

Comparative Study of the Molecular Electrostatic Potential Obtained from Different Wavefunctions. Reliability of the Semiempirical MNDO Wavefunction

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A systematic analysis of the molecular electrostatic potential (MEP) is presented. This study has been performed with a twofold purpose: first, to study the MEP dependence with regard to the quality of the basis set used to compute the *ab initio* SCF wavefunction and second, to develop and to assess a new strategy for computing isoelectrostatic potential maps using the semiempirical MNDO wavefunction. The only differences between this procedure and the *ab initio* SCF MEP computation lie in the freezing of the inner electrons and in the origin of the first-order density matrix. The statistical analysis of MEPs computed for a large number of molecules from MNDO wavefunction and *ab initio* SCF wavefunctions obtained using STO-3G, 4-31G, 6-31G, 4-31G*, 6-31G*, and 6-31G** basis sets points out the ability of any wavefunction to reproduce the general topological characteristics of the MEP surfaces. Nevertheless, split-valence basis sets including polarization functions are necessary to obtain accurate MEP minimum energy values. MNDO wavefunction tends to overestimate the MEP minima depth by a constant factor and shows an excellent ability to reflect the relative variation of MEP minima energies derived from a rather sophisticated (6-31G*) basis set, lacking of the shortcomings detected in the semiempirical CNDO approximation.

INTRODUCTION

Since the proposal of molecular electrostatic potential¹ (MEP), this quantum chemical quantity has become a valuable tool in an increasing number of chemical research fields, such as in molecular reactivity,²⁻¹⁰ biological interactions,¹¹⁻¹⁷ solvation phenomena,^{18,19} crystalline state^{20,21} and electron density studies.^{22,23}

The molecular electrostatic potential is a rigorous quantum mechanical property, which is defined as the expectation value of the one-electron operator \mathbf{r}^{-1} (in atomic units). Such a property describes the electrostatic potential generated by the electron charge density extended in the overall space plus the nuclei considered as point charges. It gives a measure, at the first order of perturbation, of the interaction energy of a molecule with a positive unit charge.

The exact calculation of MEP implies the knowledge of a molecular electronic wavefunction obtained from the suitable computational scheme. While the computation of the MEP is rather unexpensive, the calculation of the *ab initio* wave function may become a huge task as the size of the molecular system increases, thus limiting the application of MEP to chemical structures of moderate size. It must be stressed that this limitation exists even if the *ab initio* wave function is not extremely accurate.

The development of efficient computational methods and the increase in the computer power have partly minimized such problem. Nevertheless, there are numerous research fields where the *ab initio* wave function calculation remains very expensive, even at the SCF level. This is the case of biological molecular interactions, where the use of several approximations for simulating the exact molecular charge distribution appears necessary. Accordingly, net atomic charges, which

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are usually derived from Mulliken's population analysis²⁴ may be used to compute MEPs. This approximation, specially when semiempirical charges are used, is very popular due to its low computational cost. However, it is well known that the MEP obtained from atomic point charges presents several failures. Attempts have been made to correct such deficiencies, as the incorporation of higher order multipole moments,²⁵⁻²⁷ the use of net atomic charges fitted to *ab initio* SCF electrostatic potential,²⁸⁻³³ the addition of new fractional point charges to a set of Mulliken's ones³⁴ or the mixed representation derived from a multipole expansion and diffuse gaussians^{35,36}. Nevertheless, despite all the improvements incorporated, MEP calculation from atomic charges presents several shortcomings specially in the inner regions.

Other methods for computing electrostatic isopotential maps are based on the bond fragment transferability.³⁷⁻⁴⁰ A semiquantitative agreement between this approach and *ab initio* SCF results was reported.⁴⁰ Nevertheless, the absolute value of the potential is overestimated, which has been only partly corrected by addition of a 6-12 correction term mimicking the core repulsion around nuclei.⁸

Finally, an interesting approximation to computation of the MEP is provided by the use of electron charge distributions derived from semiempirical⁴¹⁻⁴⁵ or quasi-*ab initio*⁴⁶ methods. In this case, the computation of the wave function is straightforward and unexpensive even for large molecules, the introduction of further simplifications in the calculation of MEPs being not necessary. In this approach, both CNDO⁴⁷ and INDO⁴⁸ Hamiltonians have been explored. From these studies, the gross features of electrostatic potential maps are well reproduced by CNDO and INDO wave functions. Nevertheless, both semiempirical methods fail to reproduce some of the essential fine features of *ab initio* electrostatic potentials,^{13,43,49,50} which has been attributed mainly to the CNDO and INDO parametrization.⁵¹

In this work, we present a systematic study of the molecular electrostatic potentials derived from a semiempirical wave function computed using the MNDO⁵² Hamiltonian. The reliability of this approach is discussed through comparison with *ab initio* electrostatic potentials. Since MNDO Hamiltonian is parametrized to reproduce experimental values, it seems interesting to know the degree of similarity between MEPs obtained from MNDO wavefunctions with those derived from *ab initio* SCF ones using basis sets of increasing quality. For this purpose, MEPs of a wide range of molecules have been calculated from MNDO as well as from *ab initio* SCF wave functions varying from minimal STO-3G⁵³ to

rather extended 6-31G**⁵⁴ basis sets. This study permits also us to analyze the dependence between the MEP and the basis set used to compute the wave function, completing previous and less exhaustive works.^{13,44,55-58} The effect of polarization functions on MEP is specially interesting since to the authors knowledge only a few number of works⁵⁶⁻⁵⁸ (where a small number of molecules were considered) have been reported concerning this topic.

METHODS

As well known, the electrostatic potential generated by the molecular charge distribution at a point r_1 is given by eq. (1),

$$V(r_1) = \sum_A \frac{Z_A}{|r_1 - R_A|} - \int \frac{\rho(r)}{|r_1 - r|} dr \quad (1)$$

where Z_A and R_A are the atomic number and location of nucleus A and $\rho(r)$ stands for the molecular electron density. The first term in the right hand of eq. (1) reflects the nuclear electrostatic contribution of the point nuclear charges located at positions R_A , whereas the second one corresponds to the electron electrostatic term generated from the electronic charge distribution extended in the whole space. Equation (1) can be rewritten as

$$V(r_1) = \sum_A \frac{Z_A}{|r_1 - R_A|} - \sum_{\mu} \sum_{\nu} P_{\mu\nu} \int \frac{\chi_{\mu}(r)\chi_{\nu}(r)}{|r_1 - r|} dr \quad (2)$$

where χ represents the basis set of atomic orbitals and $P_{\mu\nu}$ stands for the element $\mu\nu$ of the first-order density matrix.

Pullman and Giessner-Prettre⁴¹ in the 1970s and more recently Duben⁵¹ discussed the ability of CNDO and INDO wave functions to reproduce the characteristics of *ab initio* MEPs. They concluded that reliable results can only be obtained if the zero-differential overlap (ZDO) approximation is relaxed by means of the corresponding deorthogonalization of the Slater-type orbital (STO) basis set and of the inclusion of all the integrals in computation of the MEP. The improvement in the representation of charge distributions derived from the deorthogonalization of the CNDO and INDO wave functions has been recently discussed.⁵⁹

MNDO Hamiltonian, although more elaborated than CNDO, is also based in the ZDO approximation and consequently it seems a priori that considerations noted above must be analogously applied. For this purpose, the molecular orbitals (MO) obtained from the MNDO wave function calculation are deorthogonalized using the in-

verse Löwdin transformation⁶⁰ as indicated by eq. (3), where C' and C describe eigenvectors expressed in the orthogonalized and deorthogonalized STO atomic basis sets and S is the overlap matrix

$$C = S^{-1/2}C' \quad (3)$$

over STOs. These deorthogonalized coefficients are then used to compute a new density matrix. Moreover, since MNDO MOs are expressed on such a STO basis set and computation of atomic integrals in STOs is difficult, each STO is fitted to four Gaussian functions. Afterwards, all the integrals are calculated using this Gaussian-type orbital (GTO) basis set. Finally, the nuclear electrostatic term is computed making the nuclear charge of each atom equal to the atomic number minus the number of inner electrons.

It must be noted that by means of this procedure the only differences between the exact *ab initio* MEP and the MNDO MEP are (1) the freezing of the inner electrons into the nuclei and (2) the origin of the density matrix elements.

To assess the reliability of the MNDO electrostatic potential, it is necessary to know previously the dependence of MEP on the basis set. In this sense, MEP minima were calculated at the *ab initio* SCF level using several basis sets: (1) semiempirical MNDO,⁵² (2) *ab initio* minimal basis set (STO-3G⁵³), (3) *ab initio* split-valence basis set (6-31G⁶¹ and in some cases also 4-31G⁶²), (4) *ab initio* split-valence basis set plus polarization functions on atoms other than hydrogen (6-31G*⁵⁴ and in some cases also 4-31G*⁵⁴), and (5) *ab initio* split-valence basis set plus polarization functions on all atoms (6-31G**⁵⁴) in selected cases. This procedure let us not only to gain insight into the modulation of the MEP by the basis set, but also to ascertain the reliability of the MNDO MEP.

Pople's basis sets have been used to study the dependence between the MEP and the quality of the basis set due to their large use. However, in selected cases also Dunning's basis⁶³ (9s5p/4s) contracted to [5s3p/3s] and [5s3p1d/3s] were used to assess the reliability of the conclusions obtained from Pople's basis. Exponents of polarization functions were taken from the literature.⁶⁴

Finally, since MEP is an index of the proton affinity, the ability of the MEP computed from the MNDO wavefunction to discriminate the center at which protonation occurs in molecules with two or more MEP minima in competition, as usually found in biological and pharmacological compounds, was examined.

MNDO computations have been performed from the standard parameters⁵² using a modified version⁶⁵ of MOPAC program.⁶⁶ HONDO-76⁶⁷ has been used in *ab initio* computations.

RESULTS

In order to study the influence of basis set on the MEP and to analyze the reliability of MNDO wave function in computation of the MEP, a large number of molecules were studied. These molecules were classified into five groups in order to rationalize the discussion. These groups present different kinds of MEP minima of chemical interest and correspond to (1) minima of small molecules (Table II), (2) minima on oxygen atom of carbonyl derivatives (Table III), (3) minima of methyl derivatives of ammonia and water (Table IV), (4) minima located on lone pairs of heteroaromatic compounds (Table V), and finally (5) minima above and below aromatic rings (Table VI). Tables II–VI report the energy of the MEP minima as well as the distance from them to a reference point in each group of molecules. For all the molecules MEP minima were located with an error less than 0.01 a.u.

As the main objective of this work is to make a comparative study of the MEP derived from different wavefunctions, a statistical analysis of the results has been performed in order to determine:

1. The dependence of the MEP minima location with respect to the method employed in the calculation of the wave function. For this purpose, the mean distances between the minima located from the different wavefunctions are calculated for the whole of and for each group of minima.
2. The dependence of the absolute energies of MEP minima with regard to the wavefunc-

Table I. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for the whole of molecules studied in this work: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij} MEP_j$) between the MEP minima energies, and (c) Pearson's correlation coefficients between MEP minima energies.

	MNDO	STO-3G	6-31G	6-31G*
(A)				
MNDO	0.00	0.22	0.35	0.37
STO-3G		0.00	0.15	0.20
6-31G			0.00	0.07
6-31G*				0.00
(B)				
MNDO	1.00	1.18	1.14	1.40
STO-3G	0.80	1.00	0.94	1.12
6-31G	0.86	1.05	1.00	1.21
6-31G*	0.71	0.86	0.82	1.00
(C)				
MNDO	1.00	0.89	0.96	0.98
STO-3G		1.00	0.96	0.94
6-31G			1.00	0.98
6-31G*				1.00

Table II. Molecular Electrostatic Potential minima energies (up) and distances (Å) from the minima location to a reference point (down) computed from different wavefunctions for small molecules (see text). Energy values are given in kcal/mol.

	Reference point	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*	6-31G**
H ₂	Hydrogen	-3.15 1.42	-2.35 1.58		-1.92 1.73			-2.74 1.64
F ₂	Fluorine	-7.43 1.03	-4.79 1.18	-3.11 1.43	-2.94 1.45	-3.65 1.42	-3.46 1.45	
N ₂	Nitrogen	-15.93 1.15	-33.43 1.18	-18.68 1.39	-18.11 1.39	-11.77 1.50	-10.91 1.52	
CO	Carbon	-21.96 1.26	-45.23 1.21	-19.68 1.41	-20.27 1.41	-17.81 1.48	-17.50 1.49	
CO	Oxygen	-33.80 0.96	-27.33 1.12	-28.42 1.30	-26.51 1.31	-15.78 1.42	-14.57 1.45	
HCN	Nitrogen	-41.28 1.08	-64.56 1.11	-58.26 1.25	-57.31 1.25	-49.19 1.32	-47.64 1.33	-47.67 1.33

Table III. Molecular Electrostatic Potential minima energies (up) and distances (Å) from the minima location to a reference point (down) computed from different wavefunctions for carbonyl compounds (see text). Energy values are given in kcal/mol.

	Reference point	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*	6-31G**
CH ₂ O	Oxygen	-76.28 0.84	-48.72 1.05	-63.25 1.17	-62.25 1.17	-52.01 1.21	-51.23 1.22	-51.25 1.22
CHFO ^a	Oxygen	-63.84 0.85	-45.48 1.06	-48.97 1.22	-48.14 1.21	-41.89 1.25	-41.13 1.26	-41.17 1.26
CHFO ^b	Oxygen	-69.30 0.85	-45.47 1.07	-51.84 1.22	-51.06 1.22	-44.85 1.26	-44.24 1.27	-44.31 1.27
CF ₂ O	Oxygen	-46.70 0.87	-42.88 1.07	-37.57 1.25	-36.82 1.26	-34.49 1.29	-33.78 1.30	
CHOCH ₃ ^a	Oxygen	-77.80 0.84	-51.54 1.05		-66.89 1.17		-55.83 1.22	
CHOCH ₃ ^b	Oxygen	-76.71 0.84	-50.83 1.05		-65.36 1.17		-54.40 1.22	
CO(CH ₃) ₂	Oxygen	-83.84 0.84	-55.59 1.05		-71.62 1.17		-60.78 1.21	
CO ₂	Oxygen	-26.48 0.97	-32.82 1.12	-29.50 1.30	-28.42 1.31	-18.60 1.42	-17.74 1.40	
CHONH ₂ ^a	Oxygen	-92.37 0.87	-63.95 1.03	-78.29 1.15	-77.84 1.14	-66.83 1.19	-66.22 1.20	-66.26 1.20
CHONH ₂ ^b	Oxygen	-93.41 0.83	-60.82 1.03	-74.16 1.16	-73.24 1.16	-62.67 1.20	-61.80 1.20	-61.92 1.20
CO(NH ₂) ₂	Oxygen	-104.21 0.82	-73.67 1.03		-82.88 1.15		-72.13 1.18	
COFNH ₂ ^a	Oxygen	-82.16 0.97	-61.40 1.04		-66.17 1.19		-58.58 1.23	
COFNH ₂ ^b	Oxygen	-77.77 0.97	-58.80 1.04		-60.19 1.20		-52.36 1.23	
COCH ₃ NH ₂ ^a	Oxygen	-121.96 0.80	-74.65 1.00		-89.71 1.14		-81.86 1.16	
COCH ₃ NH ₂ ^b	Oxygen	-121.99 0.79	-70.61 1.00		-84.91 1.14		-77.43 1.16	

Table IV. Molecular Electrostatic Potential minima energies (up) and distances (Å) from the minima location to a reference point (down) computed from different wavefunctions for derivatives of water and ammonia (see text). Energy values are given in kcal/mol.

	Reference point	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*	6-31G**
H ₂ O	Oxygen	-86.60 0.86	-71.97 1.01	-85.74 1.12	-85.11 1.12	-63.62 1.08	-63.03 1.08	-62.19 1.08
NH ₃	Nitrogen	-105.07 0.89	-108.57 1.00	-110.21 1.14	-109.35 1.15	-88.50 1.20	-87.89 1.21	-85.75 1.21
CH ₃ OH	Oxygen	-79.24 0.85	-67.42 1.01	-84.48 1.12	-83.67 1.12	-61.04 1.20	-60.47 1.21	-60.10 1.20
O(CH ₃) ₂	Oxygen	-88.39 0.87	-67.15 1.00		-81.84 1.12		-57.69 1.20	
CH ₃ NH ₂	Nitrogen	-117.79 0.87	-102.61 1.01	-105.85 1.14	-105.08 1.15	-86.97 1.19	-85.97 1.20	-84.09 1.20
N(CH ₃) ₃	Nitrogen	-127.03 0.86	-82.79 1.03		-86.45 1.16		-70.10 1.21	
HNCHOH	Nitrogen	-94.93 0.91	-89.40 1.02	-84.00 1.16	-83.15 1.16	-69.94 1.23	-68.96 1.23	-68.65 1.23
HNCHOH	Oxygen	-60.96 0.86	-56.07 1.00	-63.64 1.14	-62.79 1.15	-42.10 1.23	-41.34 1.23	-41.03 1.23

Table V. Molecular Electrostatic Potential minima energies (up) and distance $s(\text{Å})$ from the minima location to a reference point (down) computed from different wavefunctions for the lone pair of heteroaromatic compounds (see text). Energy values are given in kcal/mol.

	Reference point	MNDO	STO-3G	6-31G	6-31G*
Pyridine	Nitrogen	-95.99 0.92	-91.04 1.03	-89.29 1.16	-71.66 1.23
Pyrimidine	Nitrogen	-93.42 0.92	-82.78 1.04	-80.25 1.17	-64.30 1.23
Furan	Oxygen	-50.78 0.89	-44.02 1.05	-57.26 1.17	-37.04 1.26
Imidazole	Nitrogen	-96.78 0.93	-100.84 1.03	-98.34 1.16	-80.37 1.23
4-OH-Pyridine	Nitrogen	-96.51 0.92	-92.14 1.03	-88.25 1.16	
4-CH ₃ -Pyridine	Nitrogen	-97.18 0.92	-94.71 1.03	-93.01 1.16	-75.34 1.22
4-NH ₂ -Pyridine	Nitrogen	-105.64 0.91	-100.56 1.03	-98.73 1.15	-81.10 1.22
4-F-Pyridine	Nitrogen	-88.41 0.92	-89.71 1.03	-88.15 1.17	-67.58 1.23
4-NO ₂ -Pyridine	Nitrogen	-75.21 0.93	-76.05 1.04	-68.37 1.18	

tion. This analysis has been performed by means of a least-square fitting of the type $\text{MEP}_i = c_{ij} \text{MEP}_j$, where indexes i and j describe different computational methods. It must be stressed that the resulting matrix is of the form $c_{ij} \sim 1/c_{ji}$, being $c_{ij} = 1/c_{ji}$ if Pearson's correlation coefficient is one.

3. Since MEP minima are usually calculated for a series of molecules, the main interest being not to obtain the absolute value but the relative variation of MEP minima energies along the series, the ability of the different methods to provide comparatively similar relative values has been examined. For this purpose, cor-

Table VI. Molecular Electrostatic Potential minima energies (up) and distances (Å) from the minima location to a reference point (down) computed from different wavefunctions for the π -electron distribution of several compounds (see text). Energy values are given in kcal/mol.

	Reference point	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*	6-31G**
C ₂ H ₄	Center of molecule	-24.88	-13.69	-23.86	-23.57	-25.94	-25.69	-24.74
		1.26	1.43	1.54	1.56	1.56	1.51	1.52
C ₂ H ₂	Center of molecule	-33.64	-19.42	-22.14	-21.51	-26.14	-25.36	-24.91
		1.25	1.39	1.57	1.59	1.49	1.51	1.51
C ₆ H ₆	Center of molecule	-25.48	-10.44		-18.85		-20.52	
		1.33	1.59		1.84		1.76	
Pyridine	Middle point of the straight line N1-C4	-17.95	-1.55		-8.47		-11.38	
		1.41	2.45		2.14		1.96	
Pyrimidine	Middle point of the straight line C2-C5	-9.49			-1.12		-3.31	
		1.42			3.37		2.46	
Furan	Middle point of the straight line O-b:(C3-C4)	-23.09	-5.38		-13.01		-16.38	
		1.42	1.92		2.00		1.85	
Pyrrole	Middle point of the straight line N-bi(C3-C4)	-40.27	-18.77		-26.87		-28.69	
		1.18	1.52		1.75		1.69	
Imidazole	Middle point of the straight line C2-bi(C4-C5)	-30.72	-7.30		-13.56		-17.35	
		1.28	2.01		2.00		1.84	
4-OH-Pyridine	Middle point of the straight line N1-C4	-16.43	-1.08		-6.00			
		1.45	2.71		2.28			
4-CH ₃ -Pyridine	Middle point of the straight line N1-C4	-20.97	-1.16		-8.26		-11.60	
		1.37	2.15		2.05		1.88	
4-NH ₂ -Pyridine	Middle point of the straight line N1-C4	-23.49	-5.89		-13.30		-16.76	
		1.35	2.00		2.06		1.89	

relations between the MEP minima derived from the different wave functions are determined for each group and for the whole of molecules by means of the Pearson's correlation coefficient r . It must be emphasized that when r is 1 both methods provide the same information with regard to the MEP minima relative variation, but this does not imply their equivalence in providing the same absolute values.

Finally, since the interest of MEP does not lie exclusively in the minima region but also in their topology in the whole space surrounding the molecule, several MEP maps are included in order to determine the similarities between the different methods.

In the next section MEP minima for the whole of molecules will be discussed according to the statistical analysis detailed above to find the general trends characterizing the influence of MNDO wave function as well as of the *ab initio* basis set on the well depth and the location of

MEP minima. In the following sections each group of minima will be examined and its particular features will be discussed.

General Trends of the Whole of Minima

The MEP maps for pyridine derived from different wave functions are shown in Figure 1. The general topological characteristics of MEP maps are insensitive to the quality of the wavefunction, as can be seen in the figure. This trend is also reflected in the rest of molecules.

Results of the statistical study for the whole of MEP minima are shown in Table I. As stated from Table I(a), the minima location is notably influenced by the basis set. The mean difference of minima locations derived from STO-3G and 6-31G computations is 0.15 Å, whereas STO-G3 and 6-31G* minima positions differs in 0.20 Å. The mean variation in the minima location resulting from addition of polarization functions to 6-31G basis set is 0.07 Å. Accordingly, the in-

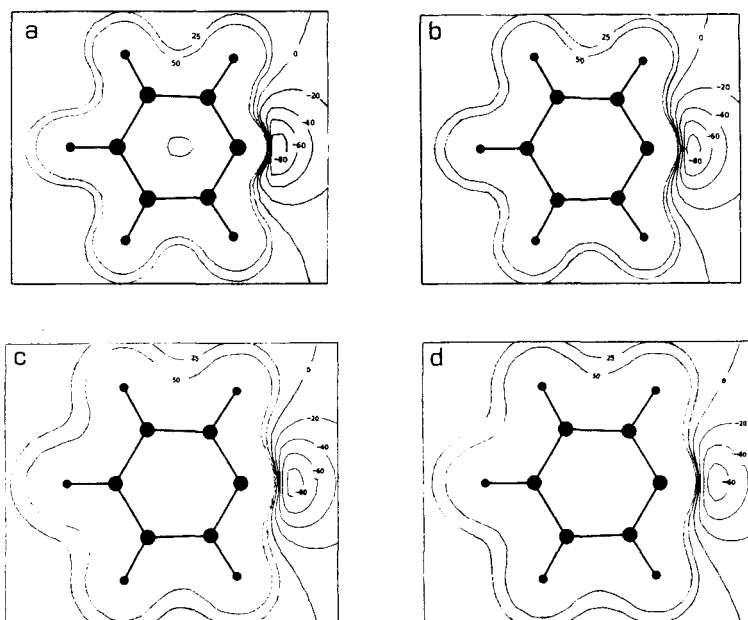


Figure 1. Molecular Electrostatic Potential maps for pyridine calculated in the molecular plane from a) semiempirical MNDO wavefunction and *ab initio* SCF Hartree-Fock wavefunctions using b) STO-3G, c) 6-31G, and d) 6-31G* basis sets. Energy values are given in kcal/mol.

crease of the basis set from STO-3G to 6-31G* considerably changes the location of the MEP minima, specially in the extension from minimal to split-valence basis sets. From Tables II–V, it can be noted that the more extended the basis set, the larger the distance between the minima location and the molecule (as mentioned later, this rule does not apply for minima located above aromatic rings). Minima derived from MNDO wavefunctions are located closer to the molecule than STO-3G ones.

Table I(b) indicates that 6-31G* basis set provides the highest MEP minima energies (the lowest minima absolute values), whereas 6-31G results correspond to the most negative ones. Table I(b) also makes evident that STO-3G MEP minima energies are slightly closer to the 6-31G* ones than those derived from 6-31G calculations. However, as can be deduced from Table I(c), 6-31G results correlate with 6-31G* energies better than STO-3G ones. MNDO appears to behave analogously to 6-31G: MNDO MEP minima energies are higher than STO-3G ones and accordingly have a poorest agreement with regard to 6-31G* results. Nevertheless, the relative variation of MNDO minima energies is better correlated with the 6-31G* ones than that of STO-3G minima energies, the correlation coefficient being of the same magnitude than that of 6-31G.

Minima of Small Molecules

Energies of MEP minima and their locations are shown in Table II. Results of the statistical study

are displayed in the appendix (Table IX). It can be stated that the larger the basis set, the better the agreement of MEP minima energies. It should be noted that this result is in contrast with trends reported in the above section, since STO-3G has the poorest fitting with 6-31G* in this group of molecules regarding the MEP minima absolute energies. It is specially remarkable the excellent ability of MNDO to reproduce the MEP minima energies of the 6-31G* basis set, particularly for H₂, N₂, and HCN, a slightly poorer agreement being obtained for F₂. The variation of the deepest MEP minimum in CO from the carbon to the oxygen atoms when changing the wave function follows the well known trend of its dipole moment and its proper description can not be reached without explicit introduction of correlation effects.⁶⁸

Formaldehyde and its Derivatives

Energies and locations of MEP minima of oxygen atom for carbonyl derivatives are displayed in Table III. When the molecule is not symmetric with respect to the plane perpendicular to the molecule passing through the CO axis the two minima near the oxygen are reported. This is noted in Table III by superscripts *a* and *b*. Results of the statistical study are shown in the appendix (Table X).

Results from Table III show that the incorporation of fluorine atoms leads to an important increase (a decrease in absolute value) of the MEP minima. Conversely, the incorporation of methyl

groups leads to a decrease in the MEP minima (an increase in absolute value), this effect being more pronounced when hydrogens of formaldehyde are replaced by amino substituents. Finally, the addition of a second oxygen attached to the carbonyl carbon atom (CO_2) lead to a drastic increase of MEP minima. These effects are well reflected irrespectively of the wave function used to compute MEP and are easily understood by means of intuitive chemical concepts such as the electron-donating and electron-withdrawing nature of substituents.

MEP minima energies computed from 4-31G and 6-31G basis are in practice of the same magnitude, as well as those corresponding to 4-31G* and 6-31G* computations, although the effect to better describe the inner shell basis set presents a slight increase of minima energies of approximately 1 kcal/mol. These characteristics are also reflected in Table II. 6-31G** minima energies differs very slightly from those of 6-31G*, but in all cases a systematic decrease lower than 0.1 kcal/mol is produced with regard to 6-31G* results (see also HCN in Table II).

6-31G provides the lowest energies of *ab initio* MEP minima (highest absolute values), STO-3G results being much closer to 6-31G* ones than those derived from computations using 4-31G or 6-31G basis sets. Nevertheless, exceptions to this rule are CF_2O and CO_2 (see also N_2 and HCN in Table II), where MEP minima increase as the basis set becomes larger. MNDO shows a tendency to maximize the depth of MEP minima.

MEP minima energies for all the methods show excellent correlations (see Appendix; Table X) when compared with 6-31G* results. It must be stressed the fact that MNDO method explains up to 98% of 6-31G* minima variance, its correlation being better than that of minimal STO-3G basis set. Therefore, an excellent predictive power of MNDO can be expected for comparative purposes in carbonyl derivatives.

Methyl Derivatives of Water and Ammonia

Energies and locations of MEP minima generated from the lone electron pairs of oxygen and nitrogen atoms of water and ammonia and their methyl derivatives are reported in Table IV, which also includes MEP minima of the enolic form of formamide. Results of the statistical analysis are shown in the appendix (Table XI).

It is interesting to note the agreement between MNDO and 6-31G MEP minima energies (see Appendix; Table XI). The ability of MNDO to reproduce 6-31G* MEP minima energies in this series of compounds is not as good as in the two previous series. The reason of this fact, which is

related to the chemical characteristics of methyl bond to sp^3 atoms, is discussed below.

Minima of ammonia is nearly 20 kcal/mol deeper than that of water in good agreement with their basicity characteristics¹³ irrespectively of the wavefunction. In addition, as is known, the experimental gas phase basicity of methyl derivatives of water and ammonia increases as the number of methyl groups incorporated into the molecule is augmented.⁷ Morokuma's analysis⁶⁹ of the interaction energy between a proton and the methylated derivatives of water and ammonia as well as MEP calculations⁷ show no relevant change in the electrostatic term of the interaction energy when methyl groups are added to water and ammonia, the increase in basicity being due to an increase in the polarization term.

Results of Table IV show a slight decrease in the absolute values of the *ab initio* MEP minima as the degree of methyl substitution increases irrespectively of the basis set employed, which is in accordance with previous works^{7,69} and in opposition to experimental data, thus making necessary the inclusion of the polarization energy term to compute relative basicities in these compounds.

MNDO results, specially those concerning methyl derivatives of ammonia, show a tendency to decrease the MEP minima energies when methyl groups are added into the molecule. These results are surprising and suggest that the MEP derived from MNDO wave function incorporates at least partially information about the polarization energy term, possibly due to the MNDO parametrization.

Heteroaromatic Compounds: Lone Electron Pairs

Several heteroaromatic compounds that can be considered as representative moieties of biologically relevant molecules have been studied and the MEP minima corresponding to lone electron pairs have been located. Energies and locations of MEP minima are shown in Table V and results of the statistical analysis are displayed in the appendix (Table XII).

The different methods correctly reproduce the effects of substituents on MEP minima of nitrogen lone electron pairs, as can be seen by comparing MEP minima energies of pyridine and its derivatives. Thus, pyrimidine exhibits a MEP minimum greater than that of pyridine irrespectively of the wave function origin in agreement with their experimental basicities,⁷⁰ which can be explained according to the electron withdrawing character of the aromatic nitrogen. Similarly, the highly electron withdrawing NO_2 group causes

an increase of around 20 kcal/mol in the minimum energy value, while the electron donating effect of NH_2 is reflected in the decrease of approximately 10 kcal/mol. Fluorine group shows a little withdrawing character, whereas OH and CH_3 behave as weak electron donors. All of these effects are well reflected irrespectively of the method used to compute MEPs, as can be noted by inspection of the excellent correlation coefficients obtained when comparing the relative variation of MEP minima energies (see Appendix; Table XII).

Heteroaromatic Compounds: π -Electron Minima

MEP minima above and below the molecular plane of several representative heteroaromatic compounds generated from the π -electron density have been calculated and are shown in Table VI. Minima of C_2H_2 and C_2H_4 have been included in Table VI since they are also originated from the π -electron charge distribution. In order to detect MEP minima above the molecular plane, we first determined the location of MEP minimum inside the aromatic ring and then we proceeded to locate the MEP minimum in the line perpendicular to the molecular plane passing through such a ring point. The computation of π -electron minima is a "fire probe" to any approximate method since it must be noted that relevant mistakes of Pullman's approximation to compute the MEP derived from the CNDO wave function appears for π -aromatic MEP minima.^{13,49}

Results reported in Table VI as well as the statistical analysis (Appendix; Table XIII) point out the existence of notable features in clear contrast with the series of MEP minima discussed above. Thus, MEP minima become more negative as the size of the basis increases, the MEP minima energies computed at the 6-31G* level being the deepest ones amongst the MEP minima derived from *ab initio* SCF wave functions. MNDO wave function provides results close to 6-31G* MEP minima energies, although the MEP minima depth is overestimated again. On the other hand, when the distance from the minima to the molecule is taken into account, the change from STO-3G to split valence basis sets implies a removal out of the MEP minima from the molecule in accordance with the general tendency mentioned above. Nevertheless, the inclusion of polarization functions locates the *ab initio* MEP minima closest to the molecule. MNDO minimizes the distance from minima to the molecules again, but it provides results not too far from 6-31G* ones. The poor ability of STO-3G basis set to detect aromatic π -electron MEP minima must be noted (see Appendix; Table XIII). Thus, no MEP minima

is found in pyrimidine from the SCF wave function computed using the STO-3G basis set.

Changes in MEP minima energies caused by the introduction of nitrogen atoms in the heteroaromatic ring are adequately reproduced irrespectively of the wave function origin, as can be seen by comparing MEP minima of benzene, pyridine, and pyrimidine. Analogously, all the methods studied reflect correctly changes due to substituents in *para* position, which alter considerably the π -electron distribution since no MEP minimum was found in NO_2 and F derivatives of pyridine. The effects of CH_3 , OH, and NH_2 are similar to those described for MEP minima of aromatic lone electron pair.

Results of Table VI stress the ability of MNDO to reproduce MEP minima of π -electron charge distribution, which was one of the gross failures of the CNDO approximation. Thus, MNDO gives a MEP minimum of -25.48 kcal/mol for benzene in good agreement with the value computed at 6-31G* level (-20.52 kcal/mol), whereas CNDO results state the existence of a positive electrostatic potential region above and below the molecular plane (the reported MEP minimum energy was nearly 10 kcal/mol^{13,49}). Similarly, the MEP minimum energies derived from MNDO and 6-31G* computations for ethene are -24.88 and -24.74 kcal/mol respectively, whereas a positive region is detected using the CNDO approximation.

MEPs Derived from Wavefunctions Computed from Dunning's Basis Sets

Energies and locations of MEP minima computed from several molecules using the contracted Dunning's basis sets [5s3p/3s] and [5s3p1d/3s] are shown in Table VII. The statistical analysis is displayed in the appendix (Table XIV).

Locations of MEP minima obtained from [5s3p/3s] and [5s3p1d/3s] basis sets do not change significantly with regard to those determined from 6-31G and 6-31G*. MEP minima energies computed from 6-31G and [5s3p/3s], as well as from 6-31G* and [5s3p1d/3s], are very similar (Table VII and Table XIV in the appendix), suggesting that the inclusion of polarization functions in the basis has an influence on the MEP minima depth greater than the increase of the basis from double to near triple-zeta quality.

On the other hand, MEP minima energies obtained from computations performed with 6-31G, 6-31G*, [5s3p/3s], and [5s3p1d/3s] basis sets exhibit the same relative variation, as can be seen in the appendix (Table XIV). Note also that results derived from MNDO computations show excellent correlations with respect to MEP minima energies determined from Dunning's basis sets.

Table VII. Molecular Electrostatic Potential minima energies (up) and distances (Å) from the minima location to a reference point (down) computed from wavefunctions determined using Dunning's basis for several compounds (see text). Energy values are given in kcal/mol.

	Reference point	5s3p/3s	5s3p1d/3s
H ₂	Hydrogen	-1.69 1.74	-2.74 1.61
F ₂	Fluorine	-2.20 1.55	-2.43 1.55
N ₂	Nitrogen	-20.00 1.37	-12.80 1.48
CO	Carbon	-17.65 1.50	-15.92 1.54
CO	Oxygen	-27.38 1.28	-15.49 1.41
HCN	Nitrogen	-56.23 1.27	-48.02 1.33
C ₂ H ₂	Center of molecule	-19.21 1.65	-23.49 1.56
C ₂ H ₄	Center of molecule	-21.57 1.64	-24.30 1.57
H ₂ O	Oxygen	-83.37 1.13	-69.68 1.17
NH ₃	Nitrogen	-103.56 1.17	-88.17 1.22
CH ₂ O	Oxygen	-61.14 1.17	-51.73 1.21
CO ₂	Oxygen	-28.19 1.30	-18.88 1.40
CO(NH ₂) ₂	Oxygen	-82.38 1.15	-73.87 1.18
CO(CH ₃) ₂	Oxygen	-70.29 1.16	-61.65 1.20
COF ₂	Oxygen	-35.61 1.25	-33.14 1.29

Molecules with Two or More MEP Minima in Competition

Another way of analyzing the reliability of MNDO wavefunction for computing MEPs consists of studying molecules with or more MEP minima in competition. The relevance of this aspect must be emphasized, since MEPs for cytosine computed from semiempirical CNDO and INDO wavefunctions present two minima located in the neighborhood of N₃ and O₂ atoms, but the relative ordering of their well depths is opposite to that observed in the MEP evaluated from the *ab initio* computation using a minimal basis set^{42,44} and opposite also to the experimental and theoretical proton affinities.^{71,72} This seems to be due to the increased proton affinity of oxygen versus nitrogen in both CNDO and INDO hamiltonians.¹³

In this context, MEPs for adenine, cytosine, 1*H*-1,2,4-triazole and oxazole were determined. These molecules possess two or more sites of protonation, but the center at which protonation occurs is well established⁷¹⁻⁷⁵ (Table VIII).

Energies of MEP minima computed at MNDO and *ab initio* STO-3G levels are shown in Table VIII. Selection of the STO-3G basis set obeys to its large use for studying molecules of this size. MNDO and STO-3G wavefunctions correctly assign the deepest MEP minimum at the protonation center determined from both experiment and theoretical calculations, although the relative well depths of MEP minima exhibit some differences between both methods. Note that MNDO, unlike CNDO and INDO, provides the correct ordering of proton affinities for N₃ and O₂ atoms of cytosine.

DISCUSSION

From the results presented in previous sections, some general features can be outlined with re-

Table VIII. Molecular Electrostatic Potential minima energies computed from MNDO and *ab initio* STO-3G wavefunctions for adenine, cytosine, 1*H*-1,2,4-triazole and oxazole. Energy values are given in kcal/mol.

	Site of protonation	MNDO	STO-3G
Adenine	N1	N1 -108.64	-91.15
		N3 -99.81	-87.87
		N7 -82.32	-84.49
Cytosine	N3	N3 -112.30	-103.48
		O2 ^a -103.63	-80.49
		O2 ^b -91.92	-69.30
1 <i>H</i> -1,2,4-Triazole	N4	N2 -71.77	-75.34
		N4 -90.03	-89.72
Oxazole	N	N -87.41	-88.39
		O -45.72	-34.19

spect to the basis set dependence and the reliability of MNDO wavefunction in the computation of MEPs. The comparison of energies and locations of MEP minima computed from 4-31G and 6-31G basis sets, as well as 4-31G* and 6-31G*, reveals that the extension of the number of primitive GTOs used to describe inner shells has, in practice, little effect as should be expected because the basis set dimension is not augmented.

In accordance with the above comments, it can be expected that the quality of the description of the outer shells decisively influences the MEP. In this sense, the extension of the basis set from minimal to split valence and the subsequent addition of polarization functions notably affects both the location and the depth of MEP minima. Energies of MEP minima and their locations derived from wave functions computed using Dunning's basis sets with and without polarization functions reinforce the relevance of the inclusion of polarization functions, which on the other hand must not be necessarily used to describe hydrogen atoms, since 6-31G* and 6-31G** basis sets do not differ significantly in their results.

Results presented in this work clearly demonstrate that in general increasing the size of the basis set, which implies an improvement in the basis flexibility, causes a removal out of the MEP minima from the molecule. The 6-31G* basis provides the highest MEP minima energies, whereas the lowest ones correspond in general to 6-31G. The wave function computed at the STO-3G level provides intermediate results between those of 6-31G and 6-31G*, being similar to 6-31G* results in the case of formaldehyde derivatives and approaching to 6-31G results in lone electron pairs of aromatic compounds. However, this ordering is altered when considering some molecules of small size such as N₂, HCN, or CO₂, where MEPs determined from the STO-3G basis set exhibit the deepest minima.

In most of the chemical research work, the dependence of the absolute values of MEP minima on the basis set quality is generally of secondary relevance providing that the main interest lies in the knowledge of the relative variation of MEP minima energies for a series of related molecules. In this context, excellent correlations are obtained between results derived from 6-31G* and 6-31G basis, a slightly poorest agreement being found between 6-31G* and STO-3G.

MEP minima originated from π -electron charge distributions have been excluded in the preceding discussion due to their particular characteristics. These MEP minima, whose description is usually a hard task, give nevertheless useful information in a wide range of chemical and bio-

chemical reactions. Our results summarized in Table VI and Table XIII reveal that the extension of the basis from STO-3G and 6-31G leads to an increase in the distance between the MEP minima and the molecular plane, but further addition of polarization functions causes a decrease in such distance. Analogously, the increase of the basis set size causes an important decrease in the MEP minima energies. These trends are in clear contrast with those reported previously on the basis set modulation of MEP minima related to lone pairs. Finally, in spite of the general satisfactory correlation between STO-3G and 6-31G* results, the minimal basis has a poor ability to reflect the real π -electron distribution over the aromatic rings.

One of the main goals of this work is to test the reliability of the MNDO wave function to compute MEPs. For this purpose, the ability of the MNDO Hamiltonian to reproduce the features of costly *ab initio* MEPs have been systematically tested in a wide range of molecules. Figure 1 shows the high degree of topological similarity between MNDO and 6-31G* electrostatic potential maps for pyridine, all of the essential characteristics of the 6-31G* MEP being correctly reflected by the MNDO wave function.

From a quantitative viewpoint, MNDO tends to minimize the distance from the MEP minimum to the molecule and exhibits a tendency to maximize the MEP minima depth. Nevertheless, it should be noted that the ratio between 6-31G* and MNDO MEP minima energies is in general a constant factor, suggesting that MNDO MEP minima energies should be scaled to approximately reproduce 6-31G* results. On the other hand, Table Ic clearly demonstrate the well performance of MNDO to reproduce the relative variation of 6-31G* MEP minima energies. It must be noted that the MEP computed from the MNDO wave function does not share the shortcomings found in the CNDO approximation in relation to the description of the π -electron charge distribution, as well as to the evaluation of relative MEP minima energies for molecules having several negative regions in competition.

CONCLUSIONS

The analysis of MEPs evaluated from the MNDO wave function as well as from the *ab initio* SCF wave functions computed using STO-3G, 4-31G, 6-31G, 4-31G*, 6-31G*, and 6-31G** basis sets reported here points out the ability of any of the corresponding wave functions to reproduce the general topology of isoelectrostatic potential surfaces for a large variety of compounds. How-

ever, neither semiempirical MNDO nor minimal STO-3G nor split-valence 6-31G wavefunctions are able to provide MEP minima energies derived from split-valence wave functions plus polarization basis set, although the ratio between

MEP minima energies computed from such wavefunctions with regard to those determined using split-valence plus polarization basis is approximately done by a constant factor. At this point, let us stress that this factor is consistently of the

Table IX. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for small molecules: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*
(A)						
MNDO	0.00	0.09	0.27	0.27	0.33	0.34
STO-3G		0.00	0.19	0.19	0.25	0.27
4-31G			0.00	0.00	0.06	0.08
6-31G				0.00	0.06	0.07
4-31G*					0.00	0.01
6-31G*						0.00
(B)						
MNDO	1.00	0.64	0.83	0.85	1.01	1.04
STO-3G	1.41	1.00	1.23	1.26	1.54	1.59
4-31G	1.13	0.75	1.00	1.02	1.24	1.28
6-31G	1.10	0.74	0.98	1.00	1.22	1.26
4-31G*	0.87	0.60	0.79	0.81	1.00	1.04
6-31G*	0.84	0.57	0.76	0.78	0.96	1.00
(C)						
MNDO	1.00	0.85	0.94	0.94	0.87	0.87
STO-3G		1.00	0.90	0.91	0.91	0.91
4-31G			1.00	1.00	0.98	0.97
6-31G				1.00	0.98	0.98
4-31G*					1.00	1.00
6-31G*						1.00

Table X. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for carbonyl compounds: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values, and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*
(A)						
MNDO	0.00	0.18	0.34	0.33	0.39	0.37
STO-3G		0.00	0.15	0.14	0.20	0.19
4-31G			0.00	0.00	0.05	0.05
6-31G				0.00	0.05	0.04
4-31G*					0.00	0.00
6-31G*						0.00
(B)						
MNDO	1.00	1.47	1.23	1.27	1.46	1.47
STO-3G	0.67	1.00	0.86	0.85	1.02	0.98
4-31G	0.81	1.15	1.00	1.01	1.18	1.20
6-31G	0.78	1.16	0.99	1.00	1.17	1.15
4-31G*	0.69	0.97	0.84	0.85	1.00	1.01
6-31G*	0.68	1.00	0.93	0.86	0.99	1.00
(C)						
MNDO	1.00	0.95	0.98	0.97	0.99	0.99
STO-3G		1.00	0.96	0.94	0.98	0.96
4-31G			1.00	1.00	0.99	0.99
6-31G				1.00	0.99	0.99
4-31G*					1.00	1.00
6-31G*						1.00

same magnitude for both lone pair and π -electron minima in the case of MNDO, but caution must be taken when dealing with STO-3G and 6-31G MEP minima, since such a factor qualitatively differs either considering lone pair (greater than unity) or π -electron minima (lower than unity). On the other hand, all of the methods reflect in general the relative variation of MEP minima energies determined from the wave function computed using the 6-31G* basis set.

Although MNDO does not reproduce the absolute values of MEP minima energies computed at the 6-31G* levels, results reported here are encouraging, specially since MNDO does not present some deficiencies found in the CNDO approximation, and consequently the use of the MNDO semiempirical wave functions for computing isopotential surfaces is a promising, unexpensive approach, particularly for large chemical and biochemical structures.

APPENDIX

Results of the statistical analysis of MEP minima for small molecules (Table IX), carbonyl compounds (Table X), derivatives of water and ammonia (Table XI), lone pair of heteroaromatic compounds (Table XII) and π -electron charge dis-

tribution of several compounds (Table XIII) are presented in this section, which also reports results concerning Dunning's basis sets (Table XIV).

Table XII. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for lone pair of heteroaromatic compounds: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	6-31G	6-31G*
(A)				
MNDO	0.00	0.11	0.25	0.31
STO-3G		0.00	0.13	0.20
6-31G			0.00	0.07
6-31G*				0.00
(B)				
MNDO	1.00	1.03	1.05	1.31
STO-3G	0.97	1.00	1.02	1.27
6-31G	0.95	0.98	1.00	1.25
6-31G*	0.76	0.79	0.79	1.00
(C)				
MNDO	1.00	0.97	0.94	0.97
STO-3G		1.00	0.96	0.99
6-31G			1.00	0.99
6-31G*				1.00

Table XI. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for derivatives of water and ammonia: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values, and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	4-31G	6-31G	4-31G*	6-31G*	6-31G**
(A)							
MNDO	0.00	0.14	0.24	0.27	0.32	0.33	0.32
STO-3G		0.00	0.13	0.13	0.18	0.19	0.18
4-31G			0.00	0.00	0.06	0.07	0.07
6-31G				0.00	0.06	0.07	0.07
4-31G*					0.00	0.00	0.00
6-31G*						0.00	0.00
6-31G**							0.00
(B)							
MNDO	1.00	1.16	1.02	1.09	1.31	1.41	1.35
STO-3G	0.84	1.00	0.93	0.93	1.20	1.21	1.23
4-31G	0.97	1.06	1.00	1.01	1.28	1.29	1.31
6-31G	0.90	1.06	0.99	1.00	1.27	1.29	1.30
4-31G*	0.76	0.83	0.78	0.79	1.00	1.01	1.03
6-31G*	0.70	0.83	0.77	0.77	0.99	1.00	1.02
6-31G**	0.74	0.81	0.76	0.77	0.97	0.98	1.00
(C)							
MNDO	1.00	0.75	0.92	0.72	0.97	0.80	0.97
STO-3G		1.00	0.93	0.92	0.97	0.97	0.97
4-31G			1.00	1.00	0.98	0.98	0.98
6-31G				1.00	0.98	0.97	0.98
4-31G*					1.00	1.00	1.00
6-31G*						1.00	1.00
6-31G**							1.00

Table XIII. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions for π -electron distribution of several compounds: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values, and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	6-31G	6-31G*
(A)				
MNDO	0.00	0.58	0.59	0.48
STO-3G		0.00	0.18	0.18
6-31G			0.00	0.20
6-31G*				0.00
(B)				
MNDO	1.00	2.24	1.55	1.35
STO-3G	0.36	1.00	0.61	0.53
6-31G	0.60	1.50	1.00	0.86
6-31G*	0.72	1.69	1.15	1.00
(C)				
MNDO	1.00	0.87	0.89	0.90
STO-3G		1.00	0.95	0.97
6-31G			1.00	0.99
6-31G*				1.00

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Table XIV. Statistical analysis of the similarity between Molecular Electrostatic Potential (MEP) minima calculated from different wavefunctions determined using Dunning's basis for several compounds: (A) mean distance (in Å) between minima locations, (B) coefficients of the least-square fitting ($MEP_i = c_{ij}MEP_j$) between the MEP minima energy values, and (C) Pearson's correlation coefficients between MEP minima energy.

	MNDO	STO-3G	6-31G	6-31G*	5s3p/3s	5s3p1d/3s
(A)						
MNDO	0.00	0.14	0.30	0.34	0.33	0.35
STO-3G		0.00	0.16	0.20	0.19	0.21
4-31G			0.00	0.04	0.03	0.05
6-31G				0.00	0.01	0.01
5s3p/3s					0.00	0.02
5s3p1d/3s						0.00
(B)						
MNDO	1.00	1.08	1.07	1.31	1.10	1.28
STO-3G	0.85	1.00	0.94	1.13	0.96	1.11
4-31G	0.91	1.02	1.00	1.21	1.03	1.19
6-31G	0.75	0.83	0.82	1.00	0.84	0.98
5s3p/3s	0.89	0.99	0.97	1.18	1.00	1.16
5s3p1d/3s	0.76	0.85	0.83	1.02	0.86	1.00
(C)						
MNDO	1.00	0.87	0.97	0.97	0.97	0.97
STO-3G		1.00	0.94	0.91	0.94	0.92
4-31G			1.00	0.99	0.99	0.99
6-31G				1.00	0.98	0.99
5s3p/3s					1.00	0.99
5s3p1d/3s						1.00

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