

Chiral discrimination and isomerization processes in monomers, dimers and trimers of sulfoxides and thioperoxides

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Abstract—The chiral discrimination in cyclic dimers and trimers of mono-substituted sulfoxides and thioperoxides has been studied by means of DFT (B3LYP/6-31+G**) and ab initio (MP2/6-311+G**) calculations. In addition, the inter- and intramolecular proton transfer processes that interconvert these two classes of compounds have been considered for the isolated molecules and clusters. The thioperoxide clusters are more stable than the corresponding sulfoxides even though the strongest hydrogen bonds are found in the latter complexes. Correlations have been found between the relative energies of the sulfoxide versus the thioperoxide compounds and the transition state barriers. The geometry of the hydrogen bonds has been analyzed using a Steiner–Limbach relationship.

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1. Introduction

Chiral discrimination is the basis for the selectivity of natural processes, both in recognition and reactivity. A number of these processes are mediated by hydrogen bonds (HBs). The mechanism responsible for the natural selection of the characteristic enantiomeric forms of aminoacids and sugars have been reviewed by Cintas et al.^{1,2} A Diels–Alder reaction using a chiral catalyst that is involved in the transition state (TS) through HBs has recently been described.³

The different reactivity of pure enantiomeric mixtures and racemic ones, as proposed by Wynberg and Feringa,⁴ is based on the difference of what they call the ‘enantiomeric recognition’ effect in the former case and ‘antipodal interaction’ in the latter. In the same year, Craig and Mellor⁵ reviewed the energetic sources of chiral discrimination in intermolecular interactions.

Chiral clusters in the gas phase have been studied in recent years using different spectroscopic techniques. King and Howard reported a microwave study of the heterochiral dimer of 2-butanol.⁶ Suhm et al. have examined the dimers of glycidol by means of FTIR spectroscopy.⁷ Beu and Buck found evidence of the

presence of different chiral isomers in the IR-spectra of hydrazine clusters.⁸ Zehnacker-Rentien et al. have studied the complexes of 2-naphthyl-1-ethanol with chiral systems using IR/UV double resonance spectroscopy.⁹ Speranza et al. used resonance-enhanced two-photon ionization (R2PI) spectroscopy to study the chiral complexes of alcohol dimers¹⁰ and mass spectrometry in the case of metallic complexes of α -amino-phosphonic acids.¹¹

Several theoretical articles have addressed chiral self-recognition as in the case of a series of α -aminoalcohols,¹² in complexes of compounds with axial chirality¹³ and in pyrrolo[2,3-*c*]pyrrole dimers including the corresponding proton transfer processes.¹⁴ The study of the diastereomeric interaction between a chiral system and the two enantiomeric forms of another molecule has been carried out for simple ethers, oxirane derivatives and hydrogen peroxide.¹⁵ The interaction of 2-naphthyl-1-ethanol with chiral and nonchiral alcohols has been both studied experimentally and theoretically.^{9,16}

Herein, the homo- and heterochiral dimers and trimers of self-associated chiral sulfoxides and thioperoxides using density functional theory (B3LYP/6-31+G**) and ab initio (MP2/6-311+G**) methods have been studied. In addition, the TSs that link these two series of compounds have been considered in the monomers, dimers and trimers. The electron density of the monomers and

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complexes has been characterized within the atoms in molecules (AIM) methodology.

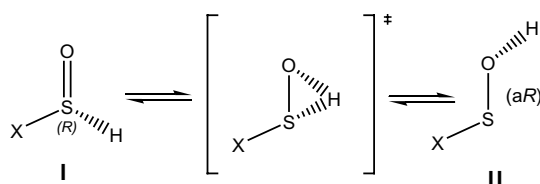
2. Methods

The geometries of the systems were fully optimized initially at the B3LYP/6-31+G**^{17,18} computational level within the Gaussian-98 program.¹⁹ Frequency calculations at the same level were performed in order to confirm the minima nature of the structures. Further optimizations have been carried out at the MP2/6-311+G** level.²⁰

The properties of the electron density of the complexes were analyzed using the atoms in molecules (AIM) methodology²¹ and the AIMPAC programs.²² The HB interactions were characterized by the formation of a bond critical point (bcp) between a hydrogen atom and an electron donor atom that are connected by the corresponding bond path. The presence of additional intermolecular interactions has been denoted, as well, by the presence of a bcp between the corresponding atoms.

3. Results and discussion

A series of mono-substituted sulfoxides **I** and corresponding thioperoxides **II** (Scheme 1) were chosen as suitable models to study the dimer and trimer self-aggregation and their transformation. The two classes of compounds studied present different types of stereogenicity. While the sulfoxides show a stereogenic sulfur atom, the thioperoxides have axial chirality (like hydrogen peroxide).¹³ The proton transfer of the (*R*)-isomer of the sulfoxides provides the *aR* (or *M*) enantiomer of the thioperoxides as shown in Scheme 1.



Scheme 1. Schematic representation of the sulfoxides and thioperoxides studied herein and the corresponding TS between them.

Table 1. Relative energies (kcal/mol) of the sulfoxides and TSs versus thioperoxides. The values of the Taft's mesomeric constants, σ_R for the substituents are included

X	Relative energy (E_{rel}) ^a		TS ^a		σ_R ^b
	B3LYP/6-31+G**	MP2/6-311+G**	B3LYP/6-31+G**	MP2/6-311+G**	
F	9.71	7.65	56.39	56.69	-0.37
Cl	15.67	14.51	58.73	59.72	-0.21
Br	16.46	15.11	58.90	59.79	-0.19
CH ₃	21.03	21.70	60.34	62.69	-0.07
CF ₃	25.70	26.84	65.71	68.80	0.08
CCH	29.01	28.44	66.04	68.21	0.10
CN	30.58	30.21	68.68	71.18	0.13
SiH ₃	30.25	32.40	65.12	68.26	0.19

^a The corresponding thioperoxide is used as reference value.

^b From Ref. 25.

3.1. Monomers

The relative energy of the sulfoxides and the corresponding TSs (Scheme 1) are reported in Table 1. The energies of the thioperoxides are given as reference (0.0). The results obtained at the two levels considered here, B3LYP/6-31+G** and MP2/6-311+G**, are very similar showing the same tendencies. For the rest of the article, only the results obtained at the MP2/6-311+G** level will be considered.

We have represented in Figure 1, a schematic energy profile. In all the cases studied, the thioperoxide structure **II** was more stable than that of the corresponding sulfoxide **I**. Furthermore, the thioperoxide structure was more stable than that of the corresponding sulfoxide. The energy differences ranged between 8 kcal/mol for the fluorine derivative up to 32 kcal/mol for the SiH₃ substituted compound. We have adopted the convention to define the TS with regard to the thioperoxide **II**, the other barrier (with regard to the most stable sulfoxide **I**) corresponds to the difference $TS - E_{rel}$. The ΔE values of Table 1 correspond to the prototropic tautomeric equilibrium between the sulfoxide and the thioperoxide. Substituent effects on tautomeric equilibria have often been modelled by means of Hammett or Taft substituent constants.²³ The ΔE values are well correlated with Taft's mesomeric constants, σ_R (and not with σ_I or E_S).^{24,25}

$$|MP2E_{rel}|(\text{kcal/mol}) = (24.0 \pm 0.2) + (44.5 \pm 1.0)\sigma_R, \\ n = 8, r^2 = 0.997 \quad (1)$$

It is difficult to know if the X substituents modify the stability of the thioperoxide or that of the sulfoxide. It is reasonable to assume that the major effects are on the sulfoxide (formal dipole, S⁺O⁻). Electron-withdrawing substituents (F) stabilize this tautomer while electron-donating ones (SiH₃) result in the opposite effect.

The calculated TSs give larger energy values (36–72 kcal/mol) due to the thioperoxide becoming less stable when compared to the corresponding sulfoxide. The TS and the relative energy $|E_{rel}|$ are linearly related as shown in Eq. (2):

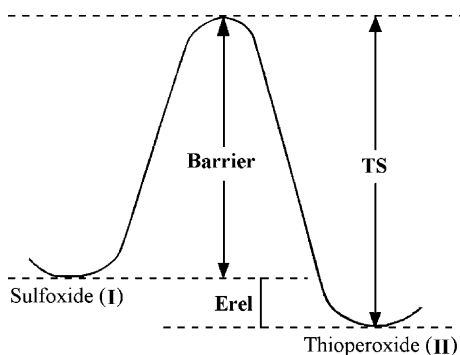


Figure 1. Schematic representation of the energetic profile.

$$\begin{aligned} \text{TS(kcal/mol)} &= (51.6 \pm 1.6) - (0.58 \pm 0.07) \\ &\quad \times |\text{MP2}E_{\text{rel}}|(\text{kcal/mol}), \\ n &= 8, r^2 = 0.93 \end{aligned} \quad (2)$$

3.2. Dimers

The dimers studied (Scheme 2) show two simultaneous HBs. In the case of the sulfoxides, they correspond to two nonlinear S–H···O contacts, while in the thioperoxides they are O–H···S HBs. The corresponding minima of the homochiral complexes show C_2 symmetry while in the heterochiral ones, the symmetry is C_i . The simultaneous double proton transfer configuration corresponds to a true TS structure (only one imaginary frequency) and maintains the symmetry of the initial and final products.

The calculated interaction energies (Table 2) show that in all cases, the S–H···O interactions are stronger than the O–H···S ones in the present complexes. The interaction energies of the sulfoxide dimers range between 8.7 and 16.7 kcal/mol, while the range for the thioperoxides dimers is from 3.7 to 8.9 kcal/mol. In order to understand the reason for these differences, the abilities of the methylated compounds as HB acceptor and donor versus HF and NH_3 , respectively, were explored. First, of all the sulfoxide is an excellent HB acceptor, especially when

compared to the thioperoxide in the interaction with FH ($E_1 = -14.14$ and -6.26 kcal/mol, respectively). As an HB donor, the thioperoxide provides a slightly larger interaction energy than the sulfoxide in the complexes with NH_3 (-10.14 and -7.64 kcal/mol, respectively).

The relative energies between the two tautomeric complexes are almost twice the size of the corresponding monomer with a minor correction due to the stronger interaction energy of the sulfoxides versus the thioperoxide dimers. The numerical values range from 12 kcal/mol for the fluorine derivatives up to 57 kcal/mol in the SiH_3 ones. The TS barriers are range between 30 and 57 kcal/mol, which represents a reduction of 12–27 kcal/mol to those of the corresponding monomers. This is due to the presence of a second molecule that intervenes in the process and relaxes the geometrical structure disposition of the TS. Similar results have been obtained in the tautomeric processes (proton transfer) of an isolated pyrazole molecule when compared to that occurring in the presence of solvent molecules like water or to the dimer.^{26,27} Cases where the energy differences are smaller than 5 kcal/mol are encountered between the sulfoxide derivatives and the TS as an indication of the easiness of the transformation in the corresponding thioperoxides.

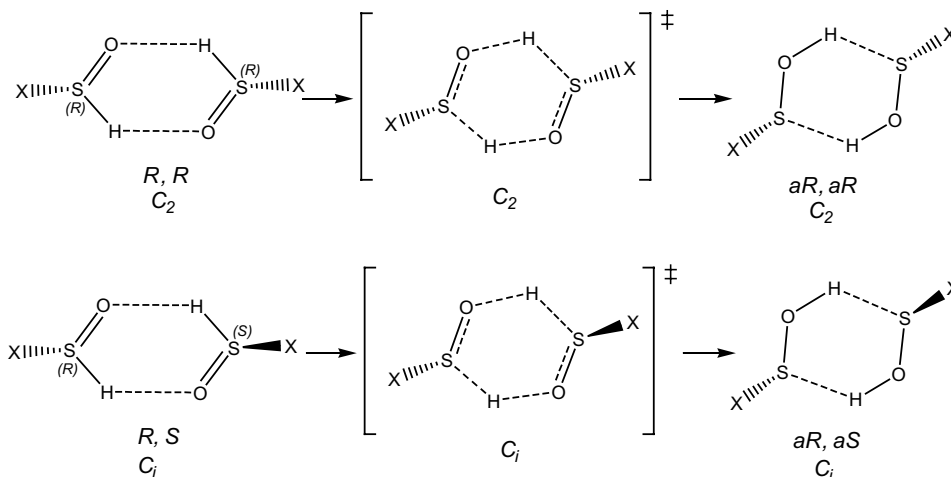
Several relationships have been found from Table 2:

$$\begin{aligned} |E_{\text{rel}}|(\text{kcal/mol}) &= (41.8 \pm 0.3) + (79.2 \pm 1.5)\sigma_{\text{R}}, \\ n &= 16, r^2 = 0.995 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{TS(kcal/mol)} &= (6.3 \pm 0.4) - (27.7 \pm 2.2)\sigma_{\text{R}}, \\ n &= 16, r^2 = 0.920 \end{aligned} \quad (4)$$

$$\begin{aligned} \text{TS(kcal/mol)} &= (21.0 \pm 0.9) - (0.35 \pm 0.02)[R_{\text{E}}] \\ &\quad (\text{kcal/mol}), \\ n &= 16, r^2 = 0.945 \end{aligned} \quad (5)$$

The values of chiral discrimination in the dimers and TS are shown in Table 3. This parameter has been



Scheme 2. Schematic representation of the sulfoxide and thioperoxide dimers and the concerted TS linking both systems.

Table 2. Interaction energy, relative energy and TS barrier (kcal/mol) calculated at the MP2/6-311+G** level

X	Configuration	Sulfoxide	Thioperoxides	Relative energy (E_{rel}) ^a	TS barrier ^a
		(E_1)	(E_1)		
Br	<i>R,R</i>	-10.49	-7.23	26.96	37.05
Br	<i>R,S</i>	-10.90	-6.99	26.31	37.81
CF ₃	<i>R,R</i>	-13.27	-5.55	45.97	52.52
CF ₃	<i>R,S</i>	-12.96	-6.04	46.76	51.65
CH ₃	<i>R,R</i>	-13.91	-8.26	37.77	43.44
CH ₃	<i>R,S</i>	-14.31	-8.90	38.00	43.79
Cl	<i>R,R</i>	-10.64	-6.77	25.15	35.89
Cl	<i>R,S</i>	-11.20	-6.63	24.46	36.68
CN	<i>R,R</i>	-12.58	-3.73	51.57	55.05
CN	<i>R,S</i>	-12.71	-4.02	51.73	56.57
F	<i>R,R</i>	-8.69	-5.44	12.05	29.89
F	<i>R,S</i>	-9.19	-6.03	12.13	30.74
HCC	<i>R,R</i>	-13.25	-7.53	51.16	53.07
HCC	<i>R,S</i>	-12.88	-7.11	51.10	54.38
SiH ₃	<i>R,R</i>	-16.06	-8.17	56.91	57.74
SiH ₃	<i>R,S</i>	-16.60	-8.03	56.23	56.94

^a The corresponding thioperoxide dimer is used as reference value.

Table 3. Chiral discrimination (kcal/mol) calculated at the MP2/6-311+G** level^a

X	Sulfoxides	Thioperoxides	TS	E_s (Taft) ^b
	Chiral disc.	Chiral disc.	Chiral disc.	
Br	-0.41	0.24	1.01	-1.16
CF ₃	0.30	-0.49	-1.35	-1.90
CH ₃	-0.40	-0.64	-0.28	-0.12
Cl	-0.56	0.14	0.93	-0.97
CN	-0.14	-0.30	1.22	-0.51
F	-0.51	-0.59	0.26	-0.55
HCC	0.37	0.43	1.74	—
SiH ₃	-0.54	0.14	-0.66	—

^a Negative values indicate that the heterochiral dimer (*R,S*) is more stable than the corresponding homochiral one (*R,R*).

^b From Ref. 25.

calculated as the energy difference of the homochiral (*R,R*) and heterochiral (*R,S*) structure in the stationary dispositions considered here (sulfoxide and thioperoxide dimers minima and TS structures). Previous experience has shown that in general the heterochiral dimer (*R,S* or *S,R*) is the most stable one. However, secondary interactions can invert this tendency. Herein, no clear tendency was observed with a relative large number of homochiral dimers (*R,R* or *SS*) being more stable than its corresponding heterochiral ones.

The differences in energy were up to 0.6 kcal/mol for the minima and up to 1.74 kcal/mol for the TS. The fact that the TS structure corresponded to a more compact one is the justification for a larger chiral discrimination as previously shown in a series of pyrrolo[2,3-*b*]pyrrole derivatives.¹⁴

Attempts to correlate the chiral discrimination in the TS structures with a steric parameter as Taft's E_s , provided poor correlations; an indication that a more complex mechanism controls these energetic differences.

$$\Delta TS(\text{kcal/mol}) = -(2.5 \pm 0.8) - (1.9 \pm 0.7)E_s, \\ n = 6, r^2 = 0.62 \quad (6)$$

$$TS(\text{kcal/mol, Table 3}) = (1.8 \pm 0.7) + (1.5 \pm 0.6)E_s, \\ n = 6, r^2 = 0.58 \quad (7)$$

The geometrical characteristics of the hydrogen bonds formed in the complexes are shown in Table 4. The HB distances range between 1.94 and 2.26 Å for the sulfoxide dimers and between 2.41 and 2.61 Å for the thioperoxide dimers. Regarding the HB bond angles, they are more linear in the second case, which is in contrast with the general tendency that shows that shorter HBs are more linear. In the TS structures, the shortest SH distance corresponds to the SiH₃ substituted derivatives while the longest one is found in the F derivatives; an indication that the TS structure is very similar to the first case of the sulfoxide initial products while in the second case, the TS is more in between the initial and final products.

In previous studies, a relationship between the HB distance and the relative stability in each pair was found,¹² with the dimers showing the shortest distances being more stable. However in the present study, only half of the cases followed this tendency.

The electron density analysis using the AIM methodology was shown to be a powerful tool for characterizing intermolecular interactions. Thus, in all the HBs a new bond critical point (bcp) was found between the hydrogen and the HB acceptor atom. In addition, other weaker interactions present similar bcp's. Some of these interactions can account for the relative stability of homo versus heterodimers in other cases.^{12,13} The corresponding additional interactions found in the dimers studied are shown in Table 5. In all the halogen substituted (X = F, Cl and Br) homo- and heterochiral dimers a bcp was found between the oxygens of the

Table 4. Intermolecular distances (Å) and bond angles (°) characteristic of the dimers studied

X	Configuration	Sulfoxides		Thioperoxides		TS		
		H···O	O···HS	S···H	OH···S	H···O	SH	OHS
Br	<i>R,R</i>	2.146	124.8	2.414	151.7	1.412	1.486	153.3
Br	<i>R,S</i>	2.174	118.7	2.470	149.5	1.403	1.491	154.0
CF ₃	<i>R,R</i>	2.097	125.2	2.567	147.1	1.481	1.460	149.7
CF ₃	<i>R,S</i>	2.074	127.7	2.527	151.0	1.504	1.452	151.3
CH ₃	<i>R,R</i>	2.247	116.9	2.409	155.7	1.481	1.452	153.2
CH ₃	<i>R,S</i>	2.256	116.0	2.407	153.2	1.485	1.455	152.0
Cl	<i>R,R</i>	2.157	123.6	2.418	152.2	1.404	1.488	153.4
Cl	<i>R,S</i>	2.176	117.9	2.456	150.4	1.396	1.493	153.9
CN	<i>R,R</i>	2.071	125.7	2.565	149.6	1.547	1.437	147.3
CN	<i>R,S</i>	2.102	123.5	2.605	148.8	1.520	1.445	148.4
F	<i>R,R</i>	2.252	121.4	2.445	152.4	1.344	1.526	155.4
F	<i>R,S</i>	2.250	117.0	2.459	150.8	1.344	1.526	155.0
HCC	<i>R,R</i>	1.996	132.6	2.511	150.4	1.556	1.431	148.3
HCC	<i>R,S</i>	2.038	130.1	2.533	149.9	1.536	1.439	149.7
SiH ₃	<i>R,R</i>	1.935	134.9	2.432	154.9	1.618	1.412	148.8
SiH ₃	<i>R,S</i>	1.959	133.2	2.434	154.6	1.629	1.411	148.3

Table 5. Electron density and laplacian of the secondary interactions found in the dimers studied at the MP2/6-311++G** level

X	Configuration	ρ	Lap	Atoms involved	Interatomic distance
<i>Sulfoxides</i>					
Br	<i>R,R</i>	0.0010	0.0024	Br···Br	4.978
		0.0103	0.0390	O···O	2.965
Br	<i>R,S</i>	0.0111	0.0419	O···O	2.926
CF ₃	<i>R,R</i>	0.0061	0.0309	CF···FC	2.863
Cl	<i>R,R</i>	0.0105	0.0394	O···O	2.957
Cl	<i>R,S</i>	0.0113	0.0425	O···O	2.921
F	<i>R,R</i>	0.0098	0.0359	O···O	2.979
F	<i>R,S</i>	0.0106	0.0391	O···O	2.945
HCC	<i>R,R</i>	0.0015	0.0043	C···C	4.655
SiH ₃	<i>R,R</i>	0.0111	0.0419	SiH···HSi	2.774
<i>Thioperoxides</i>					
Br	<i>R,R</i>	0.0027	0.0074	Br···Br	4.347
CF ₃	<i>R,R</i>	0.0069	0.0326	F···F	2.880
CH ₃	<i>R,R</i>	0.0044	0.0132	H···H	2.388
Cl	<i>R,R</i>	0.0024	0.0068	Cl···Cl	4.157
CN	<i>R,R</i>	0.0028	0.0084	C···C	3.716
HCC	<i>R,R</i>	0.0036	0.0096	C···C	3.967
SiH ₃	<i>R,R</i>	0.0029	0.0097	H···H	2.865
<i>TS</i>					
Br	<i>R,R</i>	0.0039	0.0111	Br···Br	4.132
CF ₃	<i>R,R</i>	0.0106	0.0500	F···F	2.651
CH ₃	<i>R,R</i>	0.0042	0.0126	H···H	2.421
Cl	<i>R,R</i>	0.0038	0.0117	Cl···Cl	3.901
CN	<i>R,R</i>	0.0036	0.0116	C···C	3.520
HCC	<i>R,R</i>	0.0033	0.0094	C···C	4.187
SiH ₃	<i>R,R</i>	0.0035	0.0105	H···H	2.672

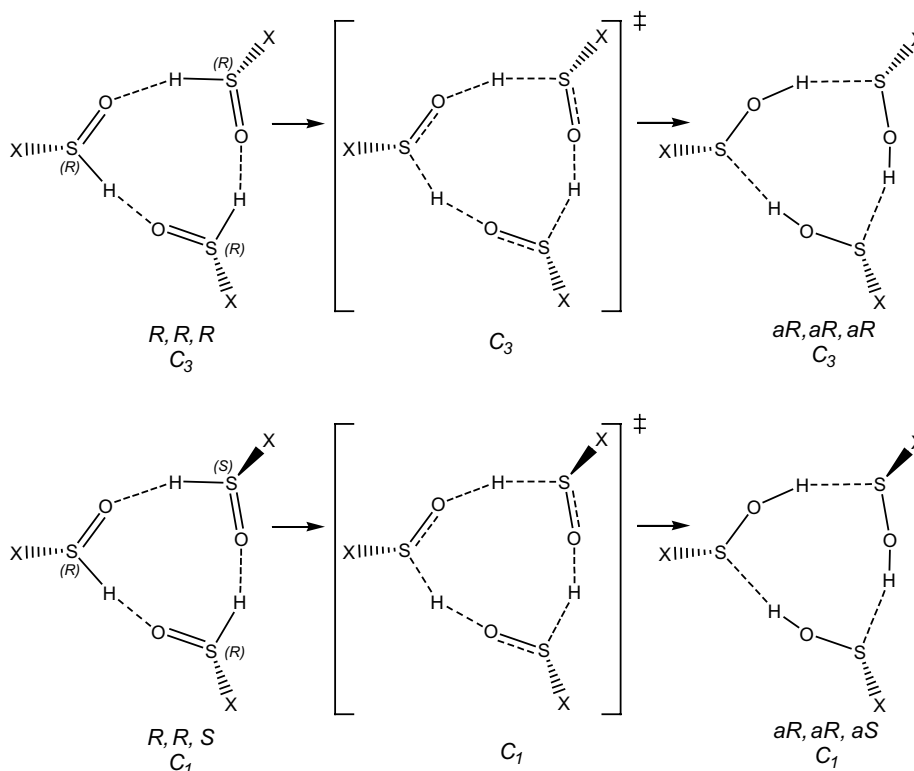
sulfoxide groups similar to that found in some of the dimers of hydrogen peroxide derivatives.¹³ The rest of the bcp's found corresponded to the contact of the X groups in the homochiral dimers.

3.3. Trimers

Only the three sulfoxides with the smallest relative energies with respect to the thioperoxides (X = F, Cl and Br) were able to form stable sulfoxide trimers. The

remaining cases studied herein were spontaneously transformed into the corresponding thioperoxides without any barrier. In the present study, only those cases where the sulfoxides and thioperoxides were stable have been considered. The trimers studied (Scheme 3) present *C*₃ symmetry for the homochiral cases and *C*₁ symmetry for the heterochiral ones.

The interaction energies (Table 6) obtained for the trimers followed the trend observed in the dimers in the sense that the sulfoxide complexes were more stable than



Scheme 3. Schematic representation of the sulfoxide and thioperoxide trimers and the concerted TS linking both systems.

Table 6. Interaction energy, relative energy and TS barrier (kcal/mol) of the trimers calculated at the MP2/6-311+G** level

X	Configuration	Sulfoxide		Thioperoxides	
		E_1	E_1	Relative energy ^a	TS ^a
Br	<i>R,R,R</i>	-23.72	-14.04	35.65	41.11
Br	<i>R,R,S</i>	-23.99	-15.02	36.36	42.04
Cl	<i>R,R,R</i>	-23.98	-13.74	33.30	39.35
Cl	<i>R,R,S</i>	-24.41	-14.68	33.81	40.29
F	<i>R,R,R</i>	-20.97	-9.87	11.84	31.78
F	<i>R,R,S</i>	-20.18	-10.57	13.33	32.01

^a The corresponding thioperoxide trimer was used as a reference value.

the corresponding thioperoxides. In addition, a clear cooperative effect was observed when compared to the dimers since in both families the interaction energy of the trimers, which corresponds to three identical HB in each family, is almost twice that of the dimers, where two identical HB are present. Regarding the relative energies, in fluoride derivatives they were analogous to the dimers but slightly larger in the Br and Cl derivatives due to the larger differences in the interaction energies of the trimers versus dimers. The TS barriers are similar to the ones obtained in the dimers; an indication that an additional molecule is not needed to provide a relaxed structure in proton transfer process.

The chiral discrimination of the trimers (Table 7) shows that in all cases, the heterochiral trimer is more stable than the homochiral one, with the exception of the

Table 7. Chiral discrimination (kcal/mol) calculated at the MP2/6-311+G** level^a

X	Sulfoxides	Thioperoxides	TS
	Chiral disc.	Chiral disc.	Chiral disc.
Br	-0.27	-0.98	-0.06
Cl	-0.43	-0.94	0.00
F	0.79	-0.70	-0.47

^a Negative values indicate that the heterochiral trimer (*R,R,S*) is more stable than the corresponding homochiral one (*R,R,R*).

fluorine derivative of the sulfoxide and the TS of the chlorine one where both give almost identical energies.

The geometrical parameters of the trimers (Table 8) show very large HB distances for the fluorine derivatives of the sulfoxide since in these cases the fluorine atoms tend to avoid each other forcing a poor HB contact. In general, the heterochiral trimers resemble a dimer system with an additional molecule while this is not possible in the homochiral trimers due to symmetry constraints. In the geometry of the TS structures, a slightly shorter O···H distance than the one obtained in the dimers is observed while the S···H ones are approximately similar to those of the dimers. The presence of a third molecule allows an almost linear OHS arrangement.

The additional interactions found within the AIM methodology are shown in Table 9. In the trimers, the contacts involve the three atoms in the homochiral tri-

Table 8. Intermolecular distances (Å) and bond angles (°) characteristic of the trimers studied

X	Configuration	Sulfoxides		Thioperoxides		TS		
		H···O	OHS	SH	OHS	H···O	SH	OHS
Br	<i>R,R,R</i>	1.816	163.5	2.283	171.2	1.3643	1.4886	173.6
Br	<i>R,R,S</i>	1.809	165.8	2.311	168.9	1.3519	1.4969	173.1
		1.830	155.0	2.328	164.7	1.3319	1.5121	176.2
		1.914	147.0	2.478	143.3	1.4207	1.4586	173.3
Cl	<i>R,R,R</i>	1.816	164.8	2.286	169.6	1.3547	1.4932	175.3
Cl	<i>R,R,S</i>	1.830	160.8	2.359	165.5	1.3327	1.5078	175.8
		1.839	158.0	2.354	161.5	1.3179	1.5183	177.0
		1.946	143.0	2.624	133.7	1.416	1.4584	173.3
F	<i>R,R,R</i>	2.401	89.6	2.307	169.4	1.288	1.5454	173.9
F	<i>R,R,S</i>	2.138	123.2	2.306	169.0	1.2628	1.5681	174.9
		2.499	89.2	2.302	171.1	1.2766	1.5550	175.7
		2.445	83.3	2.306	167.9	1.333	1.5122	174.8

Table 9. Electron density and laplacian of the secondary interactions found in the trimers studied at the MP2/6-311++G** level

X	Configuration	ρ	Lap	Atom involved	Interatomic distance
<i>Sulfoxides</i>					
Br	<i>R,R,R</i>	0.0022	0.0057	Br···Br ^a	4.477
Br	<i>R,R,S</i>	0.0024	0.0061	Br···Br	4.444
Cl	<i>R,R,R</i>	0.0022	0.0057	Cl···Cl ^a	4.246
Cl	<i>R,R,S</i>	0.0032	0.0093	Cl···Cl	4.105
<i>Thioperoxides</i>					
Br	<i>R,R,R</i>	0.0025	0.0068	Br···Br ^a	4.390
Br	<i>R,R,S</i>	0.0035	0.0101	Br···Br	4.191
Cl	<i>R,R,R</i>	0.0028	0.0081	Cl···Cl	4.073
Cl	<i>R,R,S</i>	0.0038	0.0119	Cl···Cl	3.910
<i>TS</i>					
Br	<i>R,R,R</i>	0.0034	0.0095	Br···Br ^a	4.215
Br	<i>R,R,S</i>	0.0036	0.0102	Br···Br	4.178
Cl	<i>R,R,R</i>	0.0035	0.0101	Cl···Cl ^a	3.969
Cl	<i>R,R,S</i>	0.0040	0.0123	Cl···Cl	4.909

^aThree identical interactions are obtained.

mer and the two with the same chirality in the heterochiral ones. The fluorine derivatives did not present additional interactions in any of the cases.

3.4. General discussion

The geometries of all the dimers and trimers (minima and TS) have been correlated on a single equation using the Steiner–Limbach relationships (Fig. 2). This correlation was based on the Pauling concept of the total valence of the hydrogen atom involved in the HB that should be equal to one (Eq. (8)).²⁸ The parameters r_{01} and r_{02} represent the bond distance for the isolated systems while b is an adjustable parameter that in general has an approximate value of 0.4. Eq. (8) can be rewritten as Eq. (9) and depends on the sum and difference of the O–H and S–H distances (r_1 and r_2 , Scheme 4). Figure 2 shows the mentioned correlation and how the points are grouped in the dimers of the thioperoxides (large negative values of ' $r_1 - r_2$ '), TS structures (values of ' $r_1 - r_2$ ' between -0.2 and 0.3), and dimers of the thioperoxides (large positive values of ' $r_1 - r_2$ ').

$$e^{(r_{01}-r_1)/b} + e^{(r_{02}-r_2)/b} = 1 \quad (8)$$

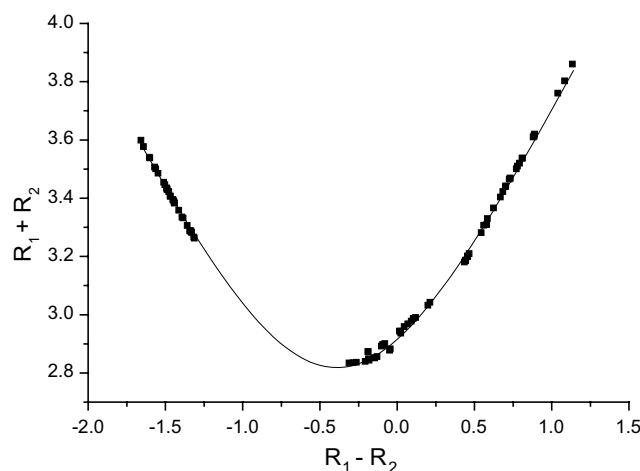
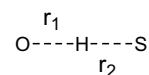


Figure 2. The fitted curve (Eq. (9)) provides the following values of the parameters: $r_{01} = 0.950 \pm 0.002$, $r_{02} = 1.342 \pm 0.002$, $b = 0.379 \pm 0.003$, $r^2 = 0.998$, $n = 88$.



Scheme 4. Definition of r_1 and r_2 .

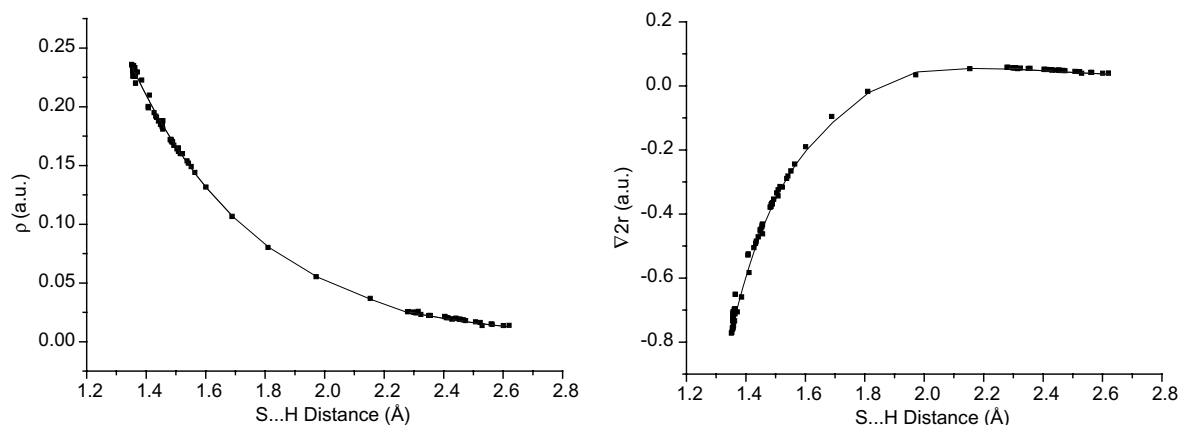


Figure 3. Electron density and Laplacian at the bcp of the S...H bonds and interactions found in the complexes studied here. The fitted curves correspond to the join function as described in Ref. 29.

$$(r_1 + r_2) = 2r_{02} + (r_1 - r_2) + 2b \ln(1 + e^{(r_{01} - r_{02} - r_1 + r_2)/b}) \quad (9)$$

In addition, the bcp (ρ and laplacian) obtained for all the S...H and O...H disposition found in the minima and TSs studied herein have been correlated versus the corresponding interatomic distances. In order, to fill the gaps and obtain a more uniform distribution of points, the reaction path of a given system (heterodimer X=F) with small steps of the O...H coordinate were calculated. The data corresponding to the stationary structures and those of the reaction coordinate, nicely overlap in all the regions considered (Fig. 3). Using all the data, excellent fits were found for the electron density and the laplacian versus the intermolecular distance using a method previously developed²⁹ that considered two different regions and a unique equation with a fitting function (see Fig. 3), which indicated the generality of these correlations.

4. Conclusions

A theoretical study of the homo and heterochiral dimers and trimers of sulfoxide and thioperoxide derivatives has been carried out using B3LYP/6-31+G** and MP2/6-311+G** computational levels. Furthermore the TSs connecting both families of compounds have been characterized. The energetic results show that the thioperoxide clusters are more stable than the corresponding sulfoxide ones in all the cases. The TS barriers have been found to correlate with the relative energy. The preference for the homo or the heterochiral cluster is variable and depends on the molecule under study in a complicated manner. The analysis of the electron density using the atoms in molecules has been used to check the existence of additional intermolecular contacts. The differences in relative energies are essentially of mesomeric origin while those in chiral discrimination appear to be related to steric effects. The geometries of the HB obtained in all the complexes studied here have been correlated in a unique Steiner–Limbach relationship.

The electron density and its Laplacian at the bond critical point have been correlated for the O...H and S...H bonds with their interatomic distances using a joint function to integrate in the same equation the covalent and HB contacts.

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