Ab initio molecular orbital study on reactivity of phenol, biphenyl, benzoate and *p*-hydroxybenzoate in the ˙OH addition reaction and stability of the corresponding ˙H and ˙OH cyclohexadienyl adducts

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The reactivity of phenol, biphenyl, benzoate and *p*-hydroxybenzoate towards ˙OH addition and the relative stability of the corresponding ˙H and ˙OH cyclohexadienyl adducts have been studied using *ab initio* molecular orbital calculations. The compounds studied were optimized at the R(O)HF/6-31G* level. The SCRF method has been used to model solvent effects. The HOMO orbital coefficients were found to explain the observed isomeric distributions in the earlier radiolytic hydroxylation studies. The stabilization energies of the cyclohexadienyl radicals as investigated using the isodesmic reaction were found to be qualitatively different at the ROHF/6-31G*//6-31G* and ROMP2/6-31G*//6-31G* levels. The ROMP2/6-31G*//6-31G* energies revealed that the OH group stabilized most *ortho* and phenyl group *para* isomers of the cyclohexadienyl radicals.

˙OH radicals react with substituted benzenes to yield hydroxylated aromatic ring products. In the aromatic hydroxylation of substituted benzenes ˙OH adds to the aromatic ring to form hydroxycyclohexadienyl radicals. These intermediates are either oxidized to hydroxylated products or undergo various uni- and bi-molecular reactions.[1–7] Owing to complex reactions of hydroxycyclohexadienyl radicals the information on the reactivity of different positions of the aromatic ring is partly lost. However, reactivity patterns of aromatic rings towards ˙OH are retained in studies where oxidants like quinones and ferricyanides are used to oxidize rapidly the hydroxycyclohexadienyl radical to aromatic species.[8,9] The radiolytic generation of ˙OH has been employed in several hyroxylation studies.[6,8,10–14] The hydroxylation reaction is important from the biological point of view. Several oxygenases contain copper or iron ions in their active-site and metal–oxygen systems are the active species in these enzymes.[15] Hydroxylation of *p*-hydroxybenzoate (*p*-OHB) catalysed by *p*-hydroxybenzoate hydroxylase, which is a flavin-containing monooxygenase, presumably proceeds through a hydroxycyclohexadienyl radical intermediate.[16,17] In this reaction the substrate is hydroxylated to the *ortho* position and the ˙OH radical comes from the homolytic cleavage of the O–O bond of flavin C(4)hydroperoxide. Furthermore, free radicals are responsible for a wide variety of cellular damage in biological systems. The ˙OH radical, which is the most reactive oxygen-centred radical, damages DNA by forming ˙OH adducts with DNA bases.[18–20]

To elucidate the general features of the hydroxylation reactions we have examined the hydroxylation of phenol, biphenyl, benzoate and *p*-OHB by ˙OH with *ab initio* quantum mechanical calculations. The product distributions of earlier experimental radiolytic hydroxylation studies[2,8,9] are compared with the calculated properties of the compounds in order to elucidate the reactivity of the compounds. In addition, we have investigated the energetics of isodesmic reactions generated for different isomeric cyclohexadienyl and hydroxycyclohexadienyl radicals of phenol, biphenyl, benzoate and *p*-OHB. The comparison of the thermodynamic stabilities of the hydroxycyclohexadienyl radicals is important when various fates of the intermediates are considered.

Computational methods

The *ab initio* molecular orbital calculations were performed using GAUSSIAN 92.[21] The restricted Hartree–Fock (RHF) method was employed for singlet and restricted open-shell Hartree–Fock (ROHF) method for doublet species. However, owing to the inability of the ROHF method to describe the ˙OH addition reaction the unrestricted Hartree–Fock (UHF) method was used to calculate reaction profiles for the addition of ˙OH to benzene, phenol and benzoate.[22] The large spin contamination (S^2 = 0.9–1.4) of UHF wavefunctions was projected out of the MP energies (PMP) by the spin-projection method.[23] Solvent effects on molecular properties of phenol, benzoate and *p*-OHB were taken into account by using the self-consistent reaction-field (SCRF)[24–28] method as implemented in GAUSSIAN 92. The SCRF method is based on Onsanger's reaction field theory of the electrostatic solute–solvent interaction in which the charge distribution of the solute is revealed by its dipole moment.[29] The SCRF calculations reported in this paper were carried out using a value of 78.5 for the relative permittivity (ε = 78.5 for water). The cavity radius (a_0) was calculated from the electron density individually for each of the molecules as implemented in GAUSSIAN 92. The geometries for all the compounds were optimized using the 6-31G* basis set.

Results and discussion

Geometry of the hydroxycyclohexadienyl radical

The ROHF/6-31G* and UHF/6-31G* optimized parameters for the hydroxycyclohexadienyl radical are presented in Table 1 and the total and relative energies of the substituted cyclohexadienyl radicals studied in Table 2. Numbering of the hydroxycyclohexadienyl radical is shown in Fig. 1. The hydroxycyclohexadienyl radicals optimized to C_s symmetry with an almost planar cyclohexadienyl ring (deviations from planarity are 0.5–1.1°). The geometries are similar at the ROHF/6-31G* and UHF/6-31G* level except the C_2–C_3 (C_5–C_6) and C_3–C_4 (C_4–C_5) distances. The C_2–C_3 bond is shorter by 0.018 Å and C_3–C_4 longer by 0.017 Å at the ROHF/6-31G* level than at the UHF/6-31G* level. This is a consequence of the spin contamination of the UHF wavefunction which results in promotion of some electron density to the lowest unoccupied molecular orbital (LUMO) with antibonding C_2–C_3 (C_5–C_6) character (Fig. 2).[30]

Reactivities of the molecules

The reactivities of phenol, biphenyl, benzoate and *p*-OHB towards hydroxylation by ˙OH are interpreted using the arguments of the qualitative frontier molecular orbital (FMO) theory.[31–33] The FMO theory should be useful in predicting radical hydroxylation reactions because free radicals have large orbital interactions[31] and thus undergo orbital controlled reactions,[34] and because the hydroxylation is fast ($k = 10^9$–10^{10} dm^{-3} mol^{-1} s^{-1}) irreversible diffusion-controlled reaction.[2,8] In addition, the hydroxylation involves an early transition state as was shown by the *ab initio* molecular orbital calculations on the hydroxylation of substituted ethenes.[35] The reaction profiles calculated for the addition of ˙OH to benzene at various computational levels are shown in Fig. 3. The structure of the ˙OH–benzene complex when the intermolecular distance O_1–C_1 is 1.9 Å is presented in Fig. 1 and selected optimized parameters are given in Table 1. The addition reaction is exothermic in the gas phase by −63.6 kJ mol^{-1} at the PMP2/6-31G*//UHF/6-31G* level and −71.1 kJ mol^{-1} at the PMP3/6-31G*//UHF/6-31G* level. The profiles with full spin annihilation at the PMP2/6-31G*//UHF/6-31G* and PMP3/6-31G*//UHF/6-31G* levels show a small energy barrier for the addition with the O_1–C_1 distance in the transition state at 2.0–2.1 Å. At the PMP2/6-31G*//UHF/6-31G* level when only the quartet spin contaminant has been projected out (PMP2′/6-31G*//UHF/6-31G* in Fig. 3) the barrier is missing. This shows that higher contaminants have large effects on energies of highly contaminated wavefunctions. The calculations revealed that the addition to benzene occurs in C_s symmetry. When the O_1–C_1 distance is 1.9 Å, the angle O_1–C_1–C_4 is 109.3°. This is close to 106.0° for the angle O–C–C at the UHF/6-31G* transition state for the addition of ˙OH to ethene.[35] The transition state for the addition of ˙OH to ethene was at the O_1–C_1 distance 2.1 Å on the spin-projected PMP4/6-31G*//UHF/6-31G* reaction profile.[35] More about the behaviour of different levels of *ab initio* theory for radical reactions can be found from refs. 22, 35–37.

Table 1 ROHF/6-31G* and UHF/6-31G* optimized parameters for hydroxycyclohexadienyl and UHF/6-31G* parameters for the ˙OH–benzene complex at O_1–C_1 = 1.9 Å[a,b]

	ROHF/6-31G*	UHF/6-31G*	UHF/6-31G*
C_1–C_2	1.506	1.507	1.434
C_2–C_3	1.335	1.373	1.390
C_3–C_4	1.435	1.419	1.407
O_1–C_1	1.414	1.415	1.9
H_7–O_1	0.948	0.949	0.955
H_1–C_1	1.086	1.086	1.072
C_1–C_2–C_3	123.07	122.70	120.48
C_2–C_3–C_4	121.25	121.11	120.40
C_3–C_4–C_5	118.85	119.85	119.94
C_6–C_1–C_2	112.46	112.49	117.64
O_1–C_1–C_4	131.66	132.18	109.33
H_7–O_1–C_1	108.44	108.53	98.85
H_1–C_1–C_4	124.76	124.37	161.91

[a] Bond lengths in Å and angles in °. [b] Complex is shown in Fig. 1.

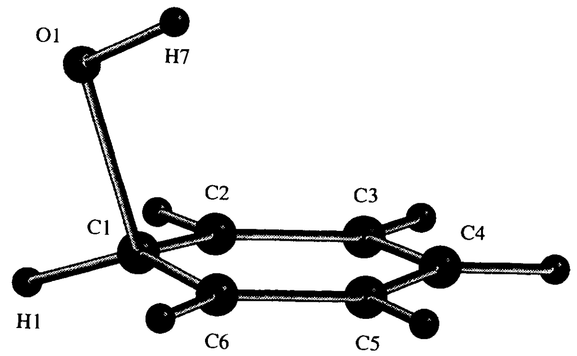


Fig. 1 UHF/6-31G* optimized geometry for the ˙OH–benzene adduct at O_1–C_1 = 1.9 Å

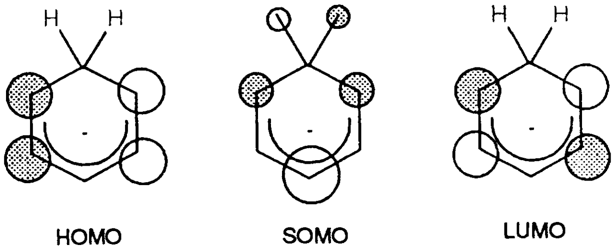


Fig. 2 HOMO, SOMO and LUMO of the cyclohexadienyl radical at the ROHF/6-31G* level

Table 2 Total and relative (in parentheses) energies for the isomeric ˙H and ˙OH adducts of benzene, phenol, biphenyl, benzoate and *p*-OHB at the ROHF/6-31G* and ROMP2/6-31G*//ROHF/6-31G* levels

	Energy/au (kJ mol^{-1})			
	˙H Adduct		˙OH Adduct	
Compound	ROHF/6-31G*	ROMP2/6-31G*	ROHF/6-31G*	ROMP2/6-31G*
Benzene	−231.222 584	−231.971 604	−306.073 567	−306.998 755
Phenol				
ortho	−306.081 968 (0.0)	−307.008 978 (0.0)	−380.930 328 (0.0)	−382.034 073 (2.2)
meta	−306.075 640 (16.6)	−307.002 450 (17.0)	−380.926 429 (10.2)	−382.028 639 (16.4)
para	−306.075 122 (18.0)	−307.004 952 (10.6)	−380.927 694 (6.9)	−382.034 893 (0.0)
Biphenyl				
ortho	−460.774 075 (6.3)	−462.284 136 (3.8)	−535.624 243 (8.1)	−537.313 147 (0.0)
meta	−460.773 092 (8.9)	−462.280 440 (13.5)	−535.624 012 (8.7)	−537.307 425 (15.0)
para	−460.776 469 (0.0)	−462.285 583 (0.0)	−535.627 323 (0.0)	−537.312 723 (1.1)
Benzoate				
ortho	−418.271 432 (8.6)	−419.505 038 (0.0)	−493.136 780 (0.0)	−494.549 046 (0.0)
meta	−418.269 142 (14.6)	−419.499 533 (14.5)	−493.125 912 (28.5)	−494.532 991 (42.2)
para	−418.274 714 (0.0)	−419.502 69 (6.2)	−493.1323 317 (11.7)	−494.537 090 (31.4)
p-OHB				
ortho	−493.128 176 (0.0)	−494.535 654 (7.4)	−567.994 618 (0.0)	−569.583 299 (0.0)
meta	−493.127 229 (2.5)	−494.538 467 (0.0)	−567.978 056 (43.5)	−569.563 031 (53.2)

Table 3 Total energies and dipole moments for phenol, biphenyl, benzoate and *p*-OHB in the gas phase ($\varepsilon = 1$) and in water (SCRF, $\varepsilon = 78.5$) at the 6-31G* level

	$\varepsilon = 1$		$\varepsilon = 78.5$	
Compound	Energy/au	Dipole moment/D	Energy/au	Dipole moment/D
Phenol	−305.558 064	1.5	−305.558 538	1.7
Biphenyl	−460.253 945	0.0		
Benzoate	−417.752 930	9.3	−417.769 847	11.7
p-OHB	−492.609 009	11.1	−492.632 280	14.4

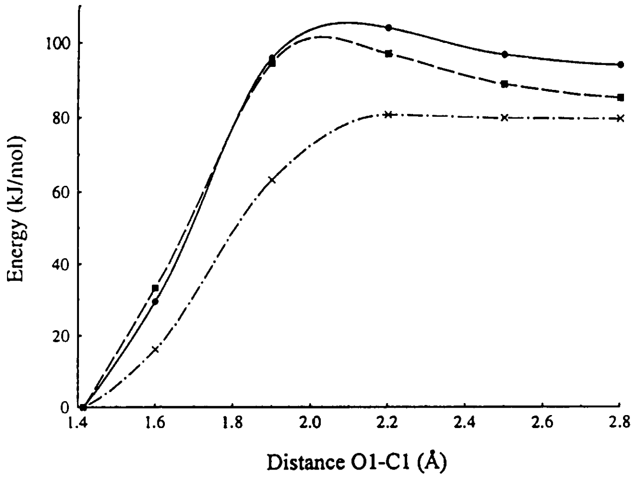


Fig. 3 Reaction profile for the addition of •OH to benzene at the PMP3/6-31G*//UHF/6-31G* (——), PMP2/6-31G*//UHF/6-31G* (– – –) and PMP2′/6-31G*//UHF/6-31G* (—•—•, only the quartet spin contaminant have been projected out) levels

Table 4 Experimental relative reactivity of *ortho*, *meta* and *para* carbons in the radiolytic •OH substitution reactions of phenol, biphenyl and *p*-OHB

	Product distribution			
Compound	*ortho*	*meta*	*para*	Ref.
Phenol	0.67	0.04	1	9
Biphenyl	0.71	0.37	1	8
p-OHB	0.09	1.0		2

Because we are comparing calculated properties of polar molecules and their reactivities in a polar environment, we took the solvent effects into account by using the SCRF method. It should be noted that the SCRF method used here takes the electrostatic solvation into account only through the molecule's dipole moment and uses a spherical cavity to represent the molecule's shape and for these reasons reproduces only approximately the solvent effects on electronic properties. Furthermore, SCRF methods cannot account for the specific solute–solvent interactions (*e.g.* hydrogen bonds).[38] Especially in the case of molecules with complex geometries, reaction field methods which use multipole expansion to represent a molecule's charge distribution[39–41] or numerical polarizable continuum methods with realistic molecular cavities[42–44] should be used to get reliable results. However, Sánchez Marcos *et al.*[45] have shown that greater values than the dipole moment in the multipole expansion affect only slightly the relative energies of the molecular orbitals of aromatic molecules.

The total energies for phenol, biphenyl benzoate and *p*-OHB with their calculated dipole moments both in the gas phase and in water (SCRF, $\varepsilon = 78.5$) are listed in Table 3. The dipole moments of the polar molecules phenol, benzoate and *p*-OHB increased expectedly when solvent was included.[46] Because •OH is an electrophilic radical[47] ($E_{\mathrm{SOMO}} = -0.156$ au) the major interaction to be considered in the addition reaction is that between the singly occupied molecular orbital (SOMO) of •OH and the highest occupied molecular orbital (HOMO) of the aromatic molecules (Fig. 4). Also, subadjacent high-energy π-orbitals can play some role in the determination of the site of hydroxylation. The three highest occupied π-orbitals of phenol, benzoate and *p*-OHB from the SCRF calculations and those of coplanar biphenyl, benzoate and *p*-OHB from the gas-phase calculations are shown in Fig. 4. The π-populations of the molecules are also shown in the figure. The two highest π-orbitals of phenol and *p*-OHB from the SCRF calculation can be seen to be similar in their spatial distribution and relative energy. The absolute energies are however higher for *p*-OHB and the stabilization of the solvent increases the difference slightly. The inclusion of the solvent has the most pronounced effect on the carboxylate lone-pair orbital which is stabilized by 0.02 and 0.03 au in benzoate and *p*-OHB, respectively. This stabilization has been accounted for by the interaction between the high dipole moment of the lone-pair orbital and the induced reaction field pointing in the opposite direction.[45] The change in the π-populations caused by the solvent is consistent with the increased dipole moments showing polarization of the π-electrons in the π-systems of the aromatic rings and carboxylate groups towards the carboxylate end of the molecules.

The HOMO orbital coefficients of the SCRF results can be seen to explain well the experimental hydroxylation results (Table 4):[2,8,9] hydroxylation takes place most favourably at the site of the highest coefficient of the HOMO. In the case of *p*-OHB the gas-phase result indicates that the *ortho* position would be more reactive than the *meta* position, while in the solvent the reactivity order is reversed to the one observed in the experiments. This shows the importance of including solvent in calculations of the molecular properties. The experimental results show that the *meta* hydroxylation of biphenyl is markedly more favourable than that for phenol and for *ortho* hydroxylation of *p*-OHB. This can be explained by the involvement of subadjecent π-orbitals of biphenyl which are located at the *ortho* and *meta* positions and appear in almost equal π-populations of *ortho*, *meta* and *para* carbons of biphenyl. The SCRF results for benzoate show that the energy difference between the HOMO and HOMO-1 orbitals is only 0.006 au while it is 0.02–0.04 au for the other other molecules. On the basis of the calculations one can predict that the reactivity of different positions decreases as *para* > *meta* > *ortho*.

The reaction profile for the addition of •OH to benzene and to the *para* and *meta* positions of phenol calculated at the PMP3/3-21G//UHF/3-21G level are shown in Fig. 5. It can be seen from the figure that the *para* and *meta* profiles of phenol are similar in shape and thus the relative stabilities of the addition products, cyclohexadienyl adducts, are retained at the longer intermolecular distances. Similar kinds of profile were calculated for the

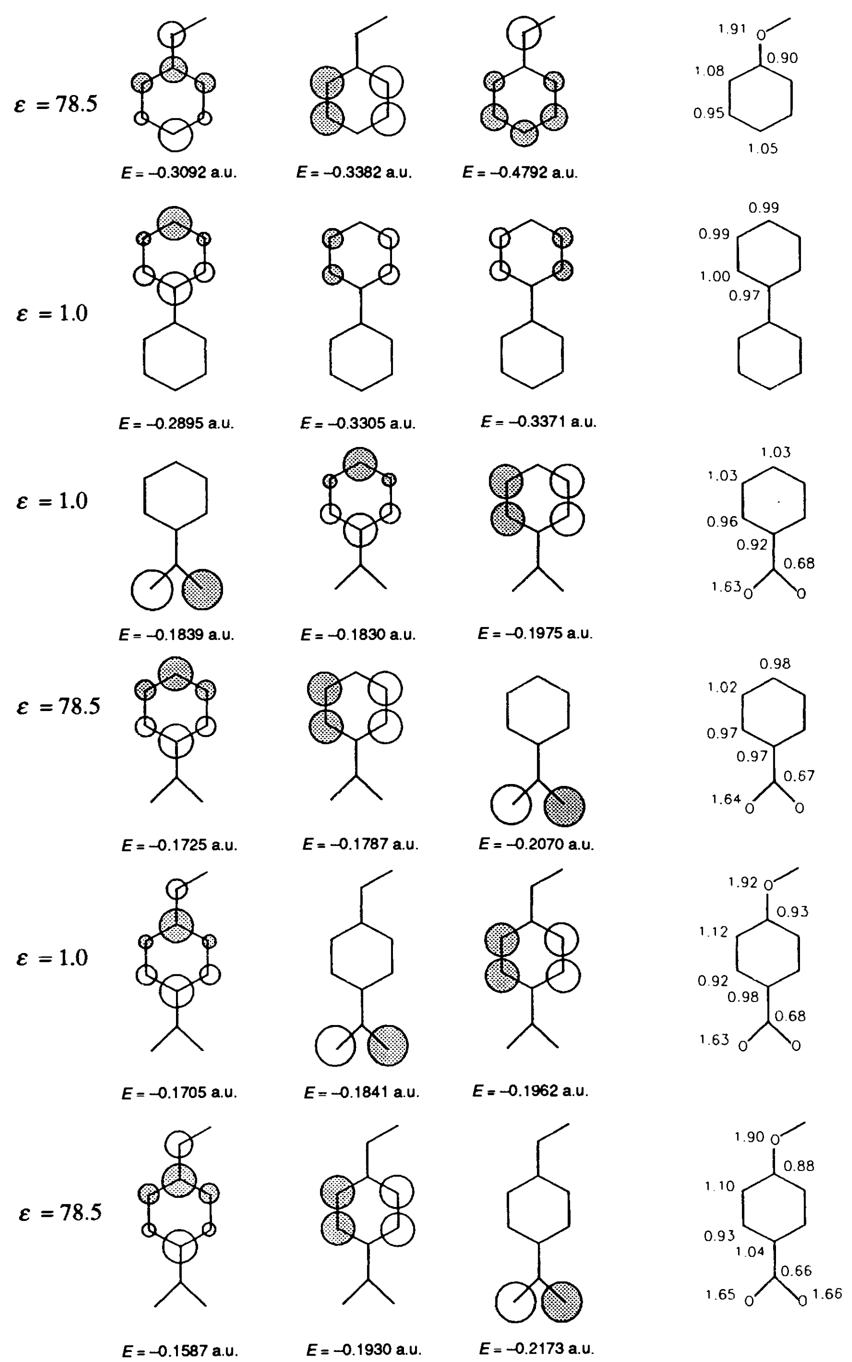


Fig. 4 Three highest π orbitals and π populations of biphenyl, benzoate and *p*-OHB in the gas phase ($\varepsilon = 1$) and phenol, benzoate and *p*-OHB in water (SCRF, $\varepsilon = 78.5$)

addition of ˙OH to *para* and *meta* positions of benzoate (profiles are not shown). In this case the energies at the point where the distance between the oxygen of ˙OH and carbon of the aromatic ring was 2.8 Å were 22 kJ mol^{-1} for *para* addition and 32 kJ mol^{-1} for *meta* addition, while the energies of the corresponding adducts as calculated with isodesmic reactions were -16.1 and -7.4 kJ mol^{-1}, respectively, at the PMP3/3-21G//UHF/3-21G level. Interestingly, these profiles and the comparison between the relative stabilities of the ˙OH adducts (Table 5) and the experimental data for the hydroxylation (Table 4) shows that there seems to be a relationship between the thermodynamic stabilities of the cyclohexadienyl adducts and the kinetic reactivity of the aromatic rings (Table 4): the more stable adducts are also the more reactive ones. This correlation between the thermodynamic stability of the products and the kinetic reactivity is due to the fact that the frontier orbitals of phenol, biphenyl, benzoate and *p*-OHB (Fig. 4) and the HOMO, SOMO and LUMO orbitals of the cyclohexadienyl radical (Fig. 2), which are the most important orbitals in determining the stability of the adducts, are located in a similar way. However, this situation could change if radicals other than ˙OH or compounds with different substituents were considered. Earlier high level *ab initio* calculations of the addition reactions of radicals to substituted alkenes have revealed that there is a correlation between the reaction enthalpy and the barrier of reaction.[48–50] These studies also indicated that both the reactant and product configurations are important in determining the transition state of the hydroxylation and, thus, the reactivity of the alkene. Wong *et al.*[48,49] have discussed the radical addition reactions of alkenes in more detail.

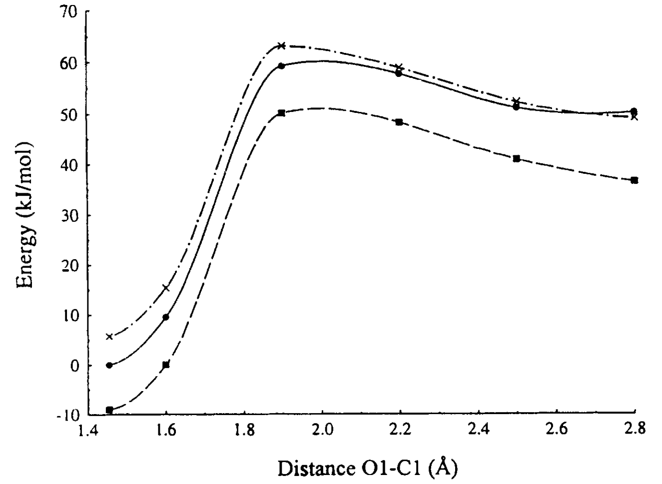
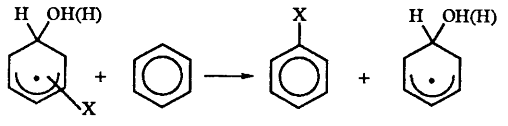


Fig. 5 Reaction profiles for the addition of $^{\bullet}OH$ to benzene (——) and to *para* (– – –) and *meta* positions (–·–·–) of phenol at the PMP3/3-21G//UHF/3-21G level



(1)

Isodesmic reactions of the isomeric cyclohexadienyl and hydroxycyclohexadienyl radicals of phenol, biphenyl, benzoate and *p*-hydroxybenzoate

Isodesmic reactions[51] of isomeric cyclohexadienyl and hydroxycyclohexadienyl radicals of phenol, benzoate, biphenyl and *p*-OHB [reaction (1)] were generated to study the relative stabilities of the adducts. The relative stabilities are important when the various fates of hydroxycyclohexadienyl radicals are considered. The cyclohexadienyls ($^{\bullet}H$ adducts) were considered to find out the effects of intramolecular hydrogen bonds of the hydroxycyclohexadienyl radicals. The energetics of the isodesmic reactions are listed in Table 5. The differences in the relative stabilities of isomeric (hydroxy)cyclohexadienyl radicals can be rationalized using the perturbation molecular orbital (PMO) theory.[31,52,53] Birch *et al.*[30] have used PMO arguments in a study of the relative stability of substituted cyclohexadienyl radicals with calculations at the UHF/STO-3G and RHF/STO-3G levels. The major interactions between the substituted (hydroxy)cyclohexadienyl radical and substituent are between the LUMO, SOMO and HOMO orbitals of the substituted cyclohexadienyl radical and the LUMO and HOMO of the substituent. The requirements for the interaction between the radical and the substituent are a small energy difference and an overlap between the interacting orbitals.[30] The SOMO of the cyclohexadienyl radical is located at *ortho* and *para* carbons in such a way that the largest coefficient of SOMO is at a *para* carbon and the LUMO is located at *ortho* and *meta* carbons (Fig. 2). The calculated spin densities for the cyclohexadienyl and hydroxycyclohexadienyl radical were typically 0.66 at the *para* and 0.15 at the *ortho* positions at the ROHF/6-31G* level. The experimental spin densities obtained from EPR measurements for cyclohexadienyl radical are 0.506 at the *para* and 0.359 at the *ortho* position.[54] In the case of $^{\bullet}OH(^{\bullet}H)$ adducts of phenol the lone pair of the phenolic OH can interact at the *para* position with the SOMO, at the *meta* with LUMO and at the *ortho* position with both LUMO and SOMO of the cyclohexadienyl radical. Because the energy of the lone-pair orbital of OH is below the energy of the SOMO, the stabilizing three-electron interaction between the lone-pair orbital (positions *ortho* and *para*) and the SOMO is larger than the two-electron interaction with the LUMO (position *meta*). This is the case for the other substituents in this study as well, (*meta* less stable than *ortho* and *para* isomers). In the case of benzoate the cyclohexadienyl ring–carboxylate group interaction is negligible owing to the lack of a suitable carboxylate C_{π}-orbital and the weak π-donor nature of carboxylate group.[30] The delocalized π- and π*-orbitals of phenyl ring of biphenyl can interact with the SOMO and LUMO of the cyclohexadienyl ring.

Table 5 Energies for the isodesmic reactions of isomeric $^{\bullet}H$ and $^{\bullet}OH$ adducts of phenol, biphenyl, benzoate and *p*-OHB at the ROHF/6-31G* and ROMP2/6-31G* levels[a,b]

	Energy/kJ mol^{-1}			
	$^{\bullet}H$ Adduct		$^{\bullet}OH$ Adduct	
Compound	ROHF	ROMP2	ROHF	ROMP2
Phenol				
ortho	−11.7	−13.6	−4.8	−8.2
meta	4.9	3.4	5.4	6.1
para	6.3	−3.0	2.1	−10.3
Biphenyl				
ortho	−1.8	−6.9	0.3	−11.4
meta	0.8	3.2	1.0	3.7
para	−8.1	−10.3	−7.7	−10.3
Benzoate				
ortho	2.5	−5.2	−35.2	−49.5
meta	8.5	9.2	−6.7	−7.3
para	−6.1	0.9	−23.5	−18.1
p-OHB				
ortho	0.7	−0.1	−39.9	−53.9
meta	3.2	−7.5	3.6	−0.7

[a] ROHF/6-31G* geometries were used. [b] Reaction (1) in the text.

The comparison of the ROHF and ROMP2 energies of the isodesmic reactions (Table 5) shows that the inclusion of correlation corrections have a noteworthy effect changing the calculated relative energies qualitatively. The energies of *ortho* and *para* isomers are changed by 12 kJ mol^{-1} while the energies of *meta* isomers are virtually unchanged. The changes for *ortho* and *para* isomers are stabilizing except for the *para* isomers of benzoate which are destabilizing by 7 and 5 kJ mol^{-1}. In the discussion below we consider only the ROMP2 energies.

The *meta* substituent can be seen to have a destabilizing effect on the radical adducts of phenol, biphenyl and the $^{\bullet}H$ adduct of benzoate. In the case of the $^{\bullet}OH$ adducts of benzoate and *p*-OHB, the higher stabilities of *meta* and *para* positions may be due to a favourable electrostatic interaction with the CO_2^- group and the *ortho* position due to a direct hydrogen bond with the CO_2^- group. However, the relative energies of the *meta* and *para* isomers of benzoate are similar both for $^{\bullet}H$ and $^{\bullet}OH$ adducts. *p*-OHB has two substituents, OH and CO_2^-, which determine the stability of the adduct. As the magnitudes of the stabilizing and destabilizing nature of these substituents in phenol and benzoate indicated, the *meta* cyclohexadienyl isomer is more stable and the *ortho* isomer is as stable as the cyclohexadienyl radical. In the case of biphenyl there is a favourable SOMO–π* interaction and this is the reason for delocalization of spin density to the phenyl ring. This is seen in the values of the total spin densities on the rings where the $^{\bullet}H$ and $^{\bullet}OH$ are attached. The spin densities of the rings with the $^{\bullet}OH$ adduct are 0.96, 0.98 and 0.90 for *ortho*, *meta* and *para* isomers, respectively. Thus, the SOMO–phenyl interaction is as expected the largest for the *para* isomer. This is seen in the values of the twist angles between the rings as well. Since both orbitals involved in the SOMO–π^*-interaction are perpendicular to the biphenyl ring, the interaction is larger the smaller the angle. The twist angle is the smallest for the *para* isomer being 32.8°, while it is 38.6° for the *ortho* and 47.4° for the *meta* isomer. The angle of the *meta* isomer is close to 45.5° for biphenyl calculated without geometric constraints at the 6-31G* level. The experimental electron diffraction value for biphenyl is 44.4°.[55]

Conclusions

The reactivity of different positions of phenol, biphenyl, benzoate and *para*-hydroxybenzoate (*p*-OHB) in the ·OH addition reaction and the relative stability of the corresponding ·H and ·OH cyclohexadienyl adducts were investigated using *ab initio* molecular orbital calculations. The reactivity patterns were elucidated using the qualitative frontier molecular orbital (FMO) theory, and the relative stability of cyclohexadienyl radicals was investigated with isodesmic reactions. The compounds studied were optimized at the R(O)HF/6-31G* level. The SCRF method was used to model the solvent effects.

The isomeric distributions in the earlier radiolytic hydroxylation studies of phenol, biphenyl and *p*-OHB are explained by the HOMO orbital coefficients: the larger the HOMO orbital coefficients the more reactive the carbon is towards the attack of ·OH. The inclusion of solvent is needed to predict correctly the reactivity of *p*-OHB. Solvent effects were also found to be important in the case of benzoate. Calculations indicated that there is a correlation between the kinetic reactivity of the atoms of the aromatic rings and the thermodynamic stabilities of the addition products.

The correlation corrections (ROHF/6-31G*/ROHF/6-31G* *vs.* ROMP2/6-31G*//ROHF/6-31G*) changed qualitatively the stabilization energies of different substituents and isomers of cyclohexadienyl radicals as calculated using isodesmic reactions. The carboxylate group stabilizes least the cyclohexadienyl radicals, the OH group stabilizes most at the *ortho* position and phenyl most at the *para* position.

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