 1.50 (m, 1H)	1.57 (d, 3H, 6.5 Hz); 3.02 (qua, 1H, 6.5 Hz); 7.30 (m, 5H)
3	3.59 (d, 6.7 Hz)	1.03 (d, 3H, 6.5 Hz); 1.05 (d, 3H, 7.0 Hz); 1.63 (m, 1H)	1.41 (d, 3H, 6.3 Hz); 3.10 (qua, 1H, 6.3 Hz); 7.30 (m, 5H)
15	H-4, 2.88 (d, 1H, 4.4 Hz); H-5, *endo*, 2.10 (m, 1H); H-5, *exo*, 2.45 (m, 1H); H-6, 1.94 (m, 2H); H-8, 3.26 (d, 1H, 14.0 Hz); 3.47 (dd, 1H, 1.1 Hz; 14.0 Hz); H-9, H-10, 1.20 (s, 3H); 1.58 (s, 3H)		
21	H-4, 2.15 (s, br); H-5, H6, 1.59 (m, 1H); 1.64 (m, 1H); 1.69 (m, 1H); 1.78 (m, 1H); H-7, 2.03 (m, 1H); 2.28 (m, 1H); H-8, 3.12 (d, 1H, 13.0 Hz); 3.40 (d, 1H), 13.0 Hz); H-9, H-10, 0.94 (s, 3H); 1.06 (s, 3H)		

[a] ^{1}H NMR data are given in the literature for the following compounds: **4**;[20] **5** and **6**;[21] **7** and **8**;[22,23] **9** and **10**;[24] **11**;[25] **12**;[16] **13**, **14** and **18**;[26] **16**;[7] **17**;[27] **19**;[13] **20**;[28] **22**.[29]
[b] For the numbering of atoms in the camphor- and fenchone-derived oxaziridines **15** and **21**, see Fig. 1.

for the assignment of the *trans* configuration to the sulphonyloxaziridines **9–11**.[39] The structure of the saccharine-derived oxaziridine **21** is obvious from the synthesis.[29]

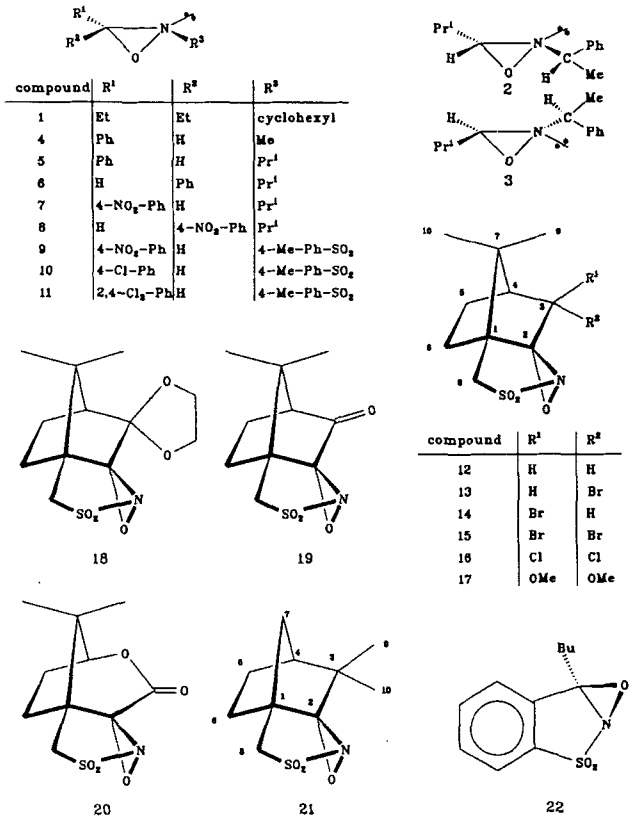
Compounds **2** and **3** have been previously described only once,[1] obviously as a racemic mixture of diastereoisomers, without any attempt at separation and further characterization. We have prepared the imine **23**, as a single isomer (presumably *trans*, as an NOE can be observed between the hydrogen at the double bond and the phenyl group) from enantiomerically pure (*S*)-2-phenylethylamine,[40] and oxidized it with MCPBA. Principally, four diastereoisomeric products can be expected (Fig 2).

Other workers observed that *trans*-imines bearing only alkyl (not aryl) substitutuents at the carbon atom are oxidized to the oxaziridines with complete retention of the stereochemistry,[38] i.e. that only two products, the *trans* isomers R_N,R_C,S and S_N,S_C,S, should be formed. Indeed, only two compounds could be detected after oxidation, in the ratio 2.3 : 1. These isomers can be partially separated by distillation and purified by chromatography. Using a similar protocol, but with a *C*-arylimine, others have found four diastereoisomers.[41,42] On the basis of an x-ray structure of one of the diastereoisomers,[42] a method for the assignment of similar compounds by analogy of their optical rotation has been suggested.[43] According to this rule, our major isomer (**2**) should be the S_N,S_C,S compound. However, the assignment by comparison of the NMR data seems more convincing to us; in the ^{1}H NMR spectra, the chemical shifts of both CH groups appear at higher field in **2**, just as in the diastereoisomer assigned as R_N,R_C,S in Ref. 43. Hence we assign

Table 2. ^{13}C NMR spectra of new or incompletely described oxaziridines[a,b]

No.	$C_{oxaz.}$	R^2	R^1	R^3
1	86.9	9.2 (CH_3); 20.2 (CH_2)	8.2 (CH_3); 28.6 (CH_2)	24.0; 24.2; 25.5; 28.9; 31.7 (CH_2); 60.0 (CH)
2	86.2	—	16.4; 16.7 (CH_3); 30.4 (CH)	21.1 (CH_3); 70.8 (CH); 127.2; 128.5 (*o,m*-CH); 128.0 (*p*-CH); 140.0
3	86.7	—	16.7; 16.9 (CH_3); 30.6 (CH)	19.2 (CH_3); 69.4 (CH); 127.0 128.4 (*o,m*-CH); 127.8 (*p*-CH); 142.3
5	78.6	—	127.2; 128.1 (*o,m*-CH); 129.7 (*p*-CH); 130.1	18.6; 20.9 (CH_3); 61.2 (CH)
6	78.5	127.8; 127.9 (*o,m*-CH); 129.9 (*p*-CH); 131.6	—	17.6; 21.3 (CH_3); 51.5 (CH)
7	78.1	—	123.3; 128.3 (CH); 139.8; 148.5	18.6; 21.0 (CH_3); 62.4 (CH)
8	78.6	123.1; 128.8 (CH); 139.8; 148.5	—	17.7; 21.4 (CH_3); 52.3 (CH)
9	74.6	—	21.8 (CH_3); 123.8; 129.3; 129.4; 130.1 (CH); 130.9; 137.3; 146.8; 149.7	
10	75.5	—	21.7 (CH_3); 128.9; 129.3; 129.5; 130.8 (CH); 130.8; 131.1; 137.4; 146.5	
15	99.4	C-1, 54.2; C-3, 59.4; C-4, 63.0; C-5, 28.7; C-6, 26.8; C.7, 47.6; C-8, 49.7; C-9, 10, 22.8; 24.2		
16	99.1	C-1, 54.6; C-3, 86.1; C-4, 62.5; C-5, 6, 25.3; 26.9; C-7, 47.3; C-8, 49.4; C-9, 10, 21.9; 23.3		
21	101.2	C-1, 50.5; C-3, 37.2; C-4, 48.0; C-5, 6, 24.1; 27.3; C-7, 37.8; C-8, 49.0; C-9, 10, 20.5; 25.3		

[a] ^{13}C NMR data are given in the literature for the following compounds: **4**;[30] **11**;[25] **12**;[16] **13**, **14** and **18**;[26] **17**;[27] **19**;[13] **20**;[28] **22**.[29]
[b] For the numbering of atoms in the camphor- and fenchone-derived oxaziridines, see Fig. 1.



compound	R^1	R^2	R^3
1	Et	Et	cyclohexyl
4	Ph	H	Me
5	Ph	H	Pr^i
6	H	Ph	Pr^i
7	4-NO_2-Ph	H	Pr^i
8	H	4-NO_2-Ph	Pr^i
9	4-NO_2-Ph	H	4-Me-Ph-SO_2
10	4-Cl-Ph	H	4-Me-Ph-SO_2
11	2,4-Cl_2-Ph	H	4-Me-Ph-SO_2

Figure 1. Structure of oxaziridines used.

R_N,R_C,S to the main product **2** and S_N,S_C,S to the minor isomer **3**.

Concerning the camphor derivatives **12–20**, x-ray structure analyses exist for **12**[16] and **20**.[28] The rigid structure of the bicyclic skeleton allows reliable configurational assignments based on the synthetic procedures and chemical correlations of **13–19**. A conformational study of **18** and similar oxaziridines by NOE measurements has been performed.[26] We shall report on the synthesis and properties of the fenchone-derived oxaziridine **21** elsewhere.

MULTINUCLEAR MAGNETIC RESONANCE OF THE OXAZIRIDINES

For oxaziridines, NMR data for the heteroatoms of the three-membered ring are rarely found in the literature (see, e.g., Ref. 20). A preliminary account on ^{17}O NMR data[14] used acetone as solvent which itself has a very strong signal, so that some chemical shifts were quoted erroneously. The chemical shifts have now been determined in $CDCl_3$ for all nuclei; this is a much better solvent for this purpose, despite the lower solubility of many sulphonyl oxaziridines. Details of the NMR techniques are given under Experimental. The results are shown in Table 3.

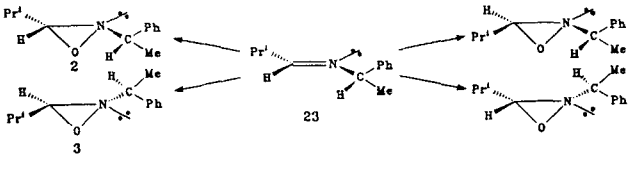


Figure 2. Expected diastereoisomeric oxaziridines from chiral imine **23**.

Let us consider the three atoms of the oxaziridine ring. Generally, the oxaziridine oxygen gives a very broad signal compared with that of other oxygen atoms in the same molecule (line widths at half height 390–1820 Hz). This points to considerable asymmetry in the vicinity of the nucleus, but the determination of the shielding tensor is not possible in solution. In close analogy with *cis*- and *trans*-oxiranes,[44] there is a characteristic upfield shift of the oxygen atom in the *cis*- *vs.* *trans*-oxaziridines ($\Delta\delta$ = 35 ppm in **5** *vs.* **6** and 27 ppm in **7** *vs.* **8**). In contrast, the corresponding carbon resonances appear at similar positions in both isomers, whereas there is a smaller but consistent downfield shift in the nitrogen signals of the *cis* isomers. Diastereoisomeric *trans* isomers such as **2** and **3** show only slight differences in the chemical shifts of all ring atoms.

Nitrogen substitutents have a pronounced influence only on the nitrogen chemical shift [deshielding of $\Delta\delta$ = 14.8 ppm on going from methyl (**4**) to isopropyl (**5**)]. The strong inductive effect of the *N*-tosyl groups leads to deshielding of nitrogen and shielding of carbon (compare **7** and **9**).

Considering substituents at carbon, there is a pronounced effect only on nitrogen chemical shifts; higher substitution as in **1** and stronger electron-withdrawing groups as in **7** *vs.* **5** and **8** *vs.* **6** lead to a deshielding of the nitrogen atom.

In the oxaziridines containing the oxaziridine and the SO_2-N group integrated in a polycyclic ring system, such as **12–22**, different steric and electronic effects are more clearly reflected in the ^{17}O (153–180 ppm) and ^{15}N chemical shifts (180.0–198.8 ppm). Halogens at carbon atoms α to the oxaziridine carbon (e.g **15** and **16**) deshield oxygen and nitrogen (γ-positon), but only a small influence on the oxaziridine carbon (β-position) is observed (compare **12** and **15**). There is almost no difference between the 3,3-dibromo- (**15**) and the 3,3-dichloro-derivatives (**16**) as far as the carbon and oxygen of the oxaziridine ring are concerned; the only atom which is influenced significantly by the Br–Cl exchange is, as expected, C-3 ($\Delta\delta$ = 26.7 ppm). Although chemical shifts and electronegatives are correlated in substituted sulphinyl compounds,[45] and the group electronegativity of the methoxy group is similar to that of chlorine, there is a substantial difference in the chemical shifts of oxygen and nitrogen in the 3,3-dichloro-substituted camphorsulphonyloxaziridine **16** compared with the 3,3-dimethoxy compound **17**, which has properties more similar to the non-substituted oxaziridine **12** and the fenchone-derived oxaziridine **21** with two methyl groups in position 3. This rules out purely steric and purely electronic effects but points to a mixture of both, which is difficult to analyse (no correlation with Hammett or Taft constants). The difference in chloro- and methoxy-substituted compounds has probably nothing to do with the so-called 'chlorine effect' on the chemical shift of oxygens in SO_2 groups directly attached, which implies conjugative interactions.[46] From models of **12–17**, one can expect that,

Table 3. Multinuclear magnetic resonance of the oxaziridine ring atoms[a]

No.	Carbon	Nitrogen	Oxygen	Other oxygens
1	86.9	175.9	147 (450)	—
2	86.2	159.4	143 (740)	—
3	86.7	158.8	143 (740)	—
4	81.2	152.3[b]	158 (390)	—
5	78.6	167.1	152 (550)	—
6	78.5	170.0	117 (430)	—
7	78.1	172.3[c]	147 (1360)	573 (950) (NO_2)
8	78.6	174.1[c]	120 (1360)	570 (950) (NO_2)
9	74.6	173.4[c]	~145[d]	141 (410); 148 (410) (SO_2); 586 (940) (NO_2)
10	75.5	172.9	~143[d]	137 (380); 148 (460) (SO_2)
11	73.2	172.8	~145[d]	140 (390); 147 (390) (SO_2)
12	100.0	185.6	153 (690)	180 (190); 183 (270) (SO_2)
13	96.1	188.7	160 (620)	178 (150); 180 (170) (SO_2)
14	99.7	191.8	156 (810)	179 (180; 181 (250) (SO_2)
15	99.4	198.8	~180[d]	182 (230) (SO_2)
16	99.1	195.1	~176[d]	180 (260) (SO_2)
17	97.6	181.3	160 (1820)	183 (380) (SO_2); 18 (820) (OCH_3)
18	99.2	—[e]	162 (900)	181 (135); 183 (210) (SO_2); 60 (670) (—O—)
19	89.7	190.6	168 (910)	186 (190); 189 (180) (SO_2); 559 (560) (C=O)
20	117.8	191.3	164 (1020)	175 (320); 181 (240) (SO_2); 200 (450 (—O—); 378 (300) (C=O)
21	101.2	180.0	159 (430)	175 (140); 177 (140) (SO_2)
22	86.3	168.0	~165[d]	163 (330); 183 (260) (SO_2)

[a] δ Values; carbon, relative to internal TMS; nitrogen, reference external CH_3NO_2 in $CDCl_3$ (1:1) with 0.03 M $Cr(acac)_3$ (δ = 379.6 ppm); oxygen, relative to external H_2O (δ = 0 ppm); line width at half-height given in parenthese; for other details, see Experimental.
[b] Ref. 20 gives the chemical shift as −232.2 ppm relative to CH_3NO_2, which corresponds to ~148 ppm on our scale.
[c] $\delta_N(NO_2)$ = 369.1 (**7**); 371.0 (**8**); 322.9 (**9**).
[d] Exact position could not be determined owing to overlap with the SO_2 signal.
[e] ^{15}N signal could not be detected owing to extremely low solubility.

for steric reasons, large *exo* substituents should mainly deshield nitrogen, whereas large *endo* substituents should deshield oxygen. The influence on carbon should not be great. The effects on nitrogen and oxygen can be confirmed on comparing *endo*- and *exo*-3-bromooxaziridines **13** and **14**, but the difference in carbon chemical shifts ($\Delta\delta$ = 3.6 ppm) is larger than expected.

The introduction of an additional oxygen atom in the norbornane substructure, as in **20** compared with **19**, has only a slight influence on oxygen and nitrogen chemical shifts, but leads to a very large deshielding of the carbon atom ($\Delta\delta$ = 28.1 ppm). In this case, not only the inductive effect of the additional oxygen, but also different ring strains resulting from different ring sizes, have to be considered.

In the saccharine derivative **22**, which is less strained than the compounds containing the norbornane skeleton, the chemical shifts of carbon and nitrogen are similar to those of the simple oxaziridines **1–11**, whereas the oxygen atom seems to have an environment more similar to that in the norbornane derivatives. Hence this compound occupies an intermediate position between the two groups.

The ^{17}O NMR spectra of SO_2 groups have been thoroughly studied (see, e.g., Refs 47–49). The chemical shifts and line widths in the open-chain compunds **9–11** agree well with published values for sulphonamides,[49] whereas there is a substantial deshielding in the ring compounds **12–22** ($\Delta\delta \geqslant 19$ ppm). The dependence of the chemical shifts of oxygen in cyclic sulphones on the ring size is well known,[47] and may account for the observed differences in our compounds which all contain the SO_2 group in a five-membered ring. In the chiral compounds **12–14** and **18–22** the two oxygens are not equivalent, but show different chemical shifts (and also often line widths). In analogy to arguments given for cyclic sulphoxides, sulphones[48,50] and sulphates,[51] we assign the signal at lower field to the *exo*-oxygen; the *endo*-oxygen should be more shielded because of its vicinity to the oxaziridine oxygen.

ENANTIOSELECTIVE OXIDATIONS AND NMR DATA

Enantioselective oxidations of several sulphides to chiral sulphoxides by various sulphonyloxaziridines have been investigated.[11–17,52–54] For convenience, we shall divide the oxaziridines considered for this study into two groups, according to their behaviour towards the model oxidation

$$Ph{-}S{-}Me \rightarrow Ph{-}S(O){-}Me.$$

The enantiomeric excesses (*e.e.*) obtained in the oxidation of methyl phenyl sulphide under standard conditions (see Experimental) are given in Table 4. Group A contains efficient oxaziridines (*e.e.* $\geqslant$ 50%) and group B inefficient oxaziridines (*e.e.* < 50%). The borderline between the two groups is arbitrary, but we think it reasonably chosen. Thus, **13**, **15**, **16**, **19** and **20** are efficient (group A), whereas **12**, **14**, **17**, **18**, **21** and **22** belong to group B.

Table 4. Enantioselective oxidation of methyl phenyl sulphide

Oxaziridine		Sulphoxide		
Compound	Group	*e.e.* (%)	Configuration	Ref.
12	B	3	*R*	13
13	A	57	*S*	14
14	B	3	*R*	14
15	A	62	*S*	—
16	A	59	*S*	—
17	B	19	*S*	—
18	B	9	*R*	14
19	A	60	*S*	13
20	A	79	*S*	14
21	B	43	*S*	—

From the discussion of the NMR data given above, it is not surprising that there is no rigorous relationship between the chemical shifts of any of the three ring atoms and the *e.e.* value of the product, as the chemical shifts are governed by both inductive and steric influences introduced by the ring systems and the substituents, and therefore cannot be considered as a simple measure of the accessibility of the oxaziridine oxygen. There is also no relationship between the line width of the ^{17}O signals in both the oxaziridine ring and the SO_2 group and the enantioselectively of the oxidation reactions, although the line widths reflect asymmetry in the surrounding of the nucleus. On the other hand, it seems that there is a general tendency within both groups concerning ^{15}N and ^{17}O chemical shifts. Thus, oxaziridines belonging to group B have comparatively low values of δ_N (180.0–191.8 ppm) and also comparatively low values of δ_O (153–162 ppm), whereas those belonging to group A show higher values ($188.7 \leqslant \delta_N \leqslant 198.8$ ppm and $160 \leqslant \delta_O \leqslant 180$ ppm). There is only a small overlap zone between the chemical shifts of the oxaziridines of both groups: in the case of the isomeric *endo*- and *exo*-bromooxaziridines **13** and **14**, the inefficient oxaziridine **14** shows the higher value for δ_N (191.8 *vs.* 188.7 ppm), and **13** also has a comparatively low value of δ_O (160 ppm), which is on the borderline to group B. Apart from this case, it seems that the assignment of a given sulphonyloxaziridine containing norbornane skeleton to either group A (high enantiomeric excess in the oxidation of sulphides to chiral sulphoxides) or group B (low enantiomeric excess) can be undertaken with some reliability on the basis of multinuclear magnetic resonance of the atoms of the oxaziridine ring.

EXPERIMENTAL

Synthesis of the compounds

The oxaziridines **12**, **16–20** and **22** were obtained by published procedures.[7,13,16,26–29] We shall report on the synthesis of oxaziridine **21** elsewhere. The *endo*- and *exo*-3-bromo-camphorsulphonyloxaziridines **13** and **14** can be separated from the mixture described in Ref. 26 by chromatography on silica gel. Hexane–dichloromethane (1:1) elutes **13** first and then **14**. The *endo*-oxaziridine **13** has already been described;[26] **14** has m.p. 166–168 °C and $[\alpha]_D^{20} = +30.3$ ($c = 1.4$, acetone). Found, C 38.8, H 4.4, N 4.6; calculated for $C_{10}H_{14}BrNO_3S$ (308.19), C 39.0, H 4.6, N 4.6%.

3,3-Dibromocamphorsulphonyloxaziridine (**15**) {*Chemical Abstracts* name: (4*a*S,8a*R*)-8,8-dibromo-9,9-dimethyl - 5,6,7,8 - tetrahydro - 4*H* - 4a,7 - methano - oxazirino[3,2 - *i*][2,1]benzisothiazole - 3,3 - dioxide} was prepared from the 3,3-dibromocamphorsulphonylimine[55] in analogy with **16**.[7] Thus, to a suspension of the imine (3.0 g, 8.1 mmol) in 20 ml of dichloromethane and 50 ml of saturated aqueous K_2CO_3, 50% 3-chloroperbenzoic acid (7.5 g, 22 mmol) was added in five portions and the mixture was stirred for 6 h at room temperature. The organic phase was separated and the aqueous phase extracted with dichloromethane (50 ml). The combined organic phases were washed with water and dried over Na_2SO_4. The solvent was evaporated and the residue purified by chromatography [silica gel, hexane–dichloromethane (1:1)] to give **15** in 60% yield; m.p. 183–186 °C, $[\alpha]_D^{22} = +65.0$ ($c = 0.8$, EtOH). Found, C 31.0, H 3.3, N 3.6; calculated for $C_{10}H_{13}Br_2NO_3S$ (387.07), C 31.0, H 3.4, N 3.6%.

The starting imines for the preparation of oxaziridines **1–11** were prepared from the carbonyl compounds by reaction with amines (for oxaziridines **1–8**) or with *N*-sulphinyl-*p*-toluenesulphonamide[56] (for oxaziridines **9–11**), using standard methods. For the oxidation of the imines to oxaziridines **1–11**, the following procedures were used:

(*i*) *With* $KHSO_5$ (*oxone*): To a solution of 20 mmol of the imine in 80 ml of dichloromethane, a saturated aqueous solution of $NaHCO_3$ (100 ml) was added. Oxone 16.0 g) and tetrabutylammonium hydrogen sulphate (0.7 g) were added in one portion. The mixture was stirred vigorously for 3 days. The layers were separated and the aqueous layer extracted with diethyl ether. The combined organic phases were dried (Na_2SO_4) and the solvent was evaporated in vacuum. To the residue, 100 ml of diethyl ether were added and the mixture was stirred for 1 h. The solid was filtered off and the solvent evaporated in vacuum. The oxaziridines were pure enough for spectroscopic measurements. New compounds were further purified by distillation. The following compounds were obtained by this method: **1**, yield 53%, b.p. (0.05 mmHg) = 42–44 °C; found, C 71.8, H 11.7, N 7.5; calculated for $C_{11}H_{21}NO$ (183.15), C 72.1, H 11.5, N 7.6%. **4**, yield 56%, *trans*:*cis* ratio = 9:1; the *cis* isomer was not separated from **4**.[38]

(*ii*) *With peracetic acid.* To a solution of imine (20 mmol) in dichloromethane (100 ml), finely powdered $KHCO_3$ (6.0 g) and finely powdered molecular sieves (3 Å) (6.0 g) were added. A solution of peracetic acid (50% in acetic acid) (5.0 ml, 30 mmol) was added dropwise with stirring. Stirring was continued for 20 h. The solid was filtered off and washed carefully with dichloromethane. The solvent was evaporated under vacuum and the residue was purified by distillation or crystallization. The following compounds were obtained by this method: **2/3**, yield 75%, **2**:**3** ratio = 2.3:1. Partial separation by distillation gives a fraction of b.p. (0.07

mmHg) = 44–48 °C, 1.7 g, **2**:**3** ratio = 4.6:1; from this fraction pure **2** can be isolated by repeated chromatography [silica gel, hexane–dichloromethane (1:1), R_F = 0.31]; $[\alpha]_D^{20} = -47.2$ (c = 0.9, EtOH). Found, C 75.7, H 8.8, N 7.6; calculated for $C_{12}H_{17}NO$ (191.16), C 75.5, H 8.9, N 7.3%. In the distillation residue, **3** is enriched (**2**:**3** ratio = 0.3:1); pure **3** can be isolated from this fraction by chromatography [silica gel, hexane–dichloromethane (1:1), $R_F = 0.43$]; $[\alpha]_D^{20} = -112.0$ (c = 0.6, EtOH). Found, C 75.8, H 8.7, N 7.5; calculated for $C_{12}H_{17}NO$ (191.16), C 75.5, H 8.9, N 7.3%. **5**/**6**, yield 80%, **5**:**6** ratio = 2.1:1, not separated.[57] **7**/**8**, yield 89%, **7**:**8** ratio = 3.2:1; **7** crystallizes from the mixture, m.p. 40–42 °C;[23] the mother liquor of the crystallization is sufficiently enriched in **8** for NMR measurements. **9**, yield 56%, m.p. 142–145 °C (ethyl acetate).[24] **10**, yield 48%, m.p. 96–98 °C (ethyl acetate–hexane).[24]

(iii) With 3-chloroperbenzoic acid (MCPBA). To a solution of the imine (20 mmol) in dichloromethane (100 ml), a saturated aqueous solution of $NaHCO_3$ (75 ml) was added. To the vigorously stirred mixture, MCPBA (50%) (22 mmol, 7.50 g) was added in five portions. Stirring was continued for 1 day. The organic layer was washed twice with saturated aqueous Na_2CO_3 and dried (Na_2SO_4). After evaporation of the solvent under vacuum, the residue was recrystallized from ethyl acetate–hexane. Oxaziridine **11** was obtained in 85% yield, m.p. 126–128 °C.[25]

Enantioselective oxidations

Oxidations of methyl phenyl sulphide by oxaziridines **12**, **13**, **14**, **18**, **19** and **20** have already been reported.[13,14] The procedure for the oxidations with **15**, **16**, **17** and **21** follows that of Ref. 14. Thus, the oxaziridine (5.5 mmol) was suspended in CCl_4 (100 ml) and methyl phenyl sulphide (5.0 mmol, 0.62 g) was added. The mixture was stirred for 2 days (**15** and **16**), 3 days (**17**) or 7 days (**21**). The solvent was evaporated and the residue stirred with hexane (50 ml) for 10 h. After filtration and evaporation of the solvent, the residue was purified (necessary only in the case of **21**) by chromatography (silica gel, methanol) and analysed for chemical purity by ^{1}H NMR and for enantiomeric excess by polarimetry (ethanol) with a Roussel Jouan Digital 71 instrument; enantiomerically pure (*R*)-methyl phenyl sulphoxide has $[\alpha]_D^{20} = +146.2$ (c = 1.76, ethanol).[58] The yields generally exceed 90%. The results are given in Table 4.

NMR measurements

All NMR measurements were performed on a Bruker AM 360 spectrometer in $CDCl_3$, using 5 mm tubes for ^{1}H and ^{13}C and 10 mm tubes for ^{15}N and ^{17}O, with sample spinning and lock on. Saturated solutions of the oxaziridines were generally used; however, with oxaziridines of high solubility, the maximum concentration was 1 mol l^{-1}. Standard techniques were applied for ^{1}H (360.14 MHz) and ^{13}C (90.56 MHz) spectra. External H_2O ($\delta = 0$ ppm) was used as reference for ^{17}O and external CH_3NO_2 [50% in $CDCl_3$ with 0.03 M $Cr(acac)_3$, δ = 379.6 ppm] for ^{15}N. Oxygen NMR was performed at 50 °C and nitrogen NMR at 28 °C. The NMR frequency for ^{17}O was 48.822 MHz and for ^{15}N 36.492 MHz, while 33.3 and 55.5 kHz were used as sweep widths, respectively. ^{15}N spectra were measured with the addition of 0.03 mol l^{-1} $Cr(acac)_3$, with inverse gated decoupling, using a 45° pulse angle and a repetition time of 2.8 s (acquisition time 0.59 s). For suppression of acoustic ringing, the pulse sequence of Ref. 59 was used for ^{17}O, with a pulse repetition time of 0.033 s (acquisition time 0.031 s). The FID was multiplied with an exponential function (line broadening 4 Hz for ^{15}N and 20 Hz for ^{17}O) before Fourier transformation. The error in the determination of the chemical shift of ^{15}N is about 0.5 ppm and of ^{17}O about 2 ppm, while the error in the determination of the line width at half-height of the ^{17}O signal can be estimated to be $\pm$10% of the measured value.

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