

Molecular electrostatic potential mapping using a dipole

ANIL KUMAR and P C MISHRA*

Department of Physics, Banaras Hindu University, Varanasi 221 005, India

Abstract. A new method of mapping molecular electrostatic potentials using a dipole of arbitrary length and strength has been developed. The dipole is allowed to move on a geometrical surface enclosing the molecule under study such that the closest distance of approach (CDA) between the two species is fixed. Potential maps of water, formaldehyde and ethylene epoxide molecules have been studied by this approach for CDA values of 2 and 5 Å. Experimental geometries for the molecules and net charge distributions obtained by the MNDO molecular orbital method were used in the calculations. Dipole potential maps obtained by the present method are compared with those obtained by the prevalent monopole mapping method. The two approaches broadly predict the same sites for potential minima in the molecules studied. The present dipole maps are however more informative, especially with regard to electric field directions, than the monopole maps, and it has been shown that this additional information is very useful.

Keywords. Electrostatic potential mapping; dipole potential mapping; molecular electric fields.

1. Introduction

Molecular electrostatic potential maps provide useful clues to favoured modes of interactions of molecules. It is particularly useful for studying biomolecular recognition where due to the large size of molecules involved, adequate molecular orbital treatments become cumbersome (Del Re *et al* 1985). A positive monopole is employed as the mapping device in the prevalent method of potential mapping (Scrocco and Tomasi 1978). As a monopole has no spatial extension and orientational capability, it cannot generally represent a molecule. Thus monopole potential maps yield no information on preferred orientations of two interacting molecules and probable hydrogen-bonding directions. Magnitudes of monopole potential energies are also generally too high to correspond to real intermolecular interactions. These considerations suggest that alternative methods of potential mapping need to be developed. As biomolecular recognition is essentially a long range interaction process where two molecules would mainly influence each other via the dipole-dipole interaction mechanism, a dipole was considered to be a suitable mapping device and used in the present approach.

* To whom all correspondence should be addressed

2. Method of calculation

The electrostatic interaction energy of a given dipole with a molecule may be evaluated using either the multipole interaction scheme or interactions of the charges directly (Gray and Gubbins 1984; Price *et al* 1984). Our computer program includes both these possibilities as options. A comparative evaluation of the two approaches (Mishra and Tewari 1986) does not show any noticeable superiority of the multipole formalism over that based on direct interactions of the net charges, though calculations using the multipole approach are generally more complex. Therefore, the potential energies of interaction of the molecules studied here were calculated using a mapping dipole of length 1 Å and strength 1 Debye, and charge-charge interactions. Experimentally determined geometries (Callomon *et al* 1976) of the molecules were employed and net charge distributions used were obtained with the MNDO molecular orbital method (Dewar and Thiel 1977). Two closest distances of approach (CDA) i.e. 2 and 5 Å, between the mapping dipole and the molecules in question were used. At each chosen point on the CDA surfaces, the mapping dipole was allowed to orient itself along the direction of minimum interaction energy; these energies were taken as characteristic potentials of the corresponding points. It is obvious that the present method of potential mapping has one aspect common with electric field mapping i.e. the direction of the mapping dipole. But while in electric field mapping the quantity evaluated is electric field, in the present approach the potential energy of electrostatic interaction between a molecule and the dipole is calculated. In other words, the present method yields information with regard to potential and electric field direction simultaneously. In order to compare the present results with those of monopole mapping, monopole potential maps for the molecules studied here were also obtained using the QCPE program no. 249 using the same net charges and geometries as mentioned above; the contours were obtained via a line printer and then redrawn manually. This limits the degree of smoothness of the contours but the potential features can still be easily extracted.

3. Results and discussion

Potential maps for three molecules: water, formaldehyde and ethylene epoxide, are presented in figures 1a and 1b to 3a and 3b, respectively. The "a" parts of the figures contain dipole potential maps obtained by the present approach whereas the "b" parts contain the corresponding monopole potential maps. In the dipole maps, potential distributions are presented with the help of certain chosen points in each case; potentials at the other points can be obtained approximately by interpolation. The monopole potentials are presented as isopotential contours. The numbers given in the dipole potential maps are potential energies in the unit of 0.1 kcal/mole; the arrows in these maps correspond to electric field directions at the corresponding points. The numbers given in the monopole potential maps are potential energies in kcal/mole. These maps exhibit the following features.

According to figure 1a, there is a fairly extended region of potential minimum near the oxygen atom of the molecule of water on the exterior side of the HOH angle. Another shallow potential minimum exists in the middle of the interior

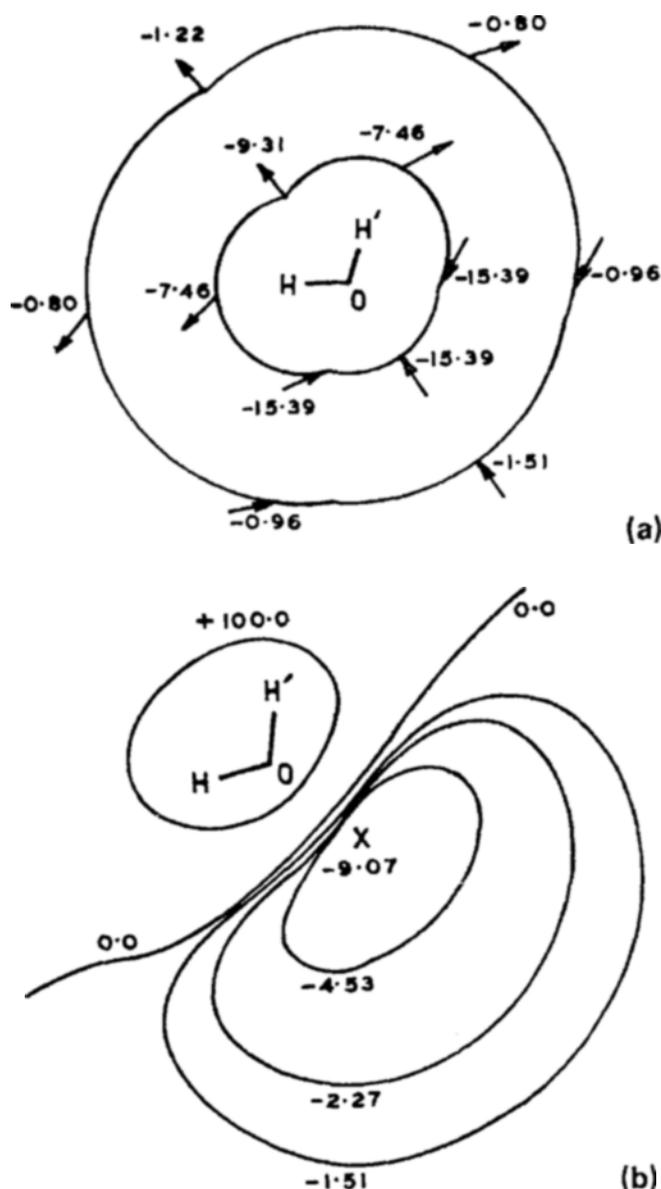


Figure 1. Dipole (a) and monopole (b) potential maps of water in molecular plane.

HOH angle also. These observations are broadly valid for both the 2 and 5 Å CDA surfaces. As *ab initio* net atomic charges are significantly larger in magnitude (Hankins *et al* 1970) than those obtained by the MNDO method, use of the former in place of the latter would result in larger magnitudes of potential energies. However, it would not significantly affect the main potential features and electric field directions especially for symmetric molecules like water. The monopole potential map presented in figure 1b also shows the minimum near the oxygen atom of water on the exterior side of the HOH angle (Scrocco and Tomasi 1978). Thus the maps of figures 1a and 1b broadly agree with regard to the location of the potential minimum. The map of figure 1a has an important additional information in comparison to that of figure 1b i.e. with regard to the directions of electric field at the various points. The importance of the electric field directions would become clear from the following discussion.

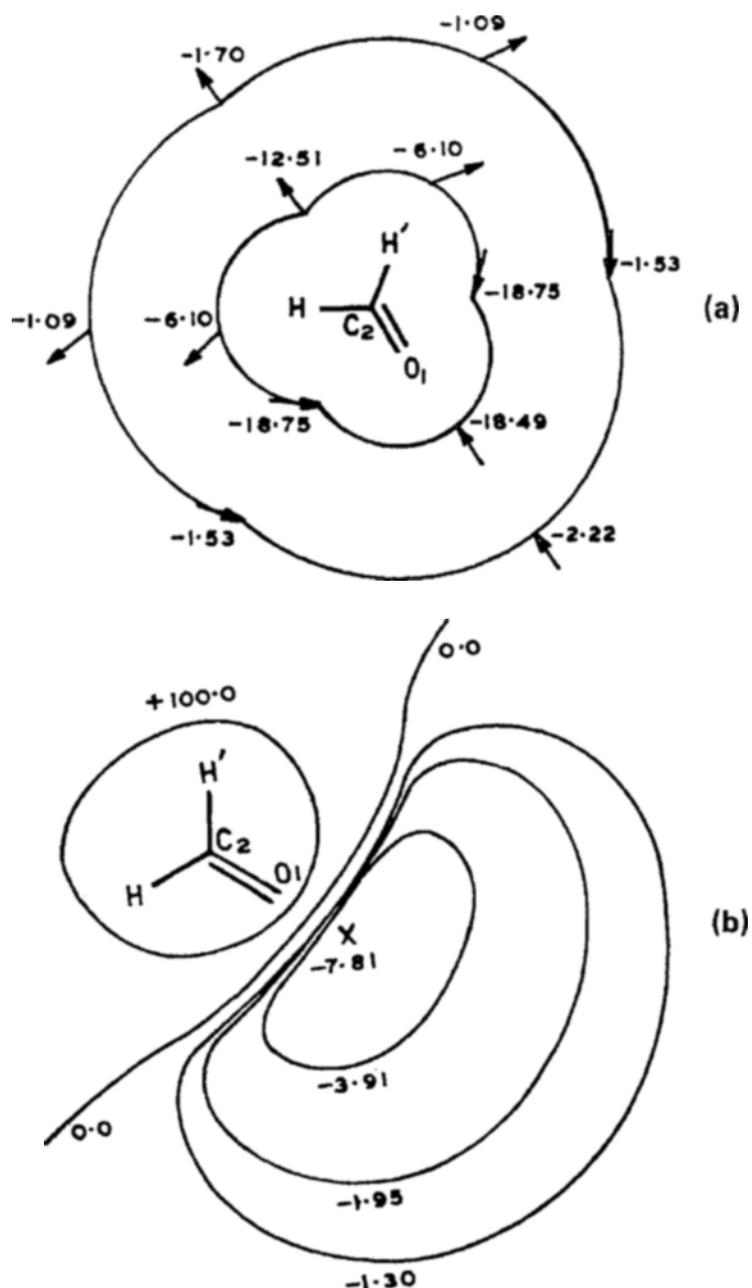


Figure 2. Dipole (a) and monopole (b) potential maps of formaldehyde in the molecular plane.

Let us consider the hydrogen-bonded dimer of water. This aspect has been discussed in the literature in several reviews and papers (Rao 1972; Hankins *et al* 1970). Thus out of the three hydrogen-bonded configurations for the water dimer—the so-called linear, cyclic and bifurcated—the linear one, having a plane of symmetry and the non-bonded protons of the monomers being *trans* to each other, has been found to be the most stable. The angle of rotation of the OHO plane of the second water molecule with respect to the OH bond of the first has been shown to be 40° (Hankins *et al* 1970). Our results presented in figure 1a show that the electric field when observed in the OH bond directions near the hydrogens is

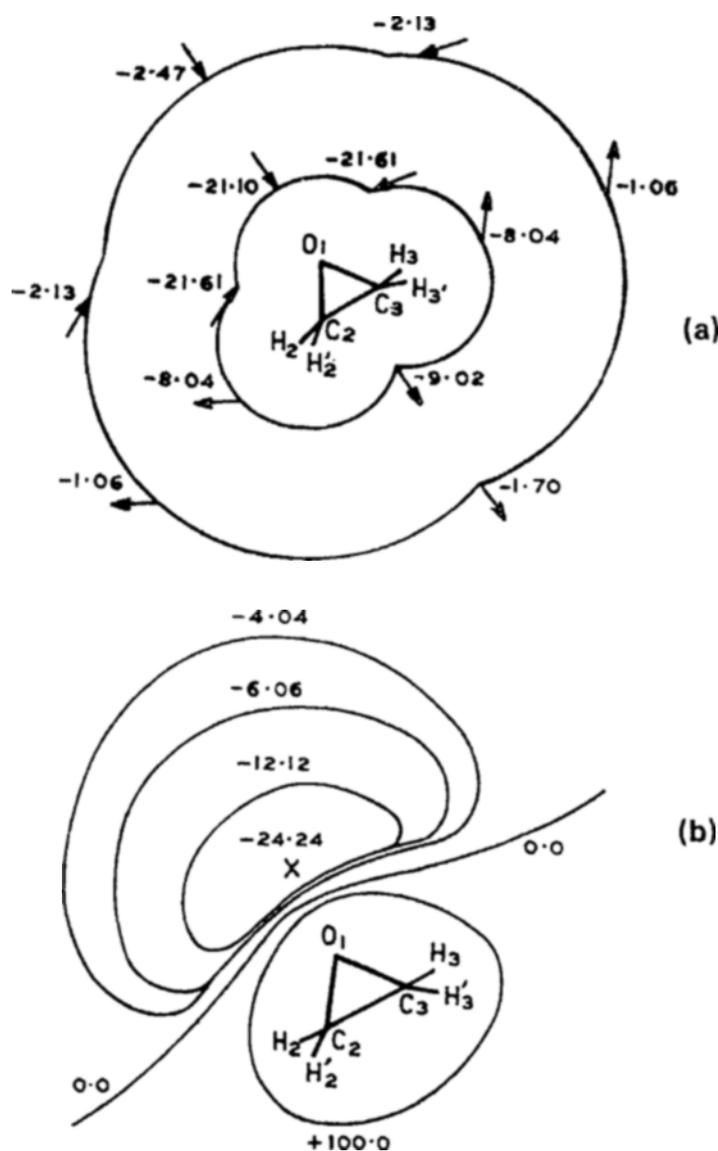


Figure 3. Dipole (a) and monopole (b) potential maps of ethylene oxide in the OCC plane.

inclined at about 30° with respect to the bonds. It is further noted that in going from one to the other CDA surfaces the electric field direction remains almost constant in a given region of the molecular space. Thus even on the basis of electric field considerations alone, one can predict the relative orientations of the two water molecules in the linear dimer with reasonable accuracy. Similarly, for the other two hydrogen-bonded configurations also, relative molecular orientations are satisfactorily predicted by the map of figure 1a. Obviously the monopole potential map of figure 1b completely fails in making predictions of this kind. It should be mentioned that despite the success of the present approach in elucidating molecular electrostatic potential and electric field features successfully, it cannot generally be used to predict relative stabilities of different hydrogen-bonded configurations. This is because in addition to electrostatic interactions, other interactions e.g.

charge transfer, polarization and overlap etc. which are not included in the present approach also contribute, more or less, to hydrogen bonds. Further, the contributions of these interactions and optimal interatomic distances, which may not be known, would be different in different configurations.

Dipole and monopole potential maps of formaldehyde are presented in figures 2a and 2b. According to figure 2a, broadly speaking, the minimum potential energy region in formaldehyde lies around the oxygen atom and is quite extended. At the 2 Å CDA surface, the potential in front of the CO bond of formaldehyde is about 0.03 kcal/mole higher than that of the minimum which is located almost in front of the HC bond. At the 5 Å CDA surface, the minimum is located in front of the CO bond. Figure 2b also shows the potential minimum, as detected by a positive monopole, as located near the oxygen atom (Scrocco and Tomasi 1978). Thus the potential maps of figures 2a and 2b are broadly in agreement.

The dipole potential map of ethylene epoxide in the plane containing the carbon and oxygen atoms is presented in figure 3a. It has features similar to those of figure 2a. The maps of figures 3a and 3b broadly agree in that the potential minimum in ethylene epoxide lies near the oxygen atom. The monopole potential map of this molecule has been studied by Politzer *et al* (1978) using an *ab initio* approach. The maps presented in the figures 3a and 3b are in agreement with those due to these authors with regard to the location of the potential minimum. It may be remarked that ethylene epoxide, in particular some of its derivatives, are known to be carcinogenic.

Electric field directions in the maps of figures 1a, 2a and 3a are very similar together. This is not surprising as the three molecules belong to the same point group.

Acknowledgement

The work was partly supported by a project grant from UGC, New Delhi, for which PCM is thankful.

References

- Callomon J H, Hirota E, Kuchitsu K, Lafferty W J, Maki A G and Pote C S 1976 *Numerical data and functional relationships in science and technology Vol. 7: Structure data of free polyatomic molecules* (ed.) K H Hellwege (New York: Springer)
- Del Re G, Pepe G, Laporte D, Minichino C and Serres B 1985 in *Molecular basis of cancer. Part B: Macromolecular recognition, chemotherapy and immunology* (New York: Alan R Liss) p. 115
- Dewar M J S and Thiel W 1977 *J. Am. Chem. Soc.* **99** 4899
- Gray C G and Gubbins K E 1984 *Theory of molecular fluids Vol. 1: Fundamentals* (Oxford: Clarendon) p. 54
- Hankins D, Moskowitz J W and Stillinger F H 1970 *Chem. Phys. Lett.* **4** 527, 581
- Mishra P C and Tewari R D 1986 *Int. J. Quantum Chem.* (submitted)
- Politzer P, Daiker K C, Estes V M and Baughman M 1978 *Int. J. Quantum Chem., Quantum Biol. Symp.* **5** 291
- Price S L, Stone A J and Alderton M 1984 *Mol. Phys.* **52** 987
- Rao C N R 1972 in *Water. Vol. 1: The physics and physical chemistry of water* (New York: Plenum) p. 93
- Scrocco E and Tomasi J 1978 *Adv. Quantum Chem.* **11** 115