

Effect of Dimerization and Racemization Processes on the Electron Density and the Optical Rotatory Power of Hydrogen Peroxide Derivatives

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The variation of the electron density properties and optical rotatory power of the monomers and dimers of seven monosubstituted hydrogen peroxide derivatives, HOOX (X = CCH, CH₃, CF₃, *t*-Bu, CN, F, Cl), upon racemization has been studied using DFT (B3LYP/6-31+G**) and MP2 (MP2/6-311+G**) methods. The geometrical results have been rationalized on the basis of natural bond orbital (NBO) analysis. The atomic partition of the electron density properties within the atoms in molecules (AIM) methodology has allowed investigating the energy and charge redistribution in the different structures considered. The calculated optical rotatory power (ORP) of the dimers are, in general, twice of the values obtained for the monomers.

Introduction

The importance of chirality in natural and bio-organic processes can be illustrated with a few examples, such as the still unknown origin of homochirality in biological building blocks (amino acids and sugars),¹ the way different enantiomeric drugs interact with a target receptor, or the formation of a unique enantiomeric form of the desired molecule in organic synthesis.²

The atoms in molecules (AIM) methodology characterizes the topological properties of the electron density of a system and is able to define atomic regions known as atomic basins. The integration within the atomic basins provides atomic partitions of the molecular properties. The sum of those atomic contributions should be equal to the results obtained for the whole molecule. Recently, we have studied, using this methodology, the electron density modification and atomic energetic contributions in the protonation of a series of small molecules³ and the differences between the meso and chiral forms of oxirane and cyclobutene derivatives.⁴

The optical rotatory power has been, historically, an important property to measure the enantiomeric excess of a given compound and one of the simplest ways to determine the presence of chiral substrates. The influence of the solvent and complexation of chiral molecules has been explored experimental and theoretically. Thus, a study of the effect of the aggregation of pantolactone shows important differences between the rotatory power of the monomer and that of the dimers (several conformations).⁵ The calculations show that although the monomer presents an almost null optical rotatory power (-1°), the value of the dimer is very large (-200°). Other theoretical articles have reported important effects due to hydrogen bond complexation in the homo-dimers of three series of α -hydroxycarbonyl⁶ and different clusters of tetrahydroimidazo[4,5-*d*]imidazole.⁷

Hydrogen peroxide and its derivatives have been widely used as models to study chiral properties due to their small size, which makes them very adequate for theoretical studies. Thus, their

optical rotatory power (ORP) shows a very interesting dependence on the dihedral angle, providing both positive and negative values in the range $0-180^\circ$.⁸⁻¹⁰ The atomic partition of the ORP has been carried out using the acceleration gauge for the electric dipole and the torque formalisms.¹¹ The chiral discrimination of the dimers (homochiral vs heterochiral) has been studied for three derivatives (HOOX, X = H, CH₃ and CF₃).¹² The results were explained on the basis of the electron density and NBO analysis of the dimers. The inclusion of the solvent effect on the chiral discrimination of the dimers of hydrogen peroxide and its methyl derivatives showed that their relative stability can be reversed due to solvent effects.^{13,14}

In the present article, a detailed study of the atomic properties derived from the electron density has been carried out for the minimum and the enantiomerization TS structures of hydrogen peroxide derivatives monomers as well as dimers. The atomic contributions to the energy, total charge and volume of the systems have been compared. In addition, the optical rotatory power (ORP) of all the structures has been calculated.

Methods

The geometry of the monomers and dimers have been optimized at B3LYP/6-31+G**¹⁵⁻¹⁷ and MP2/6-311+G**^{18,19} with the Gaussian-03 program.²⁰ These computational levels have been proven to provide an adequate description of hydrogen bonded complexes.^{12,21} The minimum and TS nature of the structures has been established on the basis of the number of imaginary frequencies (zero for the minima and 1 for the TS) calculated at the same computational level used for the optimization.

The interaction energy has been calculated as the difference between the energy of the complexes and the isolated monomers. No basis-set superposition error (BSSE) correction has been considered because BSSE corrections may not always improve binding energies of hydrogen-bonded complexes. That is due to the fact that in the counterpoise method²² a monomer may use the valence and core functions of its partner, which are not available to the monomer in the complex. In addition, basis sets that include diffuse functions markedly reduce the effect of BSSE.

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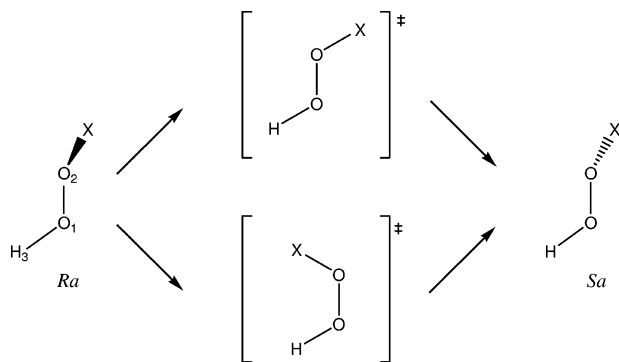


Figure 1. Two pathways for the conversion of the enantiomeric forms of the hydrogen peroxide derivatives. The atom numbering used along the text is shown

The interaction between occupied and empty orbitals has been determined with the natural bond orbital (NBO) method²³ at the B3LYP/6-31+G** computational level. The atom in molecules (AIM) methodology provides a tool for the topological analysis of the electron density.²⁴ Within this methodology, the bond path is the line of maximal electron density linking the nuclei of any two chemically bonded atoms. The bond critical point, bcp, corresponds to the minimum electron density value along the bond path. The atomic basin, or space occupied by an atom corresponds to the region of space defined by the gradient paths of the charge density which terminate at each nucleus in a molecule.

The integration within the atomic basins provides the atomic contributions. In the present study, we have focused on the energy, charge and volume. The sum of all the atomic contributions within a given system should be equal to that of the whole system.

We have used the programs AIMPAC²⁵ and MORPHY98²⁶ for the AIM analysis. The quality of the atomic integration has been estimated on the basis of the value of the integrated Laplacian. Ideally, the integrated Laplacian within the atomic basins should be equal to zero. Values of the integrated Laplacian smaller than 1.0×10^{-3} in all the atoms of a molecule have been shown to provide small errors in the total energy and charge of the molecule.³ In the present case, the average error of the absolute value of the total energy is 0.37 and 1.08 kJ/mol the maximum value. With respect to the integrated charge, the average error of the absolute value is 0.0007 e and the maximum value being 0.002 e.

ORP has been calculated at the B3LYP/6-311++G(2d,2p) level using the MP2/6-311+G** optimized geometries. This level of calculation has been considered as the minimum adequate to obtain reliable results.^{27–29}

Results and Discussion

Monomers. Two possible transition state (TS) pathways are responsible for the conversion of the two enantiomers of these compounds (Figure 1). The energy results of the barrier for the two TS have been reported in Table 1. In all the cases, the *trans*-TS shows a smaller barrier than the *cis* one, except for the fluorine derivative where the opposite happened at the B3LYP/6-31+G** level. It is interesting to notice that the *trans*-TS barriers are small (between 1.7 and 7.8 kJ/mol) for all the derivatives but the halogen ones where the barrier are 38.2 and 14.3 kJ/mol for the fluorine and chlorine derivatives at the MP2/6-311+G** level, respectively. The inclusion of the ZPE correction to evaluate the enthalpy shows negative values for some of the *trans*-TS, an indication of barrierless processes. In

TABLE 1: Energy and Enthalpy of the Racemization Barriers (kJ/mol)

		B3LYP/6-31+G**		MP2/6-311+G**	
		ΔE	ΔH	ΔE	ΔH
HOOH	<i>trans</i>	3.35	0.68	4.07	1.11
	<i>cis</i>	36.04	32.77	32.52	34.10
HOOCCH	<i>trans</i>	0.99	-1.48	2.22	-0.37
	<i>cis</i>	15.00	12.37	17.01	14.20
HOOCCH ₃	<i>trans</i>	0.68	-1.64	1.66	-0.95
	<i>cis</i>	28.62	25.57	31.62	28.25
HOOCF ₃	<i>trans</i>	6.84	4.31	7.76	4.98
	<i>cis</i>	27.56	24.72	32.04	29.05
HOO- <i>t</i> -Bu	<i>trans</i>	2.43	0.09	2.64	0.13
	<i>cis</i>	31.42	28.43	33.22	30.19
HOOCN	<i>trans</i>	1.88	-0.59	2.93	0.34
	<i>cis</i>	19.63	16.83	22.66	19.83
HOOF	<i>trans</i>	43.79	40.47	38.23	34.90
	<i>cis</i>	41.15	37.53	40.13	36.53
HOOCI	<i>trans</i>	20.75	17.88	14.43	11.45
	<i>cis</i>	33.51	30.41	31.92	28.62

TABLE 2: NBO Calculated Orbital Interaction between the Lone Pair of O1 and the O2–X Antibonding Orbital (kJ/mol)

system	minimum	TS- <i>trans</i>	TS- <i>cis</i>
HOOH	4.06	0.13	5.61
HOOCCH	3.18	3.72	11.51
HOOCCH ₃	3.64	2.47	17.49
HOOCF ₃	6.49	0.29	7.70
HOO- <i>t</i> -Bu	3.56	1.46	10.67
HOOCN	2.97	2.01	10.00
HOOF	110.00	4.06	15.90
HOOCI	54.43	0.00	17.49

general, due to the large difference between the *cis*- and *trans*-TS, only the latter will be studied in detail.

In the TS barriers, the different behavior observed for the halogen substituted derivatives can be explained on the basis of the orbital interaction between one of the lone pairs of the O1 and the antibonding C–X orbital for these derivatives (110.0 and 54.4 kJ/mol for X = F and Cl, respectively) as shown in Table 2. This interaction is similar to the one observed in the anomeric effect. In the rest of the derivatives, the interaction ranges between 3.0 and 6.5 kJ/mol. This orbital interaction is very small in the TS structures, especially in the *trans*-TS where the approximate angle between the two involved orbital is 120° whereas in the *cis*-TS their angle is approximately 60°.

Some of the geometrical parameters of the minimum and TS structures of the monomers are reported in Table 3. For each compound, the shorter O–O distance corresponds to the minimum, followed by the *cis*-TS and the longest one corresponds to the *trans*-TS, the only exception being the *cis*-TS structure of the ethynyl derivative at B3LYP/6-31+G** level that shows a O–O distance slightly shorter than the corresponding one in the minimum. The largest differences in this parameter are observed in the halogen derivatives, where an important orbital interaction between the lone pairs of the halogen and the antibonding O–O orbital are found in the NBO analysis. The larger energetic values for this orbital interaction correspond to the *trans*-TS (25.4, 26.1 kJ/mol for the F and Cl derivatives, respectively), followed by the *cis*-TS (21.4, 23.1 kJ/mol) and the smallest to the minimum structure (18.2, 19.5 kJ/mol), which is in agreement with the obtained O–O bond distances.

The dihedral HOOX angle of the minimum structures is clearly smaller for the F and Cl derivatives due to an attempt of these molecules to maximize the orbital interaction between

TABLE 3: Selected Geometrical Parameters (Å, deg) for the Minimum and TS Structures

	B3LYP/6-31+G**				MP2/6-311+G**			
	O–O distance	minimum HOOX angle	TS-trans O–O distance	TS-cis O–O distance	O–O distance	minimum HOOX angle	TS-trans O–O distance	TS-cis O–O distance
HOOH	1.457	119.4	1.467	1.465	1.450	121.6	1.460	1.459
HOOCCCH	1.507	121.9	1.515	1.506	1.479	123.2	1.487	1.484
HOOCH ₃	1.462	128.7	1.469	1.464	1.455	132.6	1.461	1.456
HOOCF ₃	1.448	105.9	1.462	1.458	1.440	107.9	1.454	1.449
HOO- <i>t</i> -Bu	1.462	120.0	1.474	1.468	1.458	121.0	1.469	1.462
HOOCN	1.487	119.8	1.494	1.490	1.467	122.9	1.474	1.473
HOOF	1.367	84.2	1.450	1.438	1.361	84.7	1.442	1.430
HOOCI	1.410	90.0	1.473	1.461	1.417	92.7	1.469	1.457

TABLE 4: Atomic and Group Contributions to the Total Energy and Charge Calculated with the AIM Methodology at the B3LYP/6-31+G Level^a**

	HOOH	HOOCCCH	HOOCH ₃	HOOCF ₃	HOO- <i>t</i> -Bu	HOOF	HOOCI	HOOCN
Energy								
O1	-11.0	-5.0	-7.0	-14.2	-14.7	-8.8	-13.0	-7.2
O2	-11.0	-20.0	-20.9	-48.5	-32.8	20.0	-118.0	-23.5
H3	12.6	1.8	6.1	11.8	12.0	13.8	12.7	4.3
X	12.6	24.2	22.0	57.4	38.6	19.0	138.6	27.9
Charge								
O1	-0.007	-0.004	-0.006	-0.009	-0.011	-0.059	-0.044	-0.004
O2	-0.007	-0.009	-0.007	-0.025	-0.016	-0.012	-0.071	-0.011
H3	0.007	0.000	0.003	0.007	0.007	0.003	0.005	0.002
X	0.007	0.013	0.011	0.027	0.020	0.067	0.108	0.013

^a Negative values indicate that the corresponding atom is more stable in the TS structure than in the minimum (energy) and increase its charge density (charge).

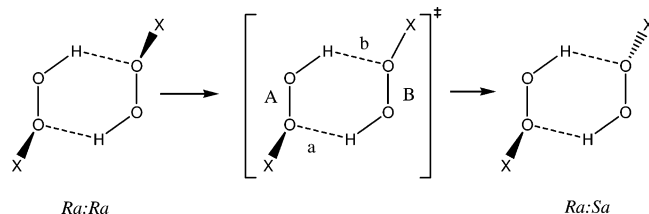
the lone pair of O1 and the antibonding O2–X orbital, previously described in the NBO analysis.

Even though the overall energy differences between the minimum and the *trans*-TS are small, a significant redistribution of the atomic energy contribution takes place as shown in the AIM analysis reported in Table 4. The atomic contribution variations, in absolute value, are as large as 139 kJ/mol. The compensation of the atomic energy gain and loss in each molecule indicates how the systems try to minimize the effect due to a geometrical distortion as the TS.

The oxygen atoms become more stable in the TS due to the energy loss of the H and the X moieties, except for the O2 of the fluorine derivative. The gain of the O2 is larger than that of O1, in the same way the groups attached to them present the largest loss for X and more moderate for H3. The O1–H3 moiety shows a small energetic gain in the TS, except for the HOOH and HOOF molecules, whereas O2–X presents a loss in all the cases.

Regarding the charge variation, the oxygen atoms increase their charge density in the TS with respect to the one in the monomers, this effect being larger for the O2 than for the O1, with the exception of the fluorine derivative. The opposite happens for the H3 and the X groups that lose energy density in the TS. Excluding the halogen derivatives, good linear correlation can be found between the atomic charge and energy variation for each atomic position. A similar correlation was found in the case of tetrahydroimidazo[4,5-*d*]imidazole.⁷

Dimers. In the case of the dimers, only those with two HBs, where each molecule acts as HB acceptor and HB donor in different centers, have been considered because previous studies have shown that they correspond to the most stable configurations.^{12–14} Thus, two configurations have been taken into account, those corresponding to the homochiral (*Ra:Ra*) and heterochiral (*Ra:Sa*) dimers (Figure 2). The symmetry of these complexes has been found to be *C*₂ and *C*_i for the homo- and heterochiral cases, respectively. The conversion of the homochiral to the heterochiral dimer occurs through a TS where one of the dimers adopts

**Figure 2.** Schematic representation of the dimers and TS considered.

a pseudoplanar *trans* disposition (Figure 2). The dimers of the fluorine derivative have not been considered in this section because their minimum structure is formed by two OH:F hydrogen bonds.

The geometrical parameters of the HB formed in the dimers have been reported in Table 5. Small differences are found in the HB distance between the homo- and heterochiral dimers of the same compound. Regarding the HB distance in the TS, it is expected that the HB denoted as “b” in Figure 2 should present longer distances than that indicated as “a” because in the former case the hydrogen atom is not pointing toward the lone pair of the oxygen. Several exceptions (X = CCH and Cl at both levels, and CF₃ at MP2 only) are observed due to a significant distortion of the general structure of the dimers in the TS that complicate the simplified picture shown before.

The energy differences between the dimers (*E*_{rel}) as well as the transition states (ΔE) have been reported in Table 6 ($E_{rel} = E_i(RR) - E_i(RS) = \Delta E(RR) - \Delta E(RS)$). The interaction energy ranges between 56.7 and 15.4 kJ/mol at the MP2/6-311+G** computational level, being the strongest complexes at both levels those of the *tert*-butyl derivatives and the weakest ones, the cyano derivatives. In three cases, the heterochiral complexes are more stable than the homochiral ones (X = H, CH₃ and *t*-Bu) and in four cases the opposite happens (X = CCH, CF₃, CN and Cl), the results of both methods being consistent. It looks like the local dipole interaction of the X's group is important, because when the dipole is expected to be small, saturated hydrocarbons and H, the favored dimer is the

TABLE 5: Geometrical Parameters (Å, deg) of the Dimers (Minima and TS)

B3LYP/6-31+G**	RR		RS		TS-a		TS-b	
	H...O	OH...O	H...O	OH...O	H...O	OH...O	H...O	OH...O
(HOOH) ₂	1.918	154.4	1.916	155.1	1.925	152.4	1.960	149.5
(HOOCCH) ₂	2.046	150.8	2.058	152.5	2.077	147.7	2.062	148.1
(HOOCCH ₃) ₂	1.905	156.8	1.902	156.8	1.905	156.2	1.951	152.2
(HOOCF ₃) ₂	2.078	144.1	2.100	145.5	2.056	146.6	2.089	142.7
(HOO- <i>t</i> -Bu) ₂	1.906	157.6	1.897	158.1	1.889	158.8	1.937	154.3
(HOOCN) ₂	2.174	141.5	2.190	143.6	2.131	146.7	2.191	141.7
(HOOCI) ₂	2.014	146.7	2.048	146.2	2.153	136.5	1.997	145.3

MP2/6-311+G**	RR		RS		TS-a		TS-b	
	H...O	OH...O	H...O	OH...O	H...O	OH...O	H...O	OH...O
(HOOH) ₂	1.929	153.6	1.935	154.5	1.949	148.3	1.959	148.3
(HOOCCH) ₂	2.021	150.8	2.040	151.0	2.055	145.4	2.023	146.7
(HOOCCH ₃) ₂	1.888	156.8	1.876	156.6	1.885	153.3	1.927	149.7
(HOOCF ₃) ₂	2.062	141.6	2.077	144.0	2.334	120.3	1.981	150.0
(HOO- <i>t</i> -Bu) ₂	1.865	157.1	1.867	155.5	1.853	155.8	1.898	151.1
(HOOCN) ₂	2.152	138.9	2.162	143.1	2.121	146.7	2.149	146.7
(HOOCI) ₂	1.951	147.0	2.013	145.2	2.094	134.7	1.949	143.4

TABLE 6: Interaction Energy (kJ/mol) of the Energy, RR vs RS and TS

		B3LYP				MP2			
		<i>E_i</i>	<i>E_{rel}</i>	Δ <i>E</i>	Δ <i>H</i>	<i>E_i</i>	<i>E_{rel}</i>	Δ <i>E</i>	Δ <i>H</i>
		(HOOH) ₂	RR	35.87		4.34	1.28	38.35	
(HOOH) ₂	RS	37.59	-1.72	6.07	2.78	39.14	-0.79	4.79	1.41
(HOOCCH) ₂	RR	20.39		1.65	-1.00	28.93		3.21	0.89
(HOOCCH) ₂	RS	19.55	0.84	0.81	-1.74	27.36	1.57	1.64	-1.13
(HOOCCH ₃) ₂	RR	35.03		2.13	-0.51	42.50		2.19	-0.58
(HOOCCH ₃) ₂	RS	37.11	-2.08	4.21	1.48	44.02	-1.51	3.70	0.83
(HOOCF ₃) ₂	RR	20.02		6.81	3.90	34.35		12.51	6.71
(HOOCF ₃) ₂	RS	18.38	1.64	5.17	2.32	29.41	4.94	7.56	2.00
(HOO- <i>t</i> -Bu) ₂	RR	34.44		1.53	-1.02	51.39		0.42	
(HOO- <i>t</i> -Bu) ₂	RS	38.30	-3.87	5.39	2.67	56.67	-5.28	5.69	
(HOOCN) ₂	RR	9.07		1.78	-0.77	17.00		3.21	0.47
(HOOCN) ₂	RS	8.15	0.91	0.86	-1.61	15.43	1.57	1.64	-0.87
(HOOCI) ₂	RR	23.94		21.81	18.37	38.09		16.06	12.64
(HOOCI) ₂	RS	23.14	0.80	21.00	17.46	34.52	3.57	12.49	8.99

TABLE 7: Atomic Energy Variation (kJ/mol) between the Monomers and the Homochiral Dimers^a

	HOOH	HOOCCH	HOOCCH ₃	HOOCF ₃	HOO- <i>t</i> -Bu	HOOCI	HOOCN
O1	-30.17	-14.11	-30.61	-12.66	-34.70	-20.59	-2.52
O2	-63.72	-14.81	-28.48	-16.93	-44.44	-44.79	-21.84
H3	55.19	31.60	51.83	30.76	62.66	37.98	20.66
X	19.84	-11.96	-11.65	-10.60	-0.75	15.78	-0.93

^a Negative values indicate that the corresponding atom is more stable in the dimer than in the monomer.

heterochiral whereas large local dipoles favor the homochiral dimer. It is significant that the shorter HB distances for each pair correspond with the most stable dimer at the B3LYP level. The effect of X on the *E_{rel}* and Δ*E* values (kJ/mol) seems to be dependent on its electronic properties. For instance, using Hammett's σ_m , the following equations are obtained:

$$E_i(RR) = (33 \pm 2) - (36 \pm 6)\sigma_m \quad n = 7, r^2 = 0.87$$

$$E_{rel} = -(1.9 \pm 0.5) + (7.0 \pm 1.6)\sigma_m \quad n = 7, r^2 = 0.80$$

Note that the barrier decreases while the difference in energy increases with σ_m .

The values of the TS barrier for the homochiral dimers do not change significantly from those obtained in the *trans*-TS of the monomers, the largest difference being only 1 kJ/mol. Thus, even though the HB in the TS cannot adopt an optimal disposition, the systems are able to minimize the penalty due to the rotation of the dihedral angle of one of the monomers.

The variation of the atomic contribution to the total energy from the monomers to the complexes (Table 7), between the

homo- and heterochiral dimers (Table 8) and between the homochiral dimer and the TS structures (Table 9) has been analyzed.

The energy gain due to the formation of the double HB within the dimers (Table 7) is reflected by an increment of the atomic energy of the two oxygen atoms and a loss of the hydrogen atom involved in the HB. These results are in agreement with the properties defined by Popelier as characteristic of HB systems.³⁰ In all the cases, save in the chloro and unsubstituted derivatives, a stabilization of the X group is observed. The hydrogen bond donor group (O1-H3) always loses energy whereas the hydrogen bond acceptor group (O2-X) gains it.

The atomic energy differences between the homochiral and heterochiral dimers (Table 8) show that in all the cases the hydrogen bond acceptor group (O2+X) favored the homochiral dimers and the H3 the heterochiral dimer. Thus, the three cases with the most negative values of the proton donor group (O1+H3) are the ones where the heterochiral dimer is more stable than the homochiral one.

TABLE 8: Atomic Energy Differences (kJ/mol) between the Homochiral and Heterochiral Dimers^a

	HOOH	HOOCCH	HOOCCH ₃	HOOCF ₃	HOO- <i>t</i> -Bu	HOOCI	HOOCN
O1	-4.25	-0.61	-0.98	1.46	-5.57	0.20	-1.30
O2	1.42	-1.57	9.05	4.23	17.62	2.41	4.75
H3	-1.08	-0.43	-2.65	-0.87	-4.63	-1.27	-1.44
X	2.97	3.25	-6.21	-4.09	-9.30	-1.29	-1.58

^a Negative values indicate that the corresponding atom is more stable in the heterochiral dimer than in the homochiral one.

TABLE 9: Energetic Variation (kJ/mol) of the Two Molecules Involved in the TS with Respect to Their Corresponding Energies in the Homochiral Dimer

	HOOH	HOOCCH	HOOCCH ₃	HOOCF ₃	HOO- <i>t</i> -Bu	HOOCI	HOOCN
molecule A	7.98	5.11	2.36	-4.65	0.70	-17.55	1.99
molecule B	-3.43	-3.72	-0.57	11.69	0.32	39.33	-0.34

TABLE 10: Optical Rotatory Power (deg) of *Ra* Monomers and Homodimers

monomers	minimum		TS	
	$\alpha_{D(0)}$	α_D	$\alpha_{D(0)}$	α_D
HOOH	-106.09	-138.63	113.60	101.06
HOOCCH	293.93	303.72	220.92	243.72
HOOCCH ₃	106.57	106.64	203.06	214.32
HOOCF ₃	53.4	55.49	87.32	92.30
HOO- <i>t</i> -Bu	58.59	57.03	118.63	127.16
HOOCN	228.74	246.41	145.93	161.15
HOOCI	173.28	210.17	240.23	286.72
HOOF	204.26	237.57		

dimers	minimum		TS	
	$\alpha_{D(0)}$	α_D	$\alpha_{D(0)}$	α_D
(HOOH) ₂	70.16	59.47	113.60	101.06
(HOOCCH) ₂	487.03	560.09	220.92	243.72
(HOOCCH ₃) ₂	210.55	218.36	203.06	214.32
(HOOCF ₃) ₂	99.77	106.04	87.32	92.30
(HOO- <i>t</i> -Bu) ₂	127.62	135.81	118.63	127.16
(HOOCN) ₂	384.55	427.56	145.93	161.15
(HOOCI) ₂	393.32	496.32	240.23	286.72

The analysis of the atomic energies in the TS shows, surprisingly, that in most cases the molecule that is supposedly responsible of the TS (B, in Figure 2) is more stable than that in the homochiral minimum (Table 9), whereas the opposite happens with molecule A. However, an inspection of the charges obtained for those molecules indicate that in those cases where molecule B is more stable than molecule A, the former one became negatively charged and the latter positively. In a previous article, it was shown a clear relationship between the electronic gain and the energetic stabilization of the atoms.⁷

Optical Rotatory Power. The calculated ORP of the monomers and dimers in their minimum and TS structures are reported in Table 10. The corresponding values of the TS of the monomers and the heterochiral dimers are zero due to their symmetry. The ORP value of the unsubstituted monomer is the only case where it is negative whereas the obtained ORPs for the substituted monomers range between 58 and 293°. The known dependence of the ORP with the dihedral angle in the isolated hydrogen peroxide is not able to explain the variation found here because four of cases present a dihedral angle of approximately 122° (X = H, CCH, *t*-Bu and CN) and their ORPs cover the whole range of the cases studied here.

The value of the dimers is, in all the cases positive, being, for the substituted derivatives, approximately, twice the one obtained for the monomers. Thus, in contrast to other cases, where the HB formation has important effects, here this effect is only observed in the unsubstituted case.

The TS structures of the unsubstituted dimer present a ORP twice of the corresponding homodimer, whereas in the substi-

tuted dimer TS, three cases present similar ORP to the dimer minima (X = CH₃, CF₃ and *t*-Bu) and three cases where it is similar to that of the monomer, that is, half of the dimer (X = CCH, CN and Cl).

Conclusion

The racemization processes in the monomers and dimers of hydrogen peroxide derivatives have been studied using DFT, B3LYP/6-31+G**, and ab initio MP2/6-311+G** methods. The two possible TS, cis and trans, that allow the racemization of the monomers have been considered. In all cases, the *trans*-TS shows smaller energetic barriers with values that range between 1.7 and 7.8 kJ/mol except for the halogen derivatives where the values are 38.2 and 14.3 kJ/mol for the fluorine and chlorine cases, respectively.

Some of the geometrical features found have been explained on the basis of the orbital interactions found in the NBO analysis.

The AIM analysis of the atomic properties has proven to be a good tool to study the energetic and electronic redistribution when the minimum and TS structures are compared. Thus, the oxygen atoms become more stable in the TS whereas the rest of the molecule overcomes this effect.

In the dimers studied, three cases show a preference for the heterochiral complex whereas in four cases the homochiral is preferred. The AIM analysis shows that the stabilization due to the dimer formation came mostly from the oxygen atoms whereas the hydrogen atom involved in the HB is destabilized. The TS barriers of the isomerization within the dimers are similar to the ones obtained for the corresponding monomers.

The optical rotatory calculations results show that the values of the homochiral dimers are, in all the substituted derivatives, approximately twice the value of the monomers.

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Supporting Information Available: Coordinates of the minima and TSs calculated at the B3LYP/6-31+G** computational level. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References and Notes

- (1) *Science* **2005**, *309*, 86.
- (2) Avalos, M.; Babiano, R.; Cintas, P.; Jimenez, J. L.; Palacios, J. C.; Barron, L. D. *Chem. Rev.* **1998**, *98*, 2391.
- (3) Alkorta, I.; Picazo, O. *Arkivoc* **2005**, *ix*, 305.

- (4) Alkorta, I.; Elguero, J. *Chem. Phys. Lett.* **2006**, *417*, 367.
- (5) Goldsmith, M. R.; Jayasuriya, N.; Beratan, D. N.; Wipf, P. *J. Am. Chem. Soc.* **2003**, *125*, 15696.
- (6) Alkorta, I.; Picazo, O.; Elguero, J. *J. Phys. Chem. A* **2005**, *109*, 3262.
- (7) Alkorta, I.; Picazo, O.; Elguero, J. *J. Phys. Chem. A* **2006**, *110*, 2259.
- (8) Ruud, K.; Helgaker, T. *Chem. Phys. Lett.* **2002**, *352*, 533.
- (9) Polavarapu, P. L.; Chakraborty, D. K.; Ruud, K. *Chem. Phys. Lett.* **2000**, *319*, 595.
- (10) Surjan, P. R.; Kertesz, M. *Theor. Chim. Acta* **1980**, *55*, 103.
- (11) Ligabue, A.; Lazzeretti, P.; Varela, M. P. B.; Ferraro, M. B. *J. Chem. Phys.* **2002**, *116*, 6427.
- (12) Alkorta, I.; Elguero, J. *J. Chem. Phys.* **2002**, *117*, 6463.
- (13) Du, D. M.; Fu, A. P.; Zhou, Z. Y. *Chem. Phys. Lett.* **2004**, *392*, 162.
- (14) Du, D.; Zhou, Z. *Int. J. Quantum. Chem.* **2005**, *106*, 935.
- (15) Becke, A. D.; Edgecombe, K. E. *J. Chem. Phys.* **1990**, *92*, 5397.
- (16) Lee, C. T.; Yang, W. T.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785.
- (17) Harihar, P.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213.
- (18) Møller, C.; Plesset, M. S. *Phys. Rev.* **1934**, *46*, 618.
- (19) Frisch, M. J.; Pople, J. A.; Binkley, J. S. *J. Chem. Phys.* **1984**, *80*, 3265.
- (20) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. *Gaussian-03*, revision C.02; Gaussian, Inc.: Wallingford, CT, 2003.
- (21) Sanchez, M.; Provasi, P. F.; Aucar, G. A.; Alkorta, I.; Elguero, J. *J. Phys. Chem. B* **2005**, *109*, 18189.
- (22) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, *19*, 553.
- (23) Reed, A. E.; Curtiss, L. A.; Weinhold, F. *Chem. Rev.* **1988**, *88*, 899.
- (24) Matta, C. F.; Hernandez-Trujillo, J.; Tang, T. H.; Bader, R. F. W. *Chem-Eur. J.* **2003**, *9*, 1940.
- (25) Bieglerkonig, F. W.; Bader, R. F. W.; Tang, T. H. *J. Comput. Chem.* **1982**, *3*, 317.
- (26) Popelier, P. L. A. with a contribution from R. G. A. Bone (UMIST, England, EU) MORPHY98, a topological analysis program, 0.2 ed., 1999.
- (27) Cheeseman, J. R.; Frisch, M. J.; Devlin, F. J.; Stephens, P. J. *J. Phys. Chem. A* **2000**, *104*, 1039.
- (28) Stephens, P. J.; Devlin, F. J.; Cheeseman, J. R.; Frisch, M. J. *J. Phys. Chem. A* **2001**, *105*, 5356.
- (29) Ruud, K.; Stephens, P. J.; Devlin, F. J.; Taylor, P. R.; Cheeseman, J. R.; Frisch, M. J. *Chem. Phys. Lett.* **2003**, *373*, 606.
- (30) Koch, U.; Popelier, P. L. A. *J. Phys. Chem.* **1995**, *99*, 9747.