

# Synthesis of sulfoxides by the oxidation of sulfides with sodium chlorite catalysed by manganese(III) acetylacetonate in acetone in the presence of alumina

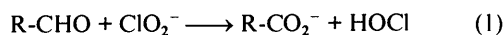
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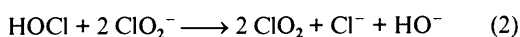
Systematic oxidations of sulfides with sodium chlorite have been investigated in aprotic solvents under mild and neutral conditions. Metal catalysis is essential for the efficient oxidation, and conversion of a wide variety of diaryl, alkyl aryl, dialkyl and cyclic sulfides into the corresponding sulfoxides can be favoured by the catalytic presence of manganese(III) acetylacetonate in acetone with the aid of moist alumina in general or dry alumina in particular cases in a rapid, high-yielding manner. This simple procedure has also been found to be an easy method for chemoselective transformation of functionalised sulfides without extensive undesirable side-reactions.

In the course of research on carbohydrates and their model compounds,<sup>1,2</sup> the unique potential offered by the NaClO<sub>2</sub>-based oxidation of an aldehyde to the corresponding carboxylic acid has been recognised [eqn. (1)]. Although a very



large number of reagents are available for oxidation of aldehydes,<sup>3</sup> the specificity of chlorite has been elegantly demonstrated in the oxidations of unsaturated and/or complex substrates,<sup>1,2,4-13</sup> to which other oxidising reagents are difficult to apply.

In spite of their apparent utility, chlorite oxidation reactions invariably need addition of what is usually termed a 'chlorine scavenger' such as resorcinol,<sup>1b,4</sup> sulfamic acid,<sup>1b,5,6</sup> hydrogen peroxide,<sup>1c,7</sup> dimethyl sulfoxide (DMSO)<sup>7,8</sup> or 2-methylbut-2-ene.<sup>9-11</sup> These are added so as to avoid the unproductive decomposition of the chlorite ion by hypochlorous acid unavoidably generated in the oxidation [eqns. (1) and (2)] and



and to prohibit undesirable side-reactions by swamping hypochlorous acid and chlorine dioxide, since the redox potential of the HOCl/Cl<sup>-</sup> couple is stronger than that of ClO<sub>2</sub><sup>-</sup>/HOCl<sup>14</sup> and chlorine dioxide is capable of oxidising organic compounds.<sup>2b,c,15</sup> Established procedures are carried out in aqueous media because of the negligible solubility of sodium chlorite **1** in common organic solvents. In addition, the instability of chlorite ion at low pH is well known and an expensive phase-transfer agent or buffering of the reaction medium is necessary to achieve efficient reaction. This leads to difficult work-up procedures of the final reaction mixtures. Consequently, these investigations have focused on conditions to improve aldehyde oxidations in aqueous media and little attention has been given to the use of chlorite **1** in a water-free medium or to the oxidative transformation of other functional groups.<sup>16</sup> Indeed, a literature survey reveals that sodium chlorite chemistry in aprotic solvents has been little researched, despite the fact that the solubility problem and disadvantages inherent to this type of reagent may be circumvented by carrying out the reaction with the aid of inorganic solid-support materials.<sup>17</sup> Consequently, the present work has been undertaken to test the

value of chlorite **1** in aprotic solvents in the presence of solid supports as a part of our ongoing investigation into the transformation of various functional groups with oxohalogen acid derivatives.<sup>17c,d,18</sup>

## Results and discussion

Although we are mindful of the diversity of methods available for oxidation of sulfide to date,<sup>19,20</sup> our recent involvement in the chemistry of sulfides has led us to choose the reaction as a target for this synthetic trial with the following viewpoints. First, a wide range of sulfides are readily available from commercial sources or by relatively simple synthetic procedures. Secondly, the resultant products, sulfoxides, are important reaction intermediates in organic syntheses. Finally, current procedures available for the oxidation of sulfides often encounter difficulties in reaction performance and/or in production of sulfoxides in a simple, rapid, selective and high-yielding manner and/or suffer from a lack of generality and/or economic applicability, which, from a practical point of view, make them less than attractive. As a consequence, there is still a significant demand for developing an effective, inexpensive, readily accessible and widely applicable method. The procedure described here would substantially meet these requirements. Indeed, the subject reaction can be readily carried out simply by placing a sulfide, an aprotic solvent, a metal catalyst, chromatographic alumina and sodium chlorite in a reaction vessel in that order and by stirring the resultant heterogeneous mixture efficiently. Depending mainly on the reactivity of the sulfide, 1.5 to 3.5 parts of sodium chlorite per part of sulfide are employed [**Caution**<sup>21</sup>]. The reaction is fairly clean, and therefore the work-up and the isolation of the product are also straightforward. Thus filtration of the insoluble materials from the mixture, followed by removal of the solvent, gives the sulfoxide and, in cases where it is contaminated with the parent sulfide and/or the sulfone, pure sulfoxide can be obtained by a single chromatographic separation.

In order to get information on the behaviour of sodium chlorite in aprotic solvents and to optimise conditions (choice of solid support, solvents, relative amounts, *etc.*)<sup>22</sup> for the selective formation of sulfoxides, the present investigation was initiated by examining reaction parameters using methyl phenyl sulfide **2** as the test substrate [eqn. (3)].

**Table 1** Oxidation of methyl phenyl sulfide **2** with NaClO<sub>2</sub> **1** in various solvents<sup>a</sup>

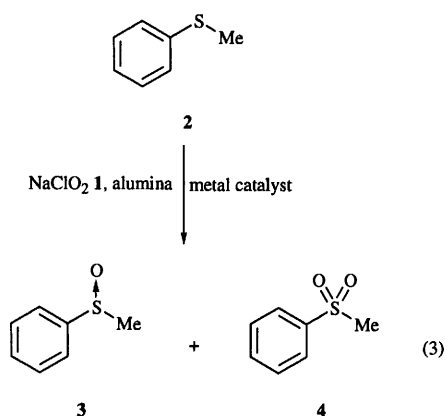
Entry	Solvent	Distribution (%) <sup>b</sup>		
		PhSMe	PhS(O)Me	PhS(O) <sub>2</sub> Me
1	Acetone	0	94	5.4
2	Acetonitrile	0	91	8.9
3	Benzene	29	59	5.2
4	Chloroform	53	36	4.4
5	Tetrachloromethane	78	12	1.0
6	Dichloromethane	0	88	5.2
7	Diethyl ether	57	37	0.9
8	Ethyl acetate	35	57	1.4
9	Ethanol	47	38	8.7
10	Hexane	86	8.9	0

<sup>a</sup> At 20 °C, for 20 min; methyl phenyl sulfide 0.2 mmol, NaClO<sub>2</sub> 0.3 mmol, solvent 1 ml, *moist* alumina 0.2 g, Mn(acac)<sub>3</sub> 1 mol% with respect to PhSMe. <sup>b</sup> Recovery of the sulfide and yields of the sulfoxide and the sulfone were determined by GLC using propiophenone as an internal standard. For details of moist alumina, see Starting materials in the Experimental section.

**Table 2** Oxidation of methyl phenyl sulfide with sodium chlorite in the absence and in the presence of various metal catalysts<sup>a</sup>

Entry	Catalyst	Distribution (%) <sup>b</sup>			Entry	Catalyst	Distribution (%) <sup>b</sup>		
		PhSMe	PhSOME	PhSO <sub>2</sub> Me			PhSMe	PhSOME	PhSO <sub>2</sub> Me
11	None	100	0	0	24	Co(OAc) <sub>2</sub> ·4H <sub>2</sub> O	55	43	0.9
12	Mn(acac) <sub>3</sub>	0	94	5.4	25	CuSO <sub>4</sub> ·5H <sub>2</sub> O	91	3.1	0
13	Mn(acac) <sub>2</sub>	0.3	90	7.0	26	CuCl	88	6.3	0
14	Mn(acac) <sub>2</sub> ·2H <sub>2</sub> O	0	90	6.1	27	CuCl <sub>2</sub>	90	2.8	0
15	Mn(OAc) <sub>2</sub>	21	73	2.1	28	Cu(NO <sub>3</sub> ) <sub>2</sub> ·3H <sub>2</sub> O	92	2.7	0
16	KMnO <sub>4</sub>	0	84	12	29	Cu(OAc) <sub>2</sub>	95	2.1	0
17	MnO <sub>2</sub>	86	8.2	0	30	MgCl <sub>2</sub> ·6H <sub>2</sub> O	97	0	0
18	MnCO <sub>3</sub>	86	6.5	0	31	MgSO <sub>4</sub>	96	2.5	0
19	MnSO <sub>4</sub> ·2H <sub>2</sub> O	93	4.9	0	32	Fe(OAc) <sub>3</sub>	85	4.0	0
20	Co(acac) <sub>3</sub>	57	33	0.9	33	VO(acac) <sub>2</sub>	82	3.5	0
21	CoSO <sub>4</sub> ·2H <sub>2</sub> O	78	15	0	34	Cr(acac) <sub>3</sub>	88	2.1	0
22	CoCl <sub>3</sub> ·6H <sub>2</sub> O	0	86	12	35	K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	79	2.1	0
23	Co(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	0	80	8.2	36	K <sub>2</sub> MoO <sub>4</sub>	89	2.5	0

<sup>a</sup> At 20 °C, for 20 min; methyl phenyl sulfide 0.2 mmol, NaClO<sub>2</sub> 0.3 mmol, acetone 1 ml, *moist* alumina 0.2 g, metal salt 2 × 10<sup>-6</sup> mol (1 mol% of PhSMe). <sup>b</sup> Recovery of the sulfide and the yields of the sulfoxide and the sulfone were determined by GLC using propiophenone as an internal standard.



Treatment of methyl phenyl sulfide with sodium chlorite **1** ([**1**]/[**2**] = 1.5; mole ratio) in acetone at 20 °C for 20 min brought about no consumption of the sulfide when no metal catalyst was added. Thus sodium chlorite alone is inert in a non-aqueous medium in the absence of metal catalyst<sup>18a</sup> (see also Entry 11 in Table 2), and therefore preliminary experiments were carried out in the presence of a metal salt, Mn(acac)<sub>3</sub>, for example. With a catalytic amount of Mn(acac)<sub>3</sub> (1 mol% with respect to the sulfide), however, it was observed that the sulfide was again hardly oxidised to the sulfoxide, either in the absence or in the presence of oven-dried alumina (*dry* alumina; *vide infra*). There have been several reports that a small but definite amount of water is essential for high performance of supported reagents, and that it sometimes plays an important role in determining the course of reactions.<sup>23-25</sup> Thus a small quantity

of water was introduced into the reaction system. GLC analyses of the crude mixtures have shown that addition of a small amount of water to the reaction media in the absence and in the presence of the *dry* alumina led to a significant improvement in rate, resulting in 43 and 100% conversions of substrate **2**, respectively, and the formation of methyl phenyl sulfoxide **3** in 29 and 87% yield, respectively. Obviously, the added water caused facilitation of the reaction, but the conversion was still unsatisfactory in the former case and an unacceptable amount of the sulfone **4** (11%) was formed in the latter. On the other hand, in the presence of *moist* alumina containing 17% of water by weight (the same amount of water added to the solvent; detailed in the Experimental section) sulfoxide **3** was produced with significant selectivity (GLC yield, 94%), being accompanied by only 5.4% of sulfone **4**. Investigations in the 0–23 wt% water range have indicated that lower or higher water loading caused a decrease in the conversion of the sulfide and/or the yield of the sulfoxide.

The effect of solvents ranging from nonpolar to highly polar on the rate of the reaction and the selectivity of formation of sulfoxide have been investigated in the presence of *moist* alumina and the comparative data are summarised in Table 1. The reaction is markedly solvent-dependent and, among the solvents examined, acetone is clearly the solvent of choice in terms of ease of the reaction and the selectivity and the yield of the sulfoxide. No relationship has been observed between the physical properties of the solvents, e.g. polarity, and the reaction rate, the selectivity or the yield of the sulfoxide.

Owing to our observed success in using metal catalysts in oxidation of the sulfide, we then looked for other efficient catalysts for the NaClO<sub>2</sub>/*moist* alumina system. Various easily handled

**Table 3** Synthesis of various sulfoxides by the oxidation of the sulfides with sodium chlorite<sup>a</sup>

Entry	Sulfide R-S-R <sup>1</sup>		NaClO <sub>2</sub> (mmol)	Time (t/min)	Yield (%) <sup>b</sup>	Entry	Sulfide R-S-R <sup>1</sup>		NaClO <sub>2</sub> (mmol)	Time (t/min)	Yield (%) <sup>b</sup>
	R	R <sup>1</sup>					R	R <sup>1</sup>			
37	Ph	Me	0.3	20	93	57 <sup>c</sup>	Ph	Ph	0.6	40	95
38	<i>p</i> -MeOC <sub>6</sub> H <sub>4</sub>	Me	0.3	30	88	58	Ph	PhCH <sub>2</sub>	0.3	20	80
39	<i>p</i> -MeC <sub>6</sub> H <sub>4</sub>	Me	0.3	25	92	59	PhCH <sub>2</sub>	PhCH <sub>2</sub>	0.3	20	87
40 <sup>c</sup>	<i>o</i> -BrC <sub>6</sub> H <sub>4</sub>	Me	0.5	50	96	60 <sup>c</sup>	Thianthrene		0.7	120	89 <sup>h</sup>
41	<i>p</i> -BrC <sub>6</sub> H <sub>4</sub>	Me	0.3	25	95	61 <sup>c,d</sup>	Thianthrene 5-oxide		0.7	120	94 <sup>f</sup>
42	<i>p</i> -ClC <sub>6</sub> H <sub>4</sub>	Me	0.3	25	92	62 <sup>c,f</sup>	Dibenzothiophene		0.6	90	79
43 <sup>c,d</sup>	<i>p</i> -O <sub>2</sub> NC <sub>6</sub> H <sub>4</sub>	Me	0.6	50	98	63	Pr	Pr	0.3	15	88
44	<i>p</i> -OHCC <sub>6</sub> H <sub>4</sub>	Me	0.3	25	91	64 <sup>g</sup>	Pr <sup>f</sup>	Pr <sup>f</sup>	0.7	50	88
45	<i>p</i> -HOH <sub>2</sub> CC <sub>6</sub> H <sub>4</sub>	Me	0.3	20	91	65	Bu	Bu	0.3	15	89
46	<i>p</i> -HOC <sub>6</sub> H <sub>4</sub>	Me	0.3	25	79	66 <sup>g</sup>	Bu <sup>s</sup>	Bu <sup>s</sup>	0.6	50	80
47 <sup>c</sup>	Ph	CH <sub>2</sub> Cl	0.6	30	95	67	Bu <sup>f</sup>	Bu <sup>f</sup>	0.3	15	83
48	Ph	[CH <sub>2</sub> ] <sub>2</sub> Cl	0.3	30	92	68	Bu <sup>f</sup>	Bu <sup>f</sup>	0.3	15	<i>j</i>
49	Ph	Et	0.3	20	90	69	C <sub>6</sub> H <sub>13</sub>	C <sub>6</sub> H <sub>13</sub>	0.3	15	84
50	Ph	Pr	0.3	20	92	70	C <sub>8</sub> H <sub>17</sub>	Me	0.3	15	79
51	Ph	Pr <sup>f</sup>	0.3	25	89	71	C <sub>8</sub> H <sub>17</sub>	C <sub>8</sub> H <sub>17</sub>	0.4	25	91
52	Ph	Bu	0.3	20	86	72	Allyl	Allyl	0.3	15	69
53	Ph	Bu <sup>s</sup>	0.3	20	80	73		Tetrahydrothiophene	0.3	15	90 <sup>c</sup>
54	Ph	Bu <sup>f</sup>	0.4	15	39 <sup>c</sup>	74 <sup>g</sup>		Tetrahydrothiopyran	0.6	50	84 <sup>c</sup>
55	Ph	C <sub>6</sub> H <sub>13</sub>	0.3	20	86	75		Tetrahydrothiopyran-4-one	0.4	15	94 <sup>c</sup>
56	Ph	Vinyl	0.6	50	64	76		1,4-Thioxane	0.4	15	86 <sup>c</sup>

<sup>a</sup> At 20 °C; sulfide 0.2 mmol, acetone 1 ml, *moist* alumina 0.2 g, Mn(acac)<sub>3</sub> 1 mol% with respect to the sulfide. <sup>b</sup> Isolated yields of chromatographically purified sulfoxides unless otherwise indicated. <sup>c</sup> Mn(acac)<sub>3</sub> 5 mol%. <sup>d</sup> At 30 °C. <sup>e</sup> GLC yield. <sup>f</sup> At 40 °C; *moist* alumina 0.6 g. <sup>g</sup> Oven-dried alumina (*dry* alumina) was used instead of the *moist* alumina. <sup>h</sup> Total isolated yield of thianthrene 5-oxide [72%, m.p. 143.5–144.0 °C; reported mp.<sup>30</sup> 143–144 °C] plus 5,10-dioxide [17%, mp 253–255 °C (*trans*) and 289–291 °C (*cis*); reported mp<sup>30</sup> 249 °C and 284 °C, respectively]. <sup>i</sup> Thianthrene 5,10-dioxide. <sup>j</sup> Crude mixture consisted of the sulfone and the disulfide (<sup>t</sup>BuS)<sub>2</sub>, but no sulfoxide, from which 44% of di-*tert*-butyl sulfone was isolated.

and inexpensive metal salts that are commercially available were tested (Table 2). The conversions of the sulfide range from 0 to 100% depending on the metal catalyst employed. Significant catalysis was observed with several manganese and cobalt salts, but Cu, Mg, Fe, V, Cr and Mo salts have been found to be ineffective. Of the metal salts examined, Mn(acac)<sub>3</sub> would appear to be the best catalyst. It should be noted that even though halogenation of sulfides employing halogen-containing agents as oxidants has been reported<sup>25,26</sup> and indeed sodium chlorite has chlorinating capability,<sup>16,27</sup> no nuclear or side-chain chlorination occurred in any experiment cited above. The activity of related halogen oxide anions, NaClO<sub>3</sub>, NaBrO<sub>2</sub>, NaBrO<sub>3</sub>, NaIO<sub>3</sub>, NaIO<sub>4</sub> and KIO<sub>4</sub>, has been tested with methyl phenyl sulfide, but none of those is effective for the oxidation with the exception of NaBrO<sub>2</sub>, which exhibited a moderate oxidative capability to afford sulfoxide **3** in 71% GLC yield, but 27% of sulfide **2** still remained unchanged after a prolonged period (60 min).

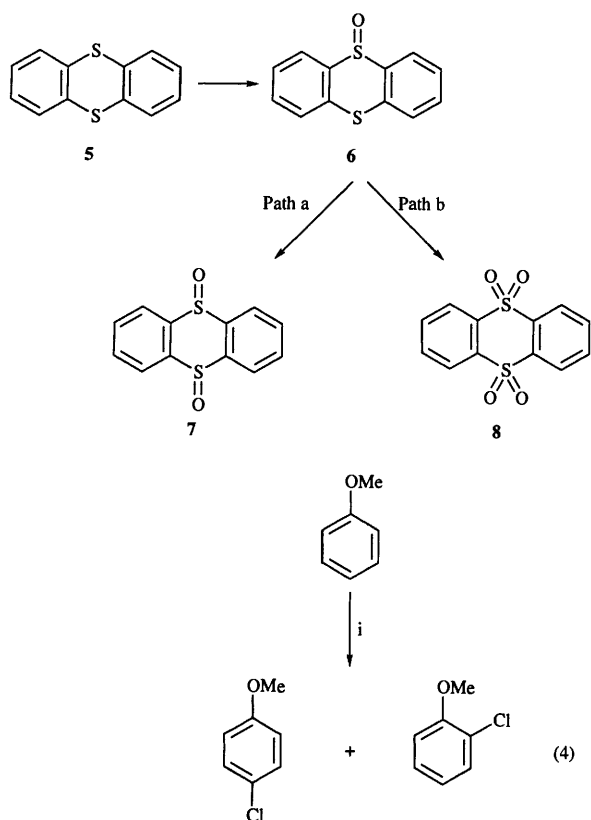
As described above, in addition to the presence of *moist* alumina, the choice of the metal salt and the solvent are critical factors in determining the efficiency of the chlorite oxidation. Consequently, synthetic reactions of sulfoxides were carried out by using Mn(acac)<sub>3</sub> as the catalyst in acetone as the solvent. Mn(acac)<sub>3</sub> is readily soluble in acetone and immediately produced a homogeneous brown solution, of which the colour was discharged within a few minutes after addition of *moist* alumina, and a light brown coloration of the alumina was observed. This indicated that the manganic species was trapped on the alumina surface and presumably subsequent reaction occurred on the surface. Indeed, atomic absorption analyses of the solvent showed no detectable amount of a manganese species. Under these circumstances, sodium chlorite acts as a highly effective oxidant for methyl phenyl sulfide, permitting selective formation of the sulfoxide in near quantitative yield (93%, isolated; *vide* Entry 37 in Table 3) in a short period of time. To demonstrate the scope of the method, oxidations of a broad range of sulfides including alkyl aryl, diaryl, dialkyl and cyclic substrates have been investigated. Table 3 shows that sulfoxides can be produced in synthetically acceptable yields by appropriately adjusting the concentrations of NaClO<sub>2</sub> and Mn(acac)<sub>3</sub> catalyst and reaction time and temperature. Noticeable observations on each class of sulfides are documented as follows.

Oxidations of alkyl aryl and dialkyl sulfides have been investigated by changing substituents on the benzene ring of a thioanisole series (Entries 37–46) and by changing the alkyl moiety of alkyl phenyl sulfides (Entries 37, 47–56) and dialkyl sulfides (Entries 63–72). It is clear from Table 3 that electronic and structural influences of the substituents on the yields of the alkyl aryl sulfoxides are small and the products can be isolated from the reaction mixture in excellent to quasi-quantitative yields, even though there is some difference in the reactivity of the sulfides. Diaryl sulfides can be successfully converted into the corresponding sulfoxides (Entries 57–59). Dialkyl sulfides were, in general, found to be more reactive than aromatic sulfides, and there is no loss in reactivity of the sulfides when the alkyl moiety becomes bulky or long. Diisopropyl (Entry 64) and di-*sec*-butyl (Entry 66) sulfides are liable to further oxidation of the initially formed sulfoxides to the sulfones. *A priori* it would appear expedient to use the *dry* alumina in place of the *moist* alumina to suppress the overoxidation to sulfone, since preliminary experiments showed methyl phenyl sulfide to have undergone sluggish oxidation in the presence of *dry* solid-support materials as noted above and elsewhere. This modification of the procedure met with success in enhancement of the sulfoxide selectivities. Surprisingly, sulfides consisting of one or two *tert*-butyl groups failed to produce the sulfoxides efficiently. Thus, oxidation of *tert*-butyl phenyl sulfide (Entry 54) gave only a mediocre yield (39%) of the corresponding sulfoxide, along with a considerable amount of the sulfone (28%), even though unchanged sulfide still remained (10%). More seriously, in the case of di-*tert*-butyl sulfide (Entry 68) the sulfone was formed as the main product in 44% yield accompanied by the oxidative S–S coupling product, the disulfide (Bu<sup>t</sup>S)<sub>2</sub>, but no sulfoxide could be obtained. Use of *dry* alumina led also to disappointing results. Regrettably, however, the unselective mode of these reactions ascribed to the lability or highly activating nature of the *tert*-butyl groups cannot be overridden by the present experimental technique.

The present catalytic system is chemoselective, tolerating a wide range of functionalities such as carbonyls (Entries 44, 75), benzylic (Entry 45) and phenolic (Entry 46) hydroxy groups, halides (Entries 47, 48) and ether (Entry 76) groups. It should

be noted that olefinic (Entry 56) and allylic (Entry 72) double bonds, which are considered to be highly susceptible to a chlorine species, mostly survive under the experimental conditions. Heterocycles were found to be active and the sulfoxides were produced in excellent yields (Entries 60–62, 73–76). Selective formation of the sulfoxide from (4-methylthio)benzaldehyde (Entry 44) in high yield should be of particular interest. This unexpected insensitivity of the aldehyde moiety illustrates a unique aspect of the present reaction system and is in sharp contrast to the previous observations that the formyl group in sulfides is highly susceptible to aqueous chlorite, which causes concurrent oxidation of aldehyde and sulfide functionalities to the sulfinyl-carboxy and/or the sulfonyl-carboxy compounds.<sup>7,13</sup>

Traditional methods for preparing  $\alpha$ -chloro sulfoxides have involved either chlorination of sulfoxides or oxidation of  $\alpha$ -chloro sulfides; however, the difficulty of preparing  $\alpha$ -chloro sulfoxides has been emphasised in several cases by virtue of the lability of the parent sulfoxides or sulfides toward degradation (S–O or C–S bond fission) during the reaction.<sup>25c,28</sup> A number of synthetic oxidations utilising sulfuryl dichloride in combination with moist silica gel,<sup>25b</sup> hydrogen peroxide catalysed by vanadium(v) oxide in Bu'OH,<sup>29</sup> *m*-chloroperbenzoic acid (MCPBA),<sup>30</sup> and ozone<sup>31</sup> have been developed for this purpose, but the yields of chloromethyl phenyl sulfoxide were lower (82, 73, > 70, and 74%, respectively) and reaction periods were longer than those of the present substrates (isolated yield 95% from 30 min reaction; Entry 47). Thus the NaClO<sub>2</sub>/moist alumina system provides a new and efficient synthetic route to chloromethyl phenyl sulfoxide.



**Scheme 1** Reagents and conditions: i, NaClO<sub>2</sub>, Mn(acac)<sub>3</sub>, moist Al<sub>2</sub>O<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>, 20 °C

The alumina-promoted process formally amounts to a simple oxygen transfer to a sulfide, but convincing evidence to enable a mechanistic route to be confirmed has not been yet provided. There is uncertainty with regard to the metal catalysis and the active species wherein the chlorite itself and/or its degradation product(s) might be involved. The following observations,

however, might help us to understand the nature of the active species. Thianthrene 5-oxide **6** has been conveniently used as a mechanistic test probe for investigating the electronic properties of oxidising reagents,<sup>32</sup> based on the assumption that an electrophilic species attacks the sulfide moiety to afford thianthrene 5,10-dioxide **7** (Path a in Scheme 1), while nucleophilic oxidation is responsible for the preferential formation of sulfone **8** (Path b). According to this classification, the result of Entry 61 clearly suggests the present active species is apparently electrophilic in nature, since the reaction occurred exclusively at the sulfide site and thus afforded solely 5,10-dioxide **7** in 94% isolated yield, but no disulfone **8**. In addition, oxidation of the parent sulfide, thianthrene **5**, yielded sulfone-free sulfoxides, a mixture of compounds **6** and **7** (Entry 60). These observations are in accord with another finding that upon subjecting anisole to the action of the NaClO<sub>2</sub>/Mn(acac)<sub>3</sub>/moist alumina system in dichloromethane at 20 °C for 50 min it was readily converted to give a mixture of monochlorinated anisoles in high yield (total 94% based on the substrate). There is an overwhelming preponderance of the *para*-isomer (*para:ortho* = 95:5) and the *meta*-isomer is absent [Equation (4); see also Ref. 26], obviously in line with the isomer distribution expected to arise from the reaction with a positive chlorine species.<sup>33</sup> These observations might favour the participation of an electrophilic species having a lower reactivity toward a strongly electron-deficient sulfide such as methyl *p*-nitrophenyl sulfide (Entry 43), for which higher concentrations of sodium chlorite and the catalyst, higher temperature, and longer reaction time are required than those used for the sulfides bearing electron-donating groups.

In short, we have demonstrated here a synthetic method for the production of sulfoxides *via* the oxidation of sulfides with sodium chlorite, a readily and cheaply available, easy-to-handle, and environmentally acceptable reagent with excellent shelf-life, in an aprotic solvent with the aid of chromatographic alumina. The advantages of the present procedure include the operational simplicity and mildness of the reaction conditions, and versatility and selectivity in its oxidising ability. Since sulfoxides are generally hydrophilic but the parent sulfides are more hydrophobic, an additional advantage might be derived from anhydrous conditions under which the present catalytic process is conducted. Thus solubility problems of the substrates and the loss of the products during the work-up stage can be eliminated. Sodium chlorite chemistry in aprotic solvents is an emerging research area and thus we believe this procedure not only provides an efficient alternative to the existing sulfoxide syntheses, but contributes to the extension of the scope and utility of sodium chlorite as a synthetic reagent.

## Experimental

### General

The <sup>1</sup>H NMR spectra were recorded with a JEOL PMX-60 (60 MHz) spectrometer for solutions in either tetrachloromethane or deuteriochloroform with SiMe<sub>4</sub> as internal standard. The IR spectra were measured on a JASCO A-100 spectrophotometer for samples as thin films (neat) or KBr disks. Analytical gas/liquid chromatography was performed on a Shimadzu GC-4CM instrument, equipped with a flame ionisation detector, through a 2 m column packed with 3% Silicone OV-17 on Uniport HP (60–80 mesh) and interfaced with an Hitachi D-2500 integrator, with temperature programming. The recovery of methyl phenyl sulfide **2** and the yields of methyl phenyl sulfoxide **3** and methyl phenyl sulfone **4** in experiments cited in Tables 1 and 2 were determined by GLC after adding propiophenone as an internal standard to the crude reaction mixtures. Mps were determined on a Yanagimoto MP-S3 melting point apparatus and are uncorrected. Atomic absorption analyses were carried out on an Hitachi 170-30 model instrument. Merck Silica gel 60 and Wakogel B-5F were used for column chromatography and preparative TLC, respectively.

## Starting materials

All sulfides, except the following six, were commercially available and were used as received. Phenyl propyl, butyl phenyl, *sec*-butyl phenyl and hexyl phenyl sulfides were synthesised from thiophenol and the corresponding alkyl bromides in benzene in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene DBU.<sup>34</sup> *tert*-Butyl phenyl sulfide was obtained from the reaction of *tert*-butyl chloride with thiophenol in the presence of anhydrous iron(III) chloride in phosphorus trichloride oxide.<sup>35</sup> Thianthrene 5-oxide **6** was isolated from the oxidation mixture of thianthrene **5** (Entry 60 in Table 3) and was characterised as usual. The purities of all sulfides were checked by GLC prior to use. Sodium chlorite and manganese(III) acetylacetonate were purchased from Kanto Chemical Co., Inc. and Tokyo Chemical Industry Co., Ltd., respectively. The *moist* alumina was prepared by adding deionised water (0.04 g) to chromatographic neutral alumina (ICN BIOMEDICAL, Alumina N, Super I; 0.2 g), which had been dried in an oven at 500 °C for 6 h before use (the *dry* alumina), in portions followed by vigorous shaking of the mixture after every addition until a free-flowing powder was obtained, 0.2 g of which was employed for the synthetic reaction. Acetone was dried over molecular sieves 4 Å.<sup>36</sup> The other solvents were purified according to methods described in the literature.<sup>37</sup>

## Oxidation procedures

Typical synthetic procedures of sulfoxides are exemplified by the oxidation of methyl phenyl sulfide **2**. A 10 ml round-bottom flask was charged with methyl phenyl sulfide **2** (0.2 mmol), acetone (1 ml), manganese(III) acetylacetonate (1 mol% of the sulfide, 0.002 mmol), the *moist* alumina (0.2 g), and sodium chlorite **1** (0.3 mmol) in that order, and the flask was then capped tightly with a glass stopper. The resultant heterogeneous mixture was vigorously magnetically stirred for 20 min at 20 °C. Insoluble materials were collected on a sintered glass funnel and washed thoroughly with portions of dichloromethane (*in toto* ~50 ml; alternatively, ethyl acetate in the exceptional case of Entry 46). Rotary evaporation of the combined clear filtrate *in vacuo* left an oil consisting of methyl phenyl sulfoxide **3** (94% by GLC) and the sulfone **4** (5.4%). Immediate chromatographic isolation on silica gel column by elution with a mixture of hexane and ethyl acetate (3:7 v/v) afforded pure (<sup>1</sup>H NMR, GLC and TLC) methyl phenyl sulfoxide **3** in 93% yield (Entry 37).

Oxidations of the other tabulated sulfides were conducted as above. Specific reaction conditions [concentrations of sodium chlorite and manganese(III) acetylacetonate and reaction time and temperature] for each sulfide were determined in terms of the reactivity of the sulfide and selectivity to the sulfoxide. All of the sulfoxides thus obtained are known compounds, identifications of which were based on a spectral comparison (<sup>1</sup>H NMR and IR) with authentic samples synthesised independently.

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