Excited-State Molecular Electric Properties of Some Biologically Important Purines, Pyrimidines, and Azines: An ab Initio Study

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Electronic charge distributions and molecular electrostatic potentials (MEP) in the ground and lowest singlet $\pi-\pi^*$ and $n-\pi^*$ excited states of certain azines, biologically important pyrimidines, and purines were studied using ab initio calculations where excited-state wave functions were generated using configuration interaction involving singly excited configurations (CIS). Further, these results were obtained by optimizing ground- and excited-state geometries of the molecules, and the 3-21G basis set was used. The MEP-fitted atomic point charges were obtained using the CHelpG procedure, and these charges were then distributed in three dimensions in the forms of the squares of the corresponding valence Slater *n*s (n = principal quantum number) atomic orbitals. It is found that while $\pi-\pi^*$ excited-state charges and MEP patterns are usually not too different from those of the ground states, the corresponding patterns in the $n-\pi^*$ excited states are drastically different. The charge redistributions in the azines following their $n-\pi^*$ excitations appear to follow an ortho, para directing effect. The computed dipole moment changes following excitations of the molecules are in satisfactory agreement with experiment.

1. INTRODUCTION

The biological importance of purines and pyrimidines has stimulated a large amount of research toward the understanding of their properties and interactions with other molecules using a wide variety of experimental and theoretical techniques.[1−11] Studies of electronic charge distributions and molecular electrostatic potential (MEP) maps are very helpful in the investigation of molecular reactivity and structure−property relationships. A large number of applications of these molecular properties have been made to characterize molecular activity, e.g. in drug design.[12−21] In these studies, mostly ground-state properties of molecules were investigated and such studies of excited-state properties are very scarce.[15,22−26] However, study of excited-state molecular properties may be highly valuable as it may help explain their structure−property relationships under electronic excitation. The knowledge about a change of charge distributions in molecules following their electronic excitation, particularly about systematics in this context, if any, can be helpful in rationalyzing the existing experimental data, in developing models and concepts for molecular behavior, and also in developing molecular electronic devices which may become important in the future. In view of this, study of excited-state electronic charge distributions, dipole moments, and MEP maps of some azines, some biologically important purines, and pyrimidines and a search of systematics in these molecular properties were considered to be highly desirable. The spectroscopic aspects of the molecules have been studied earlier using different methods.[1,7−11,22−29] and we do not intend to discuss these aspects here.

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2. COMPUTATIONAL DETAILS

Molecular electrostatic potential $V(r)$ at a point r due to a molecular charge distribution $\rho(r)$ is given by

$$V(r) = \sum_a^N \frac{Z_a}{|R_a - r|} - \int \frac{\rho(r')}{|r' - r|}\,dr' \qquad (1)$$

where Z_a is the charge on nucleus a located at R_a. Approximate MEP values can be obtained easily at points far away from a molecule using a discrete point charge distribution, but in order to obtain reliable MEP values at points close to atoms of molecules, the charges must be properly spread continuously in three dimensions. The total electronic charge located at an atomic site may be distributed continuously in three dimensions in the form given by the square of the corresponding valence Slater *n*s (n = principal quantum number 1, 2, 3, etc.) atomic orbital as has been done earlier.[30,31] Then, for $n = 1$, the electronic contribution to MEP represented by the second term of eq 1, is obtained[30,31] as

$$V^{el}(r) = \sum_a^N \frac{q_a}{|R_a - r|}[1 - (1 + \eta_a)\exp(-2\eta_a)] \qquad (2)$$

where $\eta_a = \zeta_a|R_a - r|$, q_a is the total electronic charge located at the site a and ζ_a is the Slater exponent of the 1s atomic orbital under consideration.

For $n = 2$, we have

$$V^{el}(r) = \sum_a^N \frac{q_a}{|R_a - r|} \times [1 - (1 + \eta_a(1.5 + \eta_a(1 + \eta_a/3)))\exp(-2\eta_a)] \qquad (3)$$

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Table 1. Optimized Values of ζ for CHelpG Charges of Different Non-Hydrogen Atoms

atom	ζ values	
	optimized	from Slater's rule[a]
N(pyridine)	2.055	1.950
O(C=O)	1.970	2.275
O(OH)	2.330	2.275

[a] See ref 35.

The point charges obtained by fitting of MEP, e.g. those referred to as CHelpG,[32] accurately reproduce electrostatic potentials at the van der Waals surfaces of molecules. The CHelpG charges for ground states were evaluated by employing the restricted Hartree−Fock self-consistent field ab initio theory and optimized ground-state molecular geometries. Further, the ground-state CHelpG charges were also calculated in aqueous solution using the polarizable continuum model (PCM) of the self-consistent reaction field method.[33,34] Geometries of two low-lying singlet excited states, one being the lowest of the n−π* type and the other being the lowest of the $\pi-\pi$* type, were also optimized, starting with the corresponding ground-state geometries, using configuration interaction involving singly excited configurations (CIS) in the gas phase, and the corresponding excited-state CHelpG charges were obtained.

The computed CHelpG charges were spread spherically symmetrically in forms given by the squares of valence Slater *n*s atomic orbitals, and the Slater exponents (ζ) were so adjusted to reproduce the features (not values) of full ab initio MEP maps for ground states of some molecules for which such results are available in the literature, as closely as possible. The Slater exponent corresponding to the carbon atom, irrespective of its valence state, was kept fixed at the value obtained from the Slater's rules.[35] For the other non-hydrogen atoms, ζ was found to depend strongly on the atomic valence state. The optimized ζ values for atoms occurring in the molecules studied here are presented in Table 1. The MEP values at the different sites of the molecules obtained from full ab initio calculations[15,20] which were used to optimize the parameters ζ along with the corresponding present calculated MEP values obtained using the continuously distributed CHelpG charges are presented in Table 2.[15,20] A satisfactory linear relationship exists between these two sets of MEP values, as shown in Figure 1, the linear correlation coefficient between the two sets of MEP values being 0.93. Thus, the present calculations performed using the CHelpG charges spread continuously in three dimensions are able to reproduce the features of the full ab initio MEP maps satisfactorily.[15,20] The same procedure and optimized ζ values as those used for the ground states, along with the corresponding CHelpG charges, were used to study the MEP maps of excited states also. All the ab initio calculations were performed using the 3-21G basis set and the Windows version of the Gaussian 94 program.[36]

3. RESULTS AND DISCUSSION

The lowest singlet excited state in all the molecules studied here, except hypoxanthine and cytosine, is of the n−π* type. In each of hypoxanthine and cytosine, the lowest singlet excited state was found to be of the $\pi-\pi$* type. The lowest singlet excited state of the $\pi-\pi$* type is the fourth excited state (S_4) in pyrazine, third excited state (S_3) in pyridazine, pyrimidine, and purine each, and second excited state (S_2) in each of pyridine, uracil, thymine, and guanine. The ring geometries in the excited states of all the molecules were found to be planar at the present level of calculations, except that of thymine in the n−π* excited state which was somewhat nonplanar. Further details about excited-state molecular geometries including vibrational analysis will be published separately elsewhere.

Table 2. Computed Negative MEP Values ($-V_{CHelpG}$) at the Different Sites of the Molecules Using Optimized ζ and CHelpG Charges along with the Full ab Initio ($-V_{ab}$) MEP Values

molecule/ sites[a]	MEP values		molecule/ sites[a]	MEP values	
	$-V_{CHelpG}$	$-V_{ab}$[b]		$-V_{CHelpG}$	$-V_{ab}$[b]
guanine			*cis*-glycine		
N_7	86.0	91.0	O_4	78.7	64.8
O_6	79.5	75.0	$O_5(H)$	81.0	68.8
N_3	76.2	64.0	$N_1(H_2)$		64.3
adenine			*trans*-glycine		
N_7	76.1	66.0	O_4	72.4	53.0
N_1	96.6	71.0	$N_1(H_2)$	103.7	105.0
N_3	94.6	71.0	oxazole		
cytosine			O_1	36.6	31.2
N_3	110.1	93.5	N_3	71.2	68.4
O_2	93.1	86.7	formamide		
uracil			O(C=O)	75.0	67.1
O_2	69.5	54.0	$N(NH_2)$	15.4	6.0
O_4	70.3	57.3	pyridine		
thymine			N	79.6	82.7
O_2	71.0	61.7			
O_4	66.9	61.1			

[a] For atomic numbering scheme, see Figures 2−4 and refs 15 and 20. [b] For details, see refs 15 and 20.

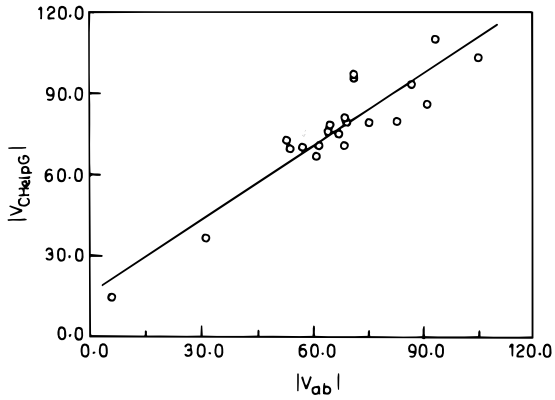

Figure 1. Variation of minimum MEP magnitudes (kcal/mol) at the different sites of the molecules obtained using CHelpG charges distributed continuously and spherically symmetrically with those obtained from full ab initio calculations. The straight line was obtained by a least-squares fitting of the two sets of MEP magnitudes.

3.1. Net CHelpG Charges. The net CHelpG charges located at the different atoms in the ground and lowest singlet n−π* and $\pi-\pi$* excited states of pyridine, pyrazine, and pyridazine are presented in Table 3. The charges are expressed in the unit of the magnitude of the electronic charge. In going from the ground to the $\pi-\pi$* excited states (Table 3), the charges undergo much smaller amounts of change in these molecules than those occurring under the corresponding n−π* excitations. Therefore, we would mainly concentrate on the charge redistributions consequent

Table 3. Computed CHelpG Charges at the Different Non-Hydrogenic Atomic Sites of Pyridine, Pyrazine, and Pyridazine in the Ground and Lowest Singlet $\pi-\pi^*$ and $n-\pi^*$ Excited States

	pyridine			pyrazine			pyridazine		
atom[a]	S_0	$S_1(n-\pi^*)$	$S_2(\pi-\pi^*)$	S_0	$S_1(n-\pi^*)$	$S_4(\pi-\pi^*)$	S_0	$S_1(n-\pi^*)$	$S_3(\pi-\pi^*)$
N_1	−0.71	0.14	−0.73	−0.50	−0.30	−0.60	−0.36	−0.17	−0.37
C_2	0.50	−0.35	0.48	0.21	0.03	0.24	0.45	0.11	0.50
C_3	−0.50	0.08	−0.35				−0.22	−0.18	−0.25
C_4	0.22	−0.38	0.04						

[a] For atomic numbering scheme, see Figure 2. The charges for those atoms which are not given here may be obtained by symmetry.

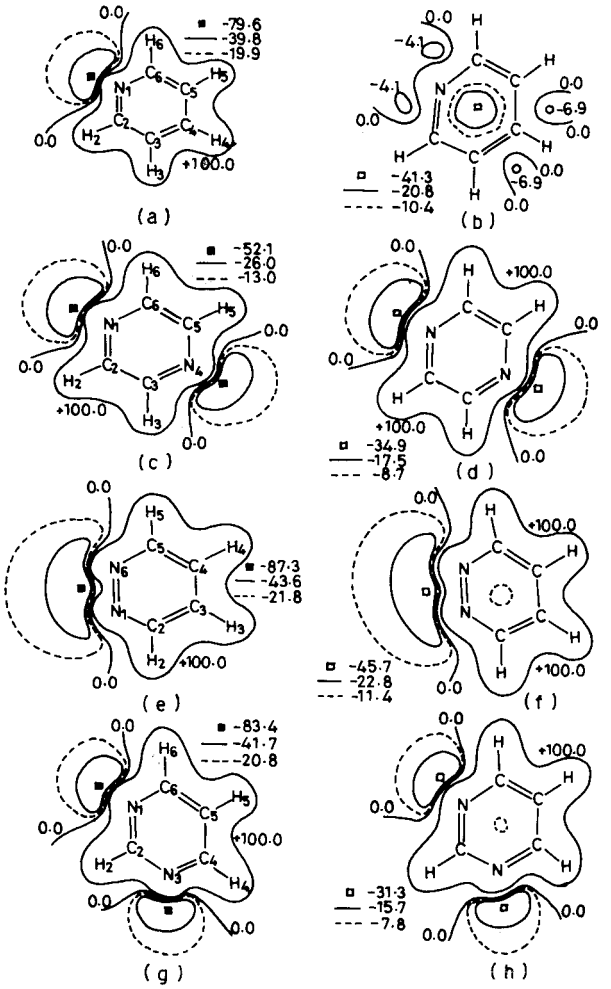

Figure 2. MEP maps (kcal/mol) obtained using CHelpG charges distributed continuously and spherically symmetrically: (a) pyridine, ground state; (b) pyridine, $S_1(n-\pi^*)$ excited state; (c) pyrazine, ground state; (d) pyrazine, $S_1(n-\pi^*)$ excited state; (e) pyridazine, ground state; (f) pyridazine, $S_1(n-\pi^*)$ excited state; (g) pyrimidine, ground state; (h) pyrimidine, $S_1(n-\pi^*)$ excited state. All the maps except that of pyridine in the $n-\pi^*$ excited state were obtained in the plane of the ring. Map b for pyridine in the $n-\pi^*$ excited state was obtained at 0.9 Å above the ring plane.

to the lowest singlet $n-\pi^*$ excitations of the molecules. We find that, in going from the ground state to the $n-\pi^*$ excited state, the nitrogen atom and the two carbon atoms located at the meta position with respect to the nitrogen atom of pyridine lose electronic charge appreciably while the ortho and para carbon atoms with respect to the nitrogen atom gain the same. Therefore, while the N_1 and C_3 atoms of pyridine (Figure 2) would act as hydrogen bond accepting sites in the ground and $\pi-\pi^*$ excited states, their role in this context would be taken over by C_2 and C_4 in the $n-\pi^*$ excited state. Thus, it appears that $n-\pi^*$ transitions possess an ortho, para directing property, with respect to the n-electron donating atom. Further, under this transition, the meta carbon atom with respect to the nitrogen atom also loses electronic charge to the carbon atoms located at the two ortho positions with respect to it. In earlier semiempirical calculations, occurrence of a para directing effect of $n-\pi^*$ transitions was found[37,38] which is partly corrected in view of the present more reliable results.

In pyrazine (Figure 2), consequent to the $n-\pi^*$ excitation, a significant amount of electron density migrates from the nitrogen atoms to the neighboring carbon atoms. However, still the nitrogen atoms are associated with a negative charge while the neighboring carbon atoms are associated with a small amount of positive charge each. As the two nitrogen atoms in pyrazine are located at para position with respect to each other, the occurrence of a negative charge at each of the nitrogens in the $n-\pi^*$ excited state, in view of the ortho, para directing effect, may be expected. In pyridazine (Figure 2), following its $n-\pi^*$ excitation, the nitrogen atoms N_1 and N_6 and carbon atoms C_3 and C_4 lose electronic charge while the carbon atoms C_2 and C_5 gain the same. However, despite this, the C_2 and C_5 atoms carry a positive charge of magnitude of about 0.11 while the nitrogen atoms carry a negative charge of magnitude of about 0.17 each in the $n-\pi^*$ excited state of pyridazine. There would be a complex consequence of the ortho, para directing effect as the two nitrogen atoms are located at the ortho position with respect to each other in pyridazine, and, therefore, occurrence of a negative charge at each of the two nitrogens in the molecule would be expected.

The electronic charge distributions in the ground and lowest $\pi-\pi^*$ and $n-\pi^*$ singlet excited states of pyrimidine, cytosine, uracil, and thymine are presented in Table 4. The excited-state properties of these molecules, e.g. the mechanism of photodimerization of uracil and thymine arising due to an increase in free valence at C_5 and C_6 following an increase in the C_5-C_6 bond length in the lowest singlet and triplet $\pi-\pi^*$ excited states of the molecules, have been discussed in the literature earlier,[39] and, therefore, these properties will not be discussed here. We find that in pyrimidine (Figure 2) also, following the $n-\pi^*$ transition, the nitrogens lose electronic charges strongly and the same are mainly gained by the two carbon atoms lying in their closest vicinity. In this case, the gain of electronic charge by the C_2 carbon is smaller than those of C_4 and C_6, which can be easily understood in terms of the ortho, para directing effect in which C_5 would also lose electronic charge to C_4 and C_6. In cytosine (Figure 3), under the $n-\pi^*$ excitation, the ring atoms gain and lose electronic charges alternately, the maximum loss occurring at N_3 while the maximum gain is made by C_4, and C_6 is also a significant gainer. Under

Table 4. Computed CHelpG Charges at the Different Non-Hydrogenic Atomic Sites of Pyrimidine, Cytosine, Uracil, and Thymine in Their Ground and Lowest Singlet $\pi-\pi^*$ and $n-\pi^*$ Excited States

	atomic sites[a]									
molecule and states	N_1	C_2	N_3	C_4	C_5	C_6	O_2	N_4	O_4	C_5
pyrimidine										
S_0	−0.88	0.94	−0.88	0.70	−0.76	0.70				
$S_1(n-\pi^*)$	−0.35	0.45	−0.35	0.01	−0.23	0.01				
$S_3(\pi-\pi^*)$	−0.84	0.96	−0.84	0.51	−0.47	0.51				
cytosine										
S_0	−0.81	1.24	−1.05	1.26	−0.84	0.39	−0.73	−1.20		
$S_1(\pi-\pi^*)$	−0.69	1.19	−0.91	0.96	−0.56	0.11	−0.61	−1.20		
$S_2(n-\pi^*)$	−0.51	0.81	−0.20	0.48	−0.40	−0.15	−0.63	−1.14		
uracil										
S_0	−0.68	1.08	−0.87	1.07	−0.68	0.26	−0.69		−0.66	
$S_1(n-\pi^*)$	−0.56	1.01	−0.80	0.56	−0.52	0.02	−0.70		−0.24	
$S_2(\pi-\pi^*)$	−0.54	0.99	−0.74	0.75	−0.40	0.07	−0.65		−0.60	
thymine										
S_0	−0.67	1.06	−0.86	0.95	−0.34	0.11	−0.68		−0.63	−0.14
$S_1(n-\pi^*)$	−0.41	0.80	−0.37	−0.05	0.19	−0.25	−0.67		−0.10	−0.41
$S_2(\pi-\pi^*)$	−0.51	0.98	−0.77	0.70	−0.10	−0.06	−0.65		−0.60	−0.30

[a] For atomic numbering scheme, see Figures 2 and 3.

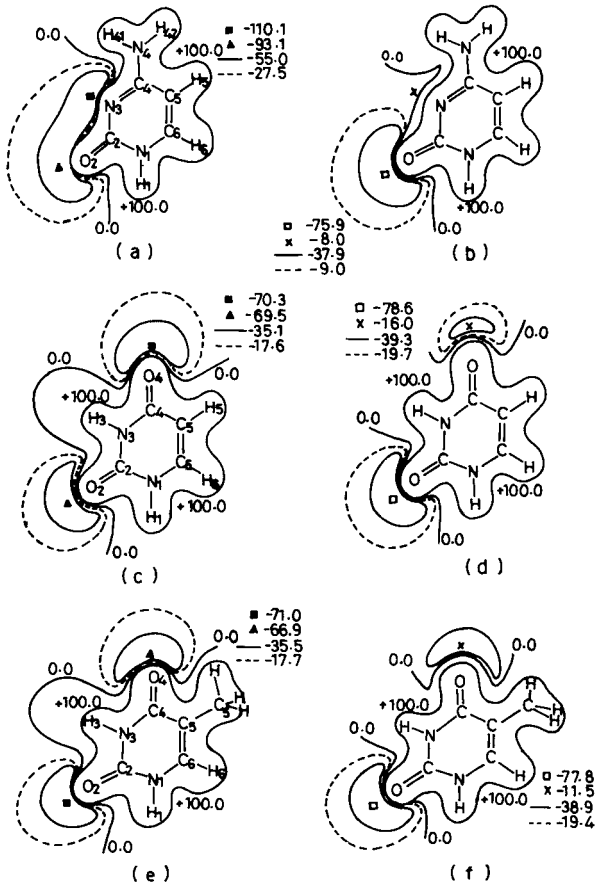

Figure 3. MEP maps (kcal/mol) obtained using CHelpG charges distributed continuously and spherically symmetrically: (a) cytosine, ground state; (b) cytosine, $S_2(n-\pi^*)$ excited state; (c) uracil, ground state; (d) uracil, $S_1(n-\pi^*)$ excited state; (e) thymine, ground state; (f) thymine, $S_1(n-\pi^*)$ excited state.

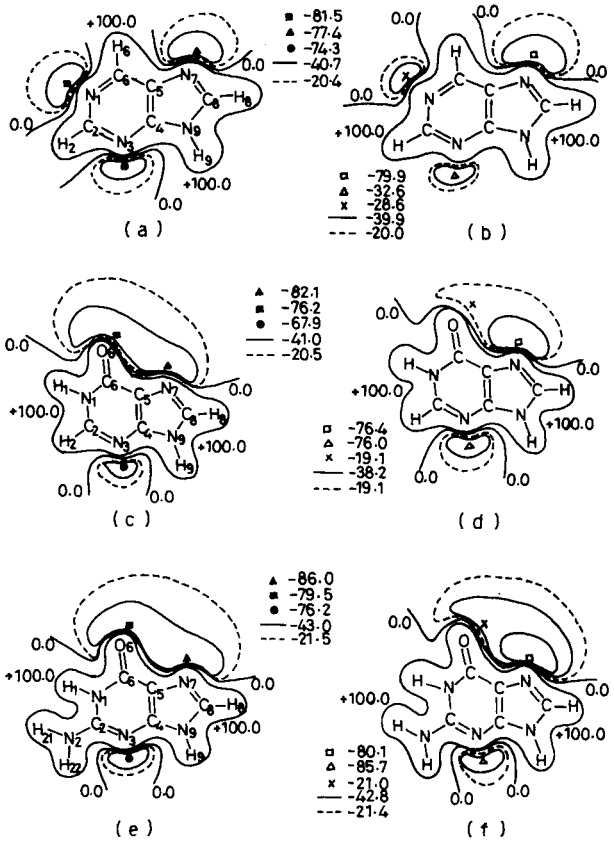

Figure 4. MEP maps (kcal/mol) obtained using CHelpG charges distributed continuously and spherically symmetrically: (a) purine, ground state, (b) purine, $S_1(n-\pi^*)$ excited state; (c) hypoxanthine, ground state; (d) hypoxanthine, $S_2(n-\pi^*)$ excited state; (e) guanine, ground state; (f) guanine, $S_1(n-\pi^*)$ excited state.

this excitation of cytosine, the carbonyl oxygen atom loses a comparatively much smaller amount of electronic charge than N_3 (Figure 3). In uracil and thymine (Figure 3), C_4 and C_6 are the major gainers of electron density while the N_1, N_3, O_4, and C_5 atoms are the losers under the $n-\pi^*$ excitations of the molecules, this charge rearrangement being more pronounced in thymine than that in uracil.

The ground-state as well as $\pi-\pi^*$ and $n-\pi^*$ excited-state atomic charge distributions in purine, hypoxanthine, and guanine (Figure 4) are presented in Table 5. We find a general feature that, under the $n-\pi^*$ excitation of each of these molecules, the C_6 atom gains electron density while the C_5 atom loses the same appreciably. Further, the O_6 atom is a major loser of electron density under the $n-\pi^*$ excitations of both hypoxanthine and guanine. In purine, under the $n-\pi^*$ excitation, in both the five- and six-

Table 5. Computed CHelpG Charges at the Different Non-Hydrogenic Atomic Sites of Purine, Hypoxanthine, and Guanine in Their Ground and Lowest Singlet $\pi-\pi^*$ and $n-\pi^*$ Excited States

	purine			hypoxanthine			guanine		
atom[a]	S_0	$S_1(n-\pi^*)$	$S_3(\pi-\pi^*)$	S_0	$S_1(\pi-\pi^*)$	$S_2(n-\pi^*)$	S_0	$S_1(n-\pi^*)$	$S_2(\pi-\pi^*)$
N_1	−0.78	−0.24	−0.71	−0.89	−0.77	−0.82	−0.96	−0.88	−0.93
C_2	0.73	0.23	0.65	0.63	0.30	0.60	1.12	1.08	0.89
N_3	−0.84	−0.44	−0.84	−0.81	−0.70	−0.76	−0.87	−0.84	−0.70
C_4	0.82	0.44	0.84	0.71	0.71	0.55	0.59	0.44	0.47
C_5	0.02	0.34	0.16	−0.14	0.01	0.06	−0.13	0.07	0.06
C_6	0.34	−0.28	0.17	0.91	0.80	0.35	0.87	0.30	0.75
N_7	−0.66	−0.63	−0.64	−0.55	−0.62	−0.53	−0.53	−0.51	−0.61
C_8	0.46	0.31	0.45	0.31	0.49	0.20	0.27	0.15	0.46
N_9	−0.76	−0.64	−0.78	−0.61	−0.74	−0.54	−0.53	−0.45	−0.66
O_6				−0.62	−0.53	−0.19	−0.62	−0.18	−0.55
N_2				−1.06	−1.06	−1.02			

[a] For atomic numbering scheme, see Figure 4.

membered rings separately, the atoms gain and lose electronic charges alternately. It is found that hypoxanthine and guanine have similar behavior with regard to electronic charge redistribution following the $n-\pi^*$ excitation, while purine shows a noticeably different behavior in this regard.

3.2. Excited-State Dipole Moments. The dipole moments in the ground and excited states of the molecules studied here along with the corresponding minimum MEP values near their different atomic sites are presented in Table 6. Dipole moment can serve as a good test of accuracy of the computed ground- and excited-state CHelpG charges. It has been shown earlier that CHelpG charges reproduce molecular dipole moments satisfactorily,[13] and the present study also led us to the same conclusion. Thus, the dipole moments obtained using SCF or SCF−CIS density matrix elements of the ground or excited states of molecules differed from those obtained using ChelpG charges, on the average, only by up to about 1%, except in the case of pyridazine where the average difference was found to be about 4.6%. We find that, according to our calculation, the dipole moment of pyridine changes by −2.3 D in going from the ground to the $n-\pi^*$ excited state (Table 6). Similarly, according to this calculation, the dipole moments of pyridazine and pyrimidine change by −2.0 and −2.1 D, respectively, in going from the ground state to the corresponding $n-\pi^*$ excited state (Table 6). Experimentally, the dipole moments of pyridine, pyridazine, and pyrimidine are found to change by −3.2, −2.84, and −2.7 D, respectively, following the corresponding $n-\pi^*$ excitation.[37] Thus, there is a satisfactory qualitative agreement between the calculated and observed dipole moment changes following the $n-\pi^*$ excitations of the molecules. The dipole moments of these molecules are not significantly changed following the respective $\pi-\pi^*$ excitations (Table 6).

In pyrimidine, cytosine, uracil, thymine, purine, hypoxanthine, and guanine also, the dipole moments decrease appreciably following the corresponding $n-\pi^*$ excitations (Table 6). In the case of purine, two appreciably different values of the ground-state dipole moment are reported i.e., 2.92 and 4.32 D in ethyl acetate and dioxane solutions, respectively.[26] Thus, the dipole moment of purine is quite sensitive to the solution environment. Our calculated value of the ground-state dipole moment of purine (3.62 D, Table 6) lies exactly midway between these two values, so it appears to be reasonable. Two $n-\pi^*$ excited-state dipole moment values have been reported for purine, i.e. 3.18 and 3.09 D,[26] which are in satisfactory agreement with our calculated value (Table 6). The dipole moment of guanine has been found[26] to change by about −2.3 D following the $n-\pi^*$ excitation of the molecule, and this is in a satisfactory agreement with our calculated value for this quantity (−1.86 D, Table 6). It is observed[26] in general that purines have smaller dipole moments in their first ($n-\pi^*$) singlet excited states, than those in the ground states and this observation is supported by the present results (Table 6). This feature, however, is not exhibited by the $\pi-\pi^*$ excited states of the molecules. Thus, dipole moments of purine, pyrimidine, uracil, and thymine are found to increase substantially following the corresponding $\pi-\pi^*$ excitations, while, in the other cases, dipole moment values are found to decrease under the corresponding $\pi-\pi^*$ excitations (Table 6). The experimental values for the increase of dipole moments of uracil and thymine following their $\pi-\pi^*$ excitations are 1.8 and 1.4 D, respectivily,[40] the corresponding present calculated values being 0.5 and 0.61 D. Thus, there is only a qualitative agreement between the experimental and calculated changes of dipole moment following the $\pi-\pi^*$ excitations of uracil and thymine. However, due to possible effects of the solvent environment and partly due to overlapping $\pi-\pi^*$ and $n-\pi^*$ bands in experimental studies, quantitative agreement between theory and experiment may sometimes not be obtained.

3.3. MEP Maps. The MEP values for the ground states of the different molecules in gas phase (Figures 2−4) and aqueous solution presented in Table 6 suggest that as a general rule ground-state MEP values increase substantially on solvation of the molecules in water. In the case of guanine, not only are the MEP values near O_6 and N_7 substantially changed following solvation in water but also their ordering is reversed with respect to that in the gas phase. The implications of the ground-state MEP values in some of the molecules in the gas phase have been discussed earlier by different authors.[12−21] In the case of guanine, in vivo, a strong interaction of both O_6 and N_7 sites takes place simultaneously with the anticancer drug *cis*-DDP, and, thus, a substantial increase in MEP values near both of these sites in water suggests that reactivity of the molecule with the drug would be appreciably enhanced in going from isolated guanine to one in aqueous solution.

The MEP values for excited states presented in Table 6 reveal the following information. Usually there is no large change in MEP patterns in going from the ground to the $\pi-\pi^*$ excited states of the molecules. However, in going

Table 6. Computed Dipole Moments (μ, in D) and Minimum MEP Values ($-V_{min}$) Near the Different Sites of the Molecules in Their Ground and Excited States

molecule and states	μ[a]	$-V_{min}$ (kcal/mol) site[b]	gas	aqueous
pyridine				
S_0	2.40	N	79.6	119.8
$S_1(n-\pi^*)$	0.10	R[c]	41.3	
$S_2(\pi-\pi^*)$	2.38	N	86.4	
pyrazine				
S_0		N	52.1	67.6
$S_1(n-\pi^*)$		N	34.9	
$S_4(\pi-\pi^*)$		N	68.4	
pyridazine				
S_0	4.67	N	87.3	145.4
$S_1(n-\pi^*)$	2.67	N	45.7	
$S_3(\pi-\pi^*)$	4.56	N	90.9	
pyrimidine				
S_0	2.51	N	83.4	110.9
$S_1(n-\pi^*)$	0.41	N	31.3	
$S_3(\pi-\pi^*)$	2.75	N	83.5	
purine (N_9H)				
S_0	3.64	N_1	81.5	104.1
		N_7	77.4	100.1
		N_3	74.3	93.3
$S_1(n-\pi^*)$	3.28	N_1	28.6	
		N_7	79.9	
		N_3	32.6	
$S_3(\pi-\pi^*)$	4.53	N_1	80.5	
		N_7	69.8	
		N_3	80.1	
hypoxanthine (keto-N_9H)				
S_0	5.63	N_7	82.1	115.9
		O_6	76.2	113.3
		N_3	67.9	73.1
$S_1(\pi-\pi^*)$	4.05	N_7	78.4	
		O_6	60.8	
		N_3	69.1	
$S_2(n-\pi^*)$	3.40	N_7	76.4	
		O_6	19.1	
		N_3	76.0	
cytosine				
S_0	7.15	N_3	110.1	145.2
		O_2	93.1	138.3
$S_1(\pi-\pi^*)$	5.38	N_3	95.8	
		O_2	67.8	
$S_2(n-\pi^*)$	4.52	N_3	8.0	
		O_2	75.9	
uracil				
S_0	4.79	O_2	69.5	97.0
		O_4	70.3	100.1
$S_1(n-\pi^*)$	3.23	O_2	78.6	
		O_4	16.0	
$S_2(\pi-\pi^*)$	5.29	O_2	63.6	
		O_4	72.6	
thymine				
S_0	4.65	O_2	71.0	103.5
		O_4	66.9	99.5
$S_1(n-\pi^*)$	3.66	O_2	77.8	
		O_4	14.1	
$S_2(\pi-\pi^*)$	5.29	O_2	65.0	
		O_4	72.6	
guanine (keto-N_9H)				
S_0	7.18	O_6	79.5	120.1
		N_7	86.0	116.7
		N_3	76.2	88.7
$S_1(n-\pi^*)$	5.32	O_6	21.0	
		N_7	80.1	
		N_3	85.7	
$S_2(\pi-\pi^*)$	6.16	O_6	72.4	
		N_7	83.6	
		N_3	61.2	

[a] In the gas phase. [b] For atomic numbering scheme, see Figures 2−4. [c] R, approximately above the center of the ring at a height of 0.9 Å.

from the ground to $n-\pi^*$ excited states of the molecules (Figures 2−4), the MEP patterns are usually found to change drastically. This difference between the $\pi-\pi^*$ and $n-\pi^*$ excited states should be expected on the basis of differences in the corresponding charge distributions discussed earlier. Thus, whereas the MEP magnitude is fairly high near the nitrogen atom in pyridine in both the ground and $\pi-\pi^*$ excited states (Figure 2), the lowest MEP value in the $n-\pi^*$ excited state of the molecule, lying near the middle portion of the ring in the molecular plane, has the value of −22.8 kcal/mol. However, the MEP minimum in the $n-\pi^*$ excited state of pyridine with magnitude −41.3 kcal/mol (Table 6) is located approximately above the middle portion of the ring at a height of about 0.9 Å from the molecular plane. Further, at this height from the molecular plane of pyridine, two pairs of low-magnitude negative MEP regions are localized, one each near the nitrogen atom and the para-carbon atom with respect to the nitrogen atom, in the $n-\pi^*$ excited state (Figure 2). In the case of pyrazine, the MEP minimum in the $n-\pi^*$ excited state is located near the nitrogen atom in the molecular plane, outside the ring, the excited-state MEP magnitude being much smaller than that near this site in the ground state (Table 6, Figure 2). Similarly, in the case of pyridazine, the MEP value is drastically reduced consequent to the $n-\pi^*$ excitation, and the minimum is located in the molecular plane at a point equidistant from the two nitrogen atoms outside the ring (Figure 2). A similar feature is observed in the $n-\pi^*$ excited state of pyrimidine also, where the MEP minimum is located in the plane of the molecule outside the ring near the two nitrogen atoms (Figure 2). In the $n-\pi^*$ excited state of each of pyridazine and pyrimidine, a low-magnitude negative MEP region is localized near the center of the ring in the molecular plane (Figure 2).

In cytosine, the MEP value near N_3 is drastically reduced, while that near O_2 is only marginally reduced in going from the ground to the $n-\pi^*$ excited state (Figure 3). In uracil, consequent to the $n-\pi^*$ excitation, the MEP magnitude near O_4 is drastically reduced, whereas that near O_2 is slightly increased in going from the ground to the $n-\pi^*$ excited state (Figure 3). This is an interesting result since the MEP values near the two oxygen atoms in uracil are similar in the ground state while they become widely different in the $n-\pi^*$ excited state. It shows that the $n-\pi^*$ excitation of uracil is mainly localized at the O_4 atom. The MEP patterns of thymine in

the ground and excited states are similar to those of uracil (Figure 3). Consequent to the n$-\pi^*$ excitation of purine, the MEP values are drastically reduced near both the N_1 and N_3 atoms, whereas there is a slight increase in the MEP value near N_7 (Figure 4). In hypoxanthine, the MEP value near O_6 is drastically reduced consequent to the n$-\pi^*$ excitation, and the same qualitatively holds true for guanine also (Figure 4).

CONCLUSIONS

We arrive at the following conclusions from the present study:

(i) MEP-derived charges such as CHelpG can be spread spherically symmetrically and continuously in three dimensions using the procedure adopted here, and, thus, MEP minima in the ground and excited states of molecules can be reliably obtained,

(ii) Rearrangement of charges following n$-\pi^*$ excitations of molecules and the accompanying changes of MEP patterns are much more drastic than those which follow $\pi-\pi^*$ excitations,

(iii) Excitations of the n$-\pi^*$ type of azines appear to possess an ortho, para directing property where the electronic charges migrate from the n-electron center to the atoms located at ortho and para positions with respect to it. Also, the atom located at the meta position with respect to the n-electron center transfers electronic charge to the atoms located at the ortho position with respect to it under the n$-\pi^*$ excitation,

(iv) In pyridine, the MEP minimum is located above the ring plane in the n$-\pi^*$ excited state, while it is located near the ring nitrogen atom in the molecular plane in the ground and $\pi-\pi^*$ excited states of the molecule. In all of the other azines studied here, in the ground and $\pi-\pi^*$ and n$-\pi^*$ excited states, the MEP minima are located near the nitrogen atoms in the molecular plane,

(v) In all the molecules studied here, n$-\pi^*$ excited-state dipole moments are smaller than those in the ground and $\pi-\pi^*$ excited states, and the available experimental data support these results.

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REFERENCES AND NOTES

(1) Broo, A.; Holmen, A. *J. Phys. Chem. A* **1997**, *101*, 3589.
(2) Holmen, A.; Norden, B.; Albinsson, B. *J. Am. Chem. Soc.* **1997**, *119*, 3114.
(3) Johnson, R. C.; Power, T. D.; Holt, J. S.; Immaraporn, B.; Monat, J. E.; Sissoko, A. A.; Yanik, M. M.; Zagorodny, A. V.; Cybulski, S. M. *J. Phys. Chem.* **1996**, *100*, 18875.
(4) Colarusso, P.; Zhang, K. Q.; Guo, B.; Bernath, P. F. *Chem. Phys. Lett.* **1997**, *269*, 39.
(5) Aamouche, A.; Ghomi, M.; Coulombeau, C.; Grajcar, L.; Baron, M. H.; Jobic, H.; Berthier, G. *J. Phys. Chem. A* **1997**, *101*, 1808.
(6) Broo, A.; Pearl, G.; Zerner, M. C. *J. Phys. Chem. A* **1997**, *101*, 2478.
(7) Shukla, M. K.; Mishra, P. C. *Spectrochim. Acta* **1996**, *52A*, 1547.
(8) Mishra, P. C. *J. Mol. Struct.* **1989**, *195*, 201.
(9) Santhosh, C.; Mishra, P. C. *Int. J. Quantum Chem.* **1992**, *42*, 1659.
(10) Sheina, G. G.; Stepanian, S. G.; Radchenko, E. D.; Blagoi, Yu. P. *J. Mol. Struct.* **1987**, *158*, 275.
(11) Chenon, M.-T. Pugmire, R. J.; Grant, D. M.; Panzica, R. P.; Townsend, L. B. *J. Am. Chem. Soc.* **1975**, *97*, 4627, 4636.
(12) Mishra, P. C.; Kumar, A. In *Molecular Similarity II*; Sen, K., Ed.; Springer-Verlag: Berlin, Heidelberg, 1995; p 27.
(13) Mishra, P. C.; Kumar, A. In *Molecular Electrostatic Potentials, Concepts and Applications*; Murray, J. S., Sen, K., Eds.; Elsevier: Amsterdam 1996; p 257.
(14) Alkorta, I.; Perez, J. J. *Int. J. Quantum Chem.* **1996**, *57*, 123.
(15) Scrocco, E.; Tomasi, J. In *Advances in Quantum Chemistry*, Vol. III; Lowdin, P.-O., Ed.; Acedemic Press: New York, 1978; p 115.
(16) Sponer, J.; Hobza, P. *Int. J. Quantum Chem.* **1996**, *57*, 959.
(17) Luque, F. J.; Orozco, M.; Bhadane, P. K.; Gadre, S. R. *J. Phys. Chem.* **1993**, *97*, 9380.
(18) Sjoberg, P.; Politzer, P. *J. Phys. Chem.* **1990**, *94*, 3959.
(19) Naray-Szabo, G.; Ferenczy, G. G. *Chem. Rev.* **1995**, *95*, 829.
(20) Politzer, P.; Laurence, P. R.; Jayasuriya, K. *Environ. Health Perspect.*, **1985**, *61*, 191.
(21) Hecht, J. L.; Honig, B.; Shin, Y.-K.; Hubbel, W. L. *J. Phys. Chem.*, **1995**, *99*, 7782.
(22) Mishra, P. C.; Jug, K. *J. Mol. Struct. (THEOCHEM)* **1994**, *305*, 139.
(23) Shukla, M. K.; Mishra, P. C. *Chem. Phys.*, in press.
(24) Slater, L. S.; Callis, P. R. *J. Phys. Chem.* **1995**, *99*, 8572.
(25) Zeng, J.; Hush, N. S.; Reimers, J. R. *J. Phys. Chem.* **1996**, *100*, 9561.
(26) Aaron, J.-J.; Gaye, M. D.; Parkanyi, C.; Cho, N. S.; Szentpaly, L. V. *J. Mol. Struct.* **1987**, *156*, 119.
(27) Walker, I. C.; Palmer, M. H. *Chem. Phys.* **1991**, *153*, 169.
(28) Walker, I. C.; Palmer, M. H. *Chem. Phys.* **1991**, *157*, 187.
(29) Mishra, P. C. *J. Mol. Struct.* **1986**, *144*, 309.
(30) Kumar, A.; Mohan, C. G.; Mishra, P. C. *Int. J. Quantum Chem.* **1995**, *55*, 53.
(31) Mohan, C. G.; Kumar, A.; Mishra, P. C. *Int. J. Quantum Chem.* **1996**, *60*, 699.
(32) Breneman, C. M.; Wiberg, K. B. *J. Comput. Chem.* **1990**, *11*, 361.
(33) Miertus, S.; Tomasi, J. *Chem. Phys.* **1982**, *65*, 239.
(34) Miertus, S.; Scrocco, E.; Tomasi, J. *Chem. Phys.* **1986**, *55*, 117.
(35) Pople, J. A.; Beveridge, D. L. *Approximate Molecular Orbital Theory*; McGraw-Hill: New York, 1970.
(36) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. *Gaussian 94W*, Revision B.3; Gaussian, Inc.: Pittsburgh, PA, 1995.
(37) Mishra, P. C.; Tewari, R. D. *Indian J. Pure Appl. Phys.* **1987**, *25*, 387.
(38) Tewari, R. D.; Mishra, P. C. *J. Comput. Chem.* **1984**, *5*, 225.
(39) Srivastava, S. K.; Mishra, P. C. *Int. J. Quantum Chem.* **1979**, *16*, 1051.
(40) Srivastava, S. K.; Mishra, P. C. *J. Mol. Struct.* **1980**, *65*, 199.

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