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Photosensitizing properties for porphyrazine and some derivatives

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Abstract

Time-dependent density functional theory (TD-DFT) calculations were performed to study photosensitizing properties for porphrazine and eleven of its related derivatives. Two model categories have been considered based on the existence of CN functional group in addition to the other functional groups; H, CH_3, F, CF_3, C_6H_5, and C_6F_5. The CN group could moderate the molecular level energy properties in which the required absorption wavelengths were almost similar in the models. The numbers of the generated $^1O_2$ molecules are almost around one and some others, in which the numbers are slightly changed for the models based on the required absorption wavelengths. As a final remark, the chemicals could be used with safer wavelength regions for applications on living tissues based on their dominant functional groups.

Keywords: Porphrazine; photosensitizer; density functional theory; photodynamic therapy.

Introduction

Photosensitizers (PS) are those chemicals which can be excited by the extra light source, in which the electrons of a lower state move to an upper state in an excited mode (PS→PS*) [1]. The PS can be also considered as an energy container, in which the excited mode of PS can be relaxed to the original PS state (ground state) by stopping the extra source. In this way, the available extra energy could be released from PS* to PS during the relaxation to make a new energy resource to be employed in the novel photodynamic therapy (PDT) of cancer cells, etc. [2] As a brief description, we need a PS* as an energy resource to convert normal triplet molecular oxygen ($^3O_2$) to activate singlet one ($^1O_2$) as an antioxidant or a good oxidant to kill the cancer cells in the PDT type-II [3]. Therefore, it is important to carefully examine the ability of candidate PS materials to generate enough $^1O_2$ counterparts [4]. Porphyrin, which could be found in nature, has always been mentioned as a proper PS material for PDT but with different efficiencies in different systems [5]. Earlier works indicated that examining the capability of other derivatives of porphyrin is also an important task to have better conditions

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in PDT [6]. Moreover, other materials have been also seen as important PS subjects for PDT as indicated for example by the work of Russo and co-workers on the squaraine dyes [7]. Further inspection of literature can show that methylene blue, pentamethincyanin, and several other dyes are the PS subjects of more targeted PDT processes [8-10]. Porphyrazine (Pz) is another porphyrin derivative by important characters for PS applications in PDT processes [11-14]. Although the earlier experimental works have been focused on the capabilities of the Pz structure, the theoretical aspects can still reveal insightful information on the details of the PS candidate material.

Within this work, we have investigated the photosensitizing properties of Pz and its derivatives based on quantum chemical density functional theory (DFT) computational procedures. To this aim, the characters of original Pz and eleven derivatives have been investigated to examine the 1O2 generation efficiency for PDT type-II. Structural geometries optimization and molecular orbital properties evaluation have been done to achieve the main goal of this work; to examine the molecular-scale efficiency and the required absorption wavelengths for Pz and also to generate $^1O_2$ molecular counterpart.

Computational details

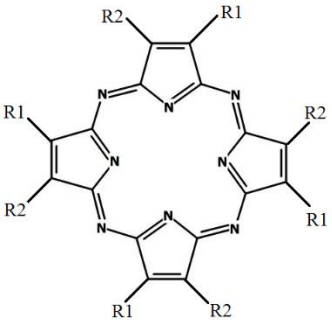
The standard B3LYP/6-31G* density functional theory (DFT) calculations [15] have been performed to optimize twelve models of Pz (porphyrazine) structures including A01 to A06 and B01 to B06. To validate the optimized structures, frequencies have been also calculated to ensure the non-imaginary frequencies for the structures. The models have been divided into two A and B categories based on the existence of the CN functional group in the B models instead of the H atom in the A models (Table 1). The other functional groups include H, CH_3, F, CF_3, C_6H_5 and C_6F_5 in both of A and B categories. After obtaining minimized-energy structures, the time-dependent (TD) DFT calculations have been subsequently performed at the same level of theory to evaluate the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) energy levels and patterns (Table 2 and Figure 1). The required 1.704 eV energy for $^3O_2 \rightarrow {}^1O_2$ conversion has been calculated to count the number of produced $^1O_2$ molecules for each Pz structure. All calculations of this work have been performed employing the Gaussian package of program [16].

Results and discussion

We have performed DFT calculations to investigate the properties of Pz derivatives for PS applications in PDT processes. The results of Table 2 for the investigated models (Table 1) indicate the computationally obtained HOMO and LUMO energy levels of the already optimized structures. Based on the structural features (Table 1), the Pz models have been divided into two six–molecule sets of A0x without –CN functional group and B0x with –CN functional group. As mentioned above, the obtained numbers of $^1O_2$ counterpart by relaxation of PS*→PS could be considered as efficacy of the PS material for application in PDT type-II. It is very much important to see what happens to the structures by the additional functional groups for the specific purposes. Based on the obtained values of HOMO and LUMO energy levels (Table 2 and Figure 1), the minimum required energy for PS→PS* conversion by the external light source can be considered. Since

the PDT is performed on the human body, the wavelength of the projected light should be seen as having the prior importance. The visible light wavelength is categorized between 400-800 nm, in which this region could be safely considered for human body. Then, as assumed that all the absorbed energy of PS→PS* would be released after stopping the light source during PS*→PS relaxation, the number of generated $^1O_2$ molecules could be counted.

Table 1. The investigated models



Model	R1	R2	Model	R1	R2
A01	H	H	**B01**	CN	H
A02	H	CH_3	**B02**	CN	CH_3
A03	H	F	**B03**	CN	F
A04	H	CF_3	**B04**	CN	CF_3
A05	H	C_6H_5	**B05**	CN	C_6H_5
A06	H	C_6F_5	**B06**	CN	C_6F_5

Table 2. HOMO–LUMO energy levels*

Pz	HOMO (eV)	LUMO (eV)	$E_{PS\rightarrow PS^*}$ (eV)	$\lambda_{PS\rightarrow PS^*}$ (nm)	$^1O_2$ (no.)
A01	–6.06	–3.51	2.55	487	1.49
A02	–5.80	–3.24	2.56	484	1.50
A03	–6.50	–3.88	2.62	473	1.54
A04	–6.99	–5.35	1.65	752	0.97
A05	–5.87	–3.34	2.53	490	1.49
A06	–6.56	–4.42	2.14	580	1.26
B01	–7.33	–4.94	2.39	519	1.40
B02	–7.04	–4.62	2.43	511	1.42
B03	–7.74	–5.24	2.50	496	1.47
B04	–7.90	–5.54	2.36	525	1.39
B05	–6.68	–4.41	2.27	547	1.33
B06	–7.28	–5.01	2.26	548	1.33

*See Table 1 for models information and Figure 1 for HOMO-LUMO schematic patterns.

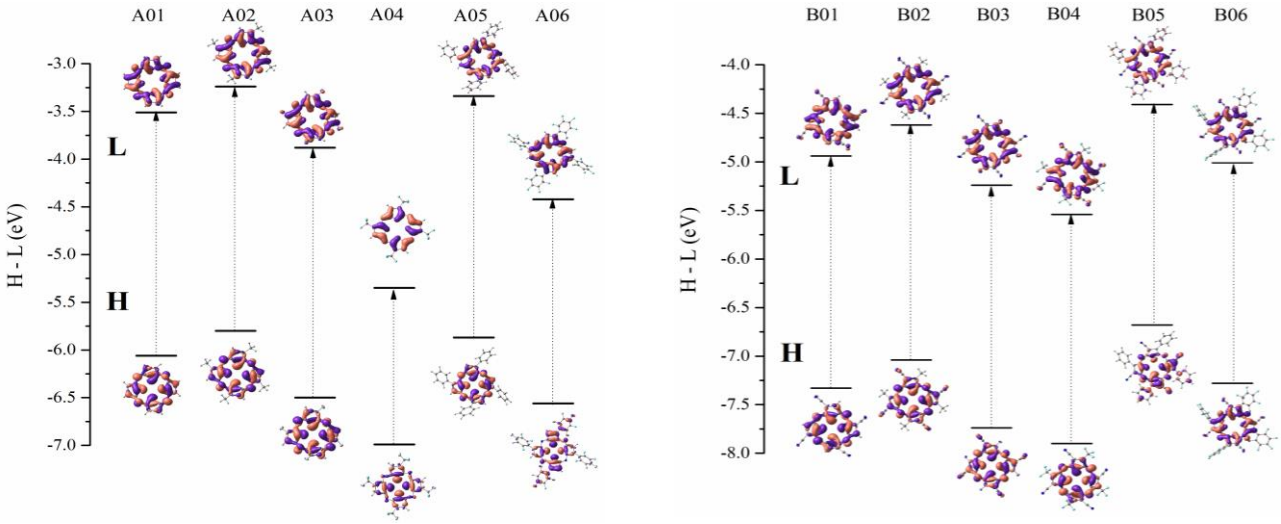


Figure 1. Schematic patterns of HOMO and LUMO energy levels for A and B models

Examining the results of Table 2 and Figure 1 indicates that the absorption wavelengths of all the considered Pz derivatives are in the safe range of visible light. Therefore, the capability of these structures for PS applications of PDT could be confirmed at the first look. Carful comparisons of the results show that the HOMO and LUMO energy level detect the fluctuations of the presence of functional groups in Pz structures but the energy differences are somehow similar to the exceptions. Comparing the properties for structures of A0x and B0x sets also indicates the role of additional –CN functional group to make changes in the values of HOMO and LUMO levels in the B0x set. Interestingly, both of HOMO and LUMO levels have been decreased to lower levels in the structures of B0x set in comparison to the A0x set. Then, it could be mentioned that the –CN functional group has a dominant role in determining the electronic properties of Pz structures. Examining the structures of A0x set show that the H–F substitutions make fluctuations for the required extra light wavelength, in which they are shifted to higher wavelengths in the case of fluorinated methyl and benzyl groups in comparison to the hydrogenated models. One of the observed exceptions is that the H–F substitution for the A01 and A02 are reversed, in which the wavelength is slightly decreased to lower number. The same trends have been seen for the B0x set but with a big difference that the differences of H–F substitutions are not very much significant for the –CN functionalized structures. It seems that the additional –CN group could somehow moderate the electronic properties of B0x. It is here assumed that the numbers of the generated $^1O_2$ molecules could be differed in the models, in which the numbers could be changed by the absorption wavelengths for PS→PS* transitions. Based on the functional groups the wavelengths are changed and the number of $^1O_2$ molecules are slightly higher than 1 for whole models with an exception of A04. In this sense, the lower wavelengths could generate more $^1O_2$ molecules; however, their required energies could be somehow harmful for the living tissues. Therefore, fewer numbers of $^1O_2$ molecules would be more favorable with slightly higher safe wavelengths. It is also the point of argument to know how to choose the chemical structures for desired photosensitizing properties.

Conclusion

The photosensitizing properties for porphrazine derivatives have been investigated based on DFT and TD-DFT calculations of the twelve models in two categories divided by the CN functional group. The results indicated that the investigated models could be seen as proper materials to be employed in the wavelength ranges of 400-700 nm, which are safe enough for biological tissues. The results also indicated that the CN functional group could play a moderating role for the required absorption wavelengths for the models by changing their HOMO and LUMO energy levels. The results indicated that A03 model colud be proposed for the best ability of $^1O_2$ production for applications in PDT type-II among the investigated models of Pz derivatives. And finally, the chemical structures could show different properties for application of the photosensitizing materials, in which the results could be very well recognized based on the detailed computational chemistry works.

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