

Electronic Structure and Serotonin Receptor Binding Affinity of 7-Substituted Tryptamines

QSAR of 7-Substituted Tryptamines

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Abbreviations

| | |
|--------|---|
| QSAR | Quantitative Structure-Activity Relationships |
| pA_2 | receptor affinity (rat stomach fundus) |
| HOMO | Highest Occupied Molecular Orbital |
| LEMO | Lowest Empty Molecular Orbital |
| MO | Molecular Orbital |
| CNDO | Complete Neglect of Differential Overlap |
| SD | Standard Deviation |
| PAA | Phenylalkylamines |
| IAA | Indolealkylamines |
| ESD | Electrophilic Superdelocalizability |
| NSD | Nucleophilic Superdelocalizability |

Abstract

A QSAR study was carried out seeking a relationship between the receptor binding affinities and the molecular-electronic structures of a group of 7-substituted tryptamines. The results suggest that these molecules interact with the rat stomach fundus serotonergic receptor by charge transfer from the aromatic nucleus and that there are pockets in the receptor which place limits on the sizes of acceptable *N*- and α -carbon substituents. Also, the charge density available at carbon atom 7 and the size of the C-7 substituent as estimated by a calculated steric factor seem to make important contributions to an optimal interaction between the IAA and the receptor molecules.

Key words: Quantitative structure-activity relationships, substituted tryptamines, rat stomach fundus, affinities in, CNDO/2 method, serotonergic receptor, steric effect, perturbation theory, hallucinogens, reactivity indexes, frontier orbitals.

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1 Introduction

One of the approaches leading towards a complete understanding of the pharmacology of any type of drug is the obtainment of significant relationships between the molecular structures of these substances, and parameters involved in the pharmaceutical, pharmacokinetic and pharmacodynamic phases of their actions. Among the parameters regulating the pharmacodynamic phase, the affinity for appropriate receptors is of paramount importance. Glennon et al. [1–9] have measured the affinities of a fairly large sample of IAA and PAA hallucinogens for the rat stomach fundus serotonergic receptor, and have also obtained a set of correlations between these receptor affinities (pA_2) and various reactivity indices [1]. Gupta, Singh and Bindal, in a recent critical review of QSAR studies on these molecules [10], concluded that none of the equations arrived at were highly significant, either because the data had been obtained using methods involving many approximations, or because only small numbers of data points had been employed. We may add that previous studies have usually examined a few individual parameters through the use of totally empirical approaches.

We have recently presented a general formal quantum- and statistical-mechanical method which relates receptor affinity to certain reactivity indices [11]. This procedure leads to so-called model-based equations which are more easily interpreted than those arising from empirical methods [12]. When applied to the study of the relationships between pA_2 and electronic structure in groups of PAA [13] and IAA [14], it has given excellent results.

Nevertheless, excessive diversity in the structures of the molecules subjected to these analyses, as in references 1 and 14, makes it difficult to obtain a good equation accounting for the variation of pA_2 . For this reason, we selected a group of 5-substituted tryptamines to carry out a QSAR study [15], including for the first time a non-empirical parameter to account for the steric effect of the substituents [16]. The results obtained in this way were the best until then (cf reference [10]).

As a further test of our method, and because of the interest that these compounds present, we have chosen a set of tryptamines bearing a substituent at position 7 of the benzene ring to study the relationships between the variation of pA_2 and the variation of the atomic reactivity indices and steric factors (see Fig. 1). In this way, all the changes in the electron distribution in the indole nucleus can be ascribed to the group located at C-7. We should point out that, for the present purposes, we consider the hydrogen atom as a substituent, and include several analogues with a substituted amine nitrogen atom.

2 Methods, Models and Calculations

The formalism employed here has been presented and discussed elsewhere [11, 13, 16]. Its basic assumptions are a state of thermodynamic equilibrium and a 1:1 stoichiometry in the formation of the drug-receptor complex:



where D is the drug molecule, R is the receptor, and DR is the complex (i stands for the i -th drug species) [11]. The equilibrium constant is

$$K_i = (Q_{D_iR}/Q_{D_i}Q_R) \exp(-\Delta E_0^i/kT) \quad (2)$$

where ΔE_0^i is the difference between the ground state energy of D_iR and the energies of the ground states of D_i and R :

$$\Delta E_i = E_{D_iR} - (E_{D_i} + E_R) \quad (3)$$

and the Q 's are the total partition functions measured from the ground state in solution.

Considering that the mass of the receptor molecule is very much larger than the mass of the drug molecule, that the Boltzmann factors of the excited electronic states are negligible compared to those of the ground state, that the rotational and vibrational motions may be treated in a first approach as independent and uncoupled, and that at 37°C the vibrational partition function is close to one, we can approximate Eq. (2) as [11]:

$$\log K_i = a + b \log M_{D_i} + c \log[(\sigma_{D_i}/(I_1 I_2 I_3)^{1/2})] + d \Delta E_i \quad (4)$$

where a , b , c and d are constants, σ is the drug molecule's symmetry number and $I_1 I_2 I_3$ is the product of its three moments of inertia around the three principal axes of rotation [11].

In general, the direct quantum-mechanical determination of ΔE_i is not possible, either due to the size of the receptor or to the lack of knowledge of its structure. Nevertheless, in the case of a mechanism implying that the two molecules are sufficiently far apart (i.e. that there is molecular attraction rather than covalent bonding), we can employ the standard Rayleigh-Schrödinger perturbation theory up to the second order to evaluate ΔE_i [17]. In this way, for a system involving pairs of interacting atoms, we obtain [18, 19]

$$\Delta E_i = \sum_{p \in D_i} \sum_{r \in R} \left\{ Q_{p_i} Q_r / R_{p_i r} + \sum_m \sum_{n'} C_{m p_i}^2 C_{n' r}^2 / (E_m - E_{n'}) \right\} + \sum_m \sum_{n'} C_{m p_i}^2 C_{n' r}^2 (E_{m'} - E_n) \quad (5)$$

where p_i and r refer, respectively, to atoms belonging to the drug and to the receptor. The summations on $m(n)$ and $m'(n')$ are, respectively, over the occupied and virtual molecular orbitals of the drug (receptor). We must note here that we have assumed that the resonance integral is dependent only on the atoms participating in the interaction; therefore, it is constant for a given group of compounds sharing a common skeleton.

The first term on the right hand side of Eq. (5) may be interpreted as an approximation to the electrostatic interaction energy of the unperturbed charge distributions of both molecules. The last two terms of Eq. (5) correspond to the polarisation energy of the interacting systems [20].

The problem at hand is related to the lack of knowledge of the occupied and virtual MO's of the receptor. Some authors have circumvented this difficulty by replacing the receptor's MO energies by average values [20, 21]. This procedure is not formally justified, however, and may shed some doubt on the formalism itself. We choose to avoid this approximation by considering a series expansion of the energy denominators of Eq. (5), as we have done before when determining polarizabilities using Perturbation Theory [22]. It can be shown [23] that this procedure leads to the following expression for ΔE_i :

$$\Delta E_i = a + \sum_{p_i} \left\{ e_{p_i} Q_{p_i} + f_{p_i} S_{p_i}^E + g_{p_i} S_{p_i}^N \right\} + \sum_{p_i} \sum_{m=z}^{\text{occ}} \left\{ h_{p_i}(m) D_{p_i}(m) + j_{p_i}(m) S_{p_i}^E(m) \right\} + \sum_{p_i} \sum_{m'=v}^x \left\{ r_{p_i}(m') D_{p_i}(m') + t_{p_i}(m') S_{p_i}^N(m') \right\} \quad (6)$$

where a , e , f , g , h , j , r , and t are constants, $S_{p_i}^E(m)$, $S_{p_i}^N(m')$, and $D_{p_i}(m)$ are respectively, the orbital ESD of MO m at atom p_i of the drug molecule, the orbital NSD of MO m' , and the orbital electron density of MO m at the same atom. $S_{p_i}^E$, $S_{p_i}^N$ and Q_{p_i} are, respectively, the atomic total ESD, the atomic total NSD, and the net charge of atom p in molecule i . The summation on m includes a group of MO's close to the HOMO, and the HOMO itself. The summation on m' includes the LEMO and a group of low-lying virtual MO's. These groups are determined with the help of statistical multiple regression analysis. Eq. (6) includes an approximate representation of the dispersion energy, which was not considered in the older treatments [18–21, 24].

The atoms p_i are those belonging to a skeleton which is common to all the drug molecules under consideration. For the physical meaning of the indices in Eq. (6), see reference [13].

It can be shown that, if we choose an appropriate coordinate system, the term related to the moments of inertia can be rewritten approximately as [16]:

$$\log(ABC) = \sum_t^{\text{subs atoms}} \sum_{j \in t} m_j R_{ij}^2 = \sum_t I_t \quad (7)$$

where the summation on t is over the different substituents and the summation on j is over the atoms belonging to the t -th substituent, m and R being, respectively, the mass of the atom and its distance to the origin of the chosen coordinate system. Eq. (7) allows, therefore, the separate analysis of the geometrical features of the substituent which may be important in the drug-receptor interaction. This steric factor

has already proven useful in another QSAR study on tryptamines [15].

Table 1. Experimental determined and calculated pA_2 -values for 7-substituted tryptamines

| Molecule | R ⁷ | R ^α | R ^N | Experimental pA_2^a | Calculated pA_2 Eq. (8) | pA_2 Eq. (9) |
|-----------------|-------------------------------|-----------------|-------------------------------|-----------------------|---------------------------|----------------|
| 1 | H | H | H | 6.27 | 5.91 | 6.22 |
| 2 | H | H | CH ₃ | 6.00 | 6.14 | 6.14 |
| 3 | CH ₃ | H | CH ₃ | 6.29 | 6.05 | 6.19 |
| 4 | OCH ₃ | H | CH ₃ | 5.33 | 5.36 | 5.20 |
| 5 | OH | H | CH ₃ | 4.88 | 5.02 | 5.12 |
| 6 ^b | H | H | CH ₃ | 6.04 | 6.22 | 5.83 |
| 7 ^c | H | H | CH ₃ | 6.02 | 6.19 | 6.31 |
| 8 ^d | H | H | CH ₃ | 6.03 | 5.93 | 5.88 |
| 9 | H | H | H and CH ₃ | 5.97 | 6.02 | 6.01 |
| 10 | Br | H | CH ₃ | 6.51 | 6.49 | 6.37 |
| 11 ^e | H | H | CH ₃ | 5.68 | 5.55 | 5.64 |
| 12 ^f | H | CH ₃ | H | 5.49 | 5.49 | 5.49 |
| 13 ^g | H | CH ₃ | H | 6.46 | 6.44 | 6.55 |
| 14 | H | H | C ₂ H ₅ | 5.79 | 5.88 | 5.84 |
| 15 | C ₂ H ₅ | H | CH ₃ | 6.31 | 6.33 | 6.24 |

^a Ref. [1–9].

^b With a CH₃ group at position 2.

^c With a CH₃ group on the indole N.

^d With a S atom instead of the indole NH.

^e With a CH₂ group instead of the indole NH.

^f (S(+)) isomer.

^g (R)(–) isomer.

The molecules selected for this study are presented in Table 1, together with their experimental pA_2 values. The geometry employed is the same as in previous studies [14, 15]. The reactivity indices were obtained using Molecular Orbital Theory at the CNDO/2 level [25]. The steric factor was calculated with reference to the point X = –5.5 Å, Y = 1.2 Å, Z = 0.0 Å, of the coordinate system shown in Figure 1.

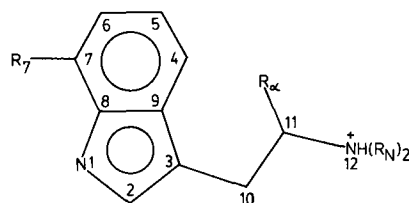


Figure 1. The 7-substituted tryptamines.

3 Results

The statistical fitting of Eq. (6) was performed by means of a stepwise regression technique with pA_2 as the independent variable. To select the common skeleton for all the IAA we analysed two possibilities:

- The atoms of the two aromatic rings plus the side chain atoms.
- The atoms of the benzene ring plus the side chain atoms, considering that IAA and PAA interact with the same receptor [14, 15].

The choice of the variables to be used in the statistical analysis was carried out in the following way:

- Considering that an analysis of the electronic structure of these molecules strongly suggests that they can transfer charge from the aromatic ring to receptor, we did not use the NSD's or the virtual densities of the rings. We also neglected the ESD's corresponding to the side chain.
- To rule out errors resulting from the above simplification, we carried out a statistical analysis with all the variables. More than 250 equations were obtained and analysed.

The best one we found, considering all aspects of statistical analysis, is (see Figure 1 for the numbering of the atoms):

$$pA_2 = 7.78 - 2.92(0.773)D_8(\text{H-2}) - 3.291(0.4092)S_7^E + 0.00136(0.00029)I_7 - 0.00076(0.00017)I_\alpha \quad (8)$$

with $R = 0.939$, $R^2 = 0.882$, mean SD = 0.181 and $n = 15$. The standard deviations of the coefficients are included in the formula in parentheses. The analysis of the variance of Eq. (8) gives $F(10,4) = 18.75$ ($p < 0.005$), showing that this equation is highly significant. The result of Student's t test for the significance of the variables appearing in Eq. (8) are presented in Table 2.

The second best equation we obtained is:

$$pA_2 = -9.27 + 3.03(0.662)S_8^E(\text{HOMO}) - 3.60(0.446)S_7^E - 0.00084(0.00016)I_\alpha - 0.00015(0.00005)I_N \quad (9)$$

where $S_8^E(\text{HOMO})$ and I_N are, respectively, the HOMO orbital ESD of atom 8 and the steric factor (see Eq. (4)) corresponding to the N substituent. Eq. (9) has $R = 0.945$, $R^2 = 0.894$ and a mean SD of 0.172. The analysis of variance gave $F(10,4) = 21.05$ ($p < 0.0005$). The results of Student's t test for the variables appearing in Eq. (9) are presented in Table 3. The squared correlation coefficient matrix for the variables appearing in Eqs. (8) and (9) is displayed in Table 4; it shows clearly that there is no significant internal correlation between the variables considered. The variables employed in the statistical analysis are presented in Table 5. The calculated pA_2 values, together with the experimental ones, are shown in Table 1.

Table 2. Results of the Student t test for the significance of the variables appearing in Eq. (8).

| Variable | t value | p |
|-------------------|---------|---------|
| $D_8(\text{H-2})$ | –3.78 | <0.005 |
| S_7^E | –8.04 | <0.0005 |
| I_7 | –4.65 | <0.0005 |
| I_α | –4.56 | <0.0005 |

Table 3. Results of the Student t test for the significance of the variables appearing in Eq. (9).

| Variable | t value | p |
|----------------------|---------|---------|
| $S_8^E(\text{HOMO})$ | –4.57 | <0.0005 |
| S_7^E | –8.07 | <0.0005 |
| I_α | –5.17 | <0.0005 |
| I_N | –2.92 | <0.0005 |

Table 4. Squared correlation coefficient matrix for the variables appearing in Eqs. (8) and (9).

| | $D_8(\text{H-2})$ | S_7^E | I_7 | I_α | S_8^E (HOMO) | I_N |
|-------------------|--------------------|---------|-------|--------------------|--------------------|-------|
| $D_8(\text{H-2})$ | 1.0 | | | | | |
| S_7^E | 4×10^{-4} | 1.0 | | | | |
| I_7 | 0.13 | 0.16 | 1.0 | | | |
| I_α | 0.16 | 0.03 | 0.02 | 1.0 | | |
| S_8^E (HOMO) | 0.04 | 0.38 | 0.46 | 6×10^{-4} | 1.0 | |
| I_N | 0.25 | 0.03 | 0.05 | 0.16 | 9×10^{-3} | 1.0 |

Before discussing the results, it must be mentioned that using these variables the probability of finding a chance correlation with $R^2 > 0.9$ is 1% or less [26].

4 Discussion

From Eq. (9) it can be appreciated that the pA_2 value diminishes if the steric factor of the N substituent increases. This is in perfect agreement with the experimentalist's observations [3] and with our previous QSAR study on 5-substituted IAA [15], indicating that an unsubstituted amine nitrogen atom is conducive to high receptor affinity.

On the other hand, from Eqs. (8) and (9) it can be seen that if the steric factor of the α -carbon substituent grows, the pA_2 value falls. This result must be interpreted with caution because we have considered only one enantiomeric pair. Table 1 shows that the experimental pA_2 value for the (*R*)(-)-isomer is greater than the value for the molecule with no α -substituent, while the pA_2 value for its enantiomer is lower. Before a firm opinion can be given it is necessary to wait for more receptor affinity measurements on individual optical isomers. Nevertheless, we may conjecture that the pA_2 value increases in one case as a consequence of the substituent fitting into a hydrophobic pocket in the receptor, and decreases in the other due to the existence of steric repulsion with a neighbouring region of the receptor surface. As there are no data available for α -substituents larger than CH_3 , nothing can be said about the maximal size of this group.

The electron density of the (H-2) MO at C-8 and the atomic ESD at this position affect the pA_2 value, as seen in Eqs. (8) and (9), respectively. In both cases, pA_2 diminishes if these parameters increase, as $D_p(m)$ is always positive and S_7^E is always negative. These results suggest that, for an optimal interaction, the electron density at C-8 should be low. Considering that this atom is part of an aromatic ring, the associated electron density will depend on the nature of the substituents attached to the neighbouring atoms, especially C-7.

The two equations show that pA_2 values increase when the atomic ESD at C-7 increases. This fact may be explained by assuming that the receptor possesses an electrophilic centre that interacts directly with C-7.

The problem of the nature of the C-7 substituent seems to be more complex. In 1-phenyl-2-aminopropanes, where C-4 can be considered to be congruous with C-7 of the IAA, it has been suggested that the 4-substituent interacts directly with the receptor [6]. Also, in the case of a methyl group at this position, a hydrophobic interaction has been mentioned [2]. On the other hand, it is well known that the

substitution of a methyl or ethyl group or a bromine atom at the 4-position of hallucinogenic PAA enhances activity [4], and the aminopropanes bearing these substituents in addition to the 2,5-dimethoxy pattern are very potent hallucinogens.

Other researchers have found a parabolic dependence of potency on the net total atomic charge on C-7, such that an optimal charge can be calculated for this position [27]. According to these authors, the charge must be close to zero for high potency to be observed, a suggestion which contradicts the involvement of the atomic ESD at C-7 in our correlations. They postulated that the C-7 region may come into contact with a hydrophobic region of the receptor; and that a charge of either sign at C-7 would result in decreased hydrophobicity. Finally, they noted that this effect could not be quantitatively accounted for by including a term to estimate substituent volume (molar volume, polarisability, or Taft's steric coefficient). It is also pointed out that if a specific hydrophobic site exists, the introduction of a polar substituent at C-7 of an IAA should be expected to have a detrimental effect on the pA_2 value. This is found to be the case, as 7-hydroxy-*N,N*-dimethyltryptamine (5 in Table 1) possesses the lowest affinity of any congener examined thus far [2, 3].

In a QSAR study based exclusively on electronic parameters [1], two of the statistical regression equations were found to improve when 7-methoxy-*N,N*-dimethyltryptamine (4 in Table 1, the only 7-substituted compound in Ref. [1]) was deleted. This immediately suggests that electronic properties alone are unable to account for the variation of pA_2 . In fact, an older paper relating the contraction of rat stomach fundus strips to MO parameters and Hansch hydrophobicity coefficients [27] had already shown that inclusion of this constant for the C-7 substituent raises the significance level of half a dozen different equations.

To analyse the influence of the steric factor for the C-7 substituent appearing in Eq. (8), we shall order molecules 2, 3, 4, 5, 10 and 15 in the following way:

- pA_2 values: $\text{Br} > \text{C}_2\text{H}_5 \approx \text{CH}_3 > \text{H} > \text{OCH}_3 > \text{OH}$
- I_7 values: $\text{Br} > \text{OCH}_3 > \text{C}_2\text{H}_5 > \text{OH} > \text{CH}_3 > \text{H}$
- S_7^E values: $\text{H} > \text{Br} \approx \text{CH}_3 \approx \text{C}_2\text{H}_5 > \text{OCH}_3 \approx \text{OH}$

It can be seen immediately that the orders of the pA_2 , I_7 and S_7^E values do not run parallel to each other. Nevertheless, if we neglect the molecules substituted at C-7 with the hydrophilic OH or OCH_3 groups, an interesting fact emerges: the pA_2 value parallels the value of I_7 and the value of S_7^E , with the exception of the H-substituted molecule, for which S_7^E is highest. If we now consider only the deleted molecules, all three parameters are greater for the methoxy than for the hydroxy compound. All this clearly indicates that it is not the hydrophobicity that regulates pA_2 , but the values of I_7 and S_7^E taken together. The H-substituted molecule (2 in Table 1) is the most representative case. It has the highest value for S_7^E but the lowest for I_7 , and its pA_2 value lies between those of the molecules bearing hydrophobic substituents and those with hydrophilic ones. The OH and OCH_3 derivatives, having fairly high I_7 values, possess low receptor affinities because of their very low S_7^E values.

From these results, a tentative picture emerges for the serotonergic receptor, shown in Fig. (2). Now, from this study and others [13-15], the receptor appears to be a

highly complex structure interacting with the phenyl ring and the side chain, and with pockets that restrict the recognition of these moieties. Also, our results support the contention that IAA interact with the receptor in such a way that their aromatic ring always adopt the same orientation in contrast with other suggestions [28, 29].

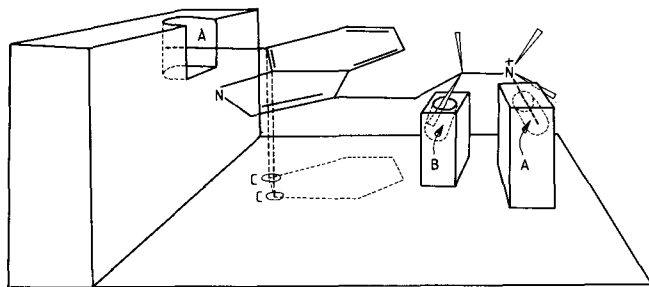


Figure 2. Some of the possible features of the rat stomach fundus serotonergic receptor:

- A) pockets controlling the size of substituents at the amine N and at C-7;
 B) possible interaction area for one of the α -carbon substituents;
 C) areas interacting by charge transfer.

Our QSAR equations for IAA [14, 15] and PAA [13] are very similar for both kinds of compounds. If these different groups of drugs interact with the receptor by analogous mechanisms, then a PAA with a small hydrophilic group at C-4 but with a high I_4 value (i.e. with a large mass) must have a high pA_2 value if its S_4^E is high enough. If such a compound is able to pass through the blood-brain barrier, it may be hallucinogenic at low doses. These considerations apply perfectly to 1-(2,5-dimethoxy-4-nitrophenyl)-2-aminopropane (DON), with a pA_2 value of 7.07 for the racemic mixture [6]. Our pharmacological studies, which will be published elsewhere, show that (\pm)-DON is a very potent hallucinogen, comparable to DOB (its 4-bromo analogue) and DOM (the 4-methyl analogue), which carry hydrophobic substituents at C-4 [30]. The same argument may be applied to 7-substituted IAA and, therefore, 7-nitrotryptamine would be expected to exhibit a high affinity for the rat stomach fundus serotonergic receptor.

The equations presented here can be refined in principle as more pA_2 values become available. Also, it seems necessary to improve the term describing the steric factors by decomposing it into three terms accounting for the orientation of the substituent. Nevertheless, our correlations are the most significant obtained so far for IAA (cf. Ref. [10]).

These results, together with other reported previously [13–15], are convincing evidence that so-called theoretical equations [12] are much better than empirical ones (i.e., those derived by Hansch analysis and other similar techniques). Furthermore, they provide a deeper insight into the mechanism by which these molecules interact with their receptor.

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