Bonding in 1,2,3-Triazoles. VI. The Effects of the

N-Substituents on the Geometry of the Triazole Ring

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An investigation of the effects of the N-substituents on the geometry of the 1,2,3-triazole ring has been carried out based on crystal structures determined by X-ray diffraction. In the compounds chosen for analysis, the N-substituted atom is either a carbon or a hydrogen atom. It is concluded that only the position of the N-substituent has a significant effect on the ring geometry. Two models for the substitution effects on the endocyclic angles are analyzed. The first model establishes an approximately linear relation between the endocyclic angle at a nitrogen atom and the sum of the endocyclic angles at its neighbours, a relation that possibly may be explained by changes in hybridization induced by substitution. In the second model the sum of the endocyclic angles at the carbon atoms is analyzed as a function of the position of the substitutents. This angular sum seems to be almost constant for each type of substituted compound. The small deviations from constancy may be related to the length of the C–C bond. Also the substitution effects on the distances are discussed. The relations found have been applied to selected imidazole compounds.

In previous papers[1-4] the molecular structures of some 4-sulfur substituted 1,2,3-triazoles are reported. A comparison of the geometry of the triazole ring in these and related compounds[5-30] reveals the possibility of a systematic description of the ring geometry as a function of its substituents. The geometry of the triazole ring is affected by the nature of the C-substituents and the position and nature of the N-substituents. In this paper the effects of the N-substituents are analyzed, and the results applied to selected imidazole compounds.

The structural information used in the analyses is based on crystal structures determined by X-ray diffraction. The compounds chosen meet three requirements: The R-value is not greater than 0.075, the standard deviations of the endocyclic angles are not greater than 1°, and the standard deviations of the bond lengths in the triazole ring are less than 0.01 Å. In the majority of compounds meeting these requirements, the N-substituent is either a carbon or a hydrogen atom. The analyses are therefore restricted to compounds of these types. Table 1 contains a list of the 35 compounds together with a symbol and the number reference. The letters A, B, C, D and E in the symbol refer to 1-, 2-, 1,3-, 1,2-substituted and unsubstituted compounds, respectively. Inspection of Table 1 shows that the selection of compounds for structure determination is influenced by the interests of the authors. Thus it is seen that most of the 11 structures of aza analogs of purine derivatives have authors in common. This is also the case for the 7 structures of 4-sulfur substituted triazoles. It must

Table 1. Compounds used in the analyses, their abbreviation and reference.

Name of compound	Symbol	Ref.
8-Azaguanine monohydrate	A1	6
cis-1-(6-Acetoxymethyltetrahydro-2-pyranyl)-5,6-dichlorobenzotriazole	A2	7
2-(4-O-Acetyl-2,3-dideoxy-β-L-glycero-pent-2-enopyranosyl-5,6-dichlorobenzotriazole	A3	8
5-Amino-1H-1,2,3-triazole-4-carboxamide	A4	9
1-Benzotriazoleacetic acid	A5	10
8-Azaadenosine monohydrate	A6	11
7-Methyl-8-azaadenine	A7	12
2-Phenyl-7-methyl-8-azahypoxanthine	A8	13
9-Diethylcarbamoyl-2-(2-propoxyphenyl)-8-azahypoxanthine	A9	14
2-(2-Propoxyphenyl)-8-azahypoxanthine	A10	15
2-(2-Propoxy-5-(N-methyl-N-isopropylsulfamoyl)phenyl)-8-azahypoxanthine	A11	15
8-Azaguanine hydrochloride monohydrate	B1	16
8-Aza-2,6-diaminopurine sulfate monohydrate	B2	17
7-Amino-2H,4H-vic-triazolo[4,5-c]-1,2,6-thiadiazine-1,1-dioxide	B3	18
7-Amino-2H,4H-vic-triazolo[4,5-c]-1,2,6-thiadiazine-1,1-dioxide monohydrate	B4	19
5-Mesylamino-2H-1,2,3-triazole-4-carbonitrile monohydrate	B5	20
2-(3'4'-Di-O-acetyl-2'-deoxy-β-L-erythro-pentapyranosyl-5,6-dimethylbenzotriazole	B6	21
6-Acetyl-8-(acetyloxyimino)-2-phenyl-4-oxo-4,8-dihydro-2H,6H-pyrazolo[3,4-f]-1,2,3-benzotriazole—dioxane(2:1)	B7	22
2-Phenyl-4,5-dianilino-2H-1,2,3-triazole	B8	23
Benzotriazol-2-ylacetic acid	B9	24
3-Methyl-8-azaguanine hydrobromide monohydrate	B10	25
4,6-Diphenyl-2-methylthieno[3,4-d]-1,2,3-triazole	B11	26
2-Methyl-5-[methyl(mesyl)amino]-2H-1,2,3-triazole-4-carbonitrile	B12	27
2-Phenyl-8-methyl-8-azahypoxanthine	B13	13
2-Phenyl-4-chloro-1,2,3-triazole	B14	5
1,3-Dimethyl-4-(1,2,3-triazolio)sulfide	C1	1
1-Phenyl-3-methyl-4-(1,2,3-triazolio)sulfide	C2	2
1-Methyl-3-phenyl-4-(1,2,3-triazolio)sulfide (P2₁/a-form)	C3	2
1-Methyl-3-phenyl-4-(1,2,3-triazolio)sulfide (Cc-form)	C4	2
1-Methyl-3-benzyl-4-(1,2,3-triazolio)sulfide	C5	3
Benzotriazolium tetrachlorocobaltate(II)	C6	28
Benzotriazolium hydrogensulfate	C7	29
2,3-Dimethyl-1,2,3-triazol-1-in-4-thione	D1	4
2-Phenyl-3-methyl-1,2,3-triazol-1-in-4-thione	D2	4
Tetramethylammonium benzotriazolide	E1	30

therefore be emphasized that this lack of random sampling may bias the results arrived at in this paper.

The labelling of the atoms, distances and angles is shown in Fig. 1. The direction of numbering is chosen such that the N(1)−N(2) distance, d_1, is the larger of the two N−N distances. This convention has the effect that only the substitution types mentioned above occur.

The analyses comprise least-aquares estimation of parameters, and all least-squares equations are weighted. Each compound is assigned a weight in accordance with the average variance of the angles or distances in the triazole ring.
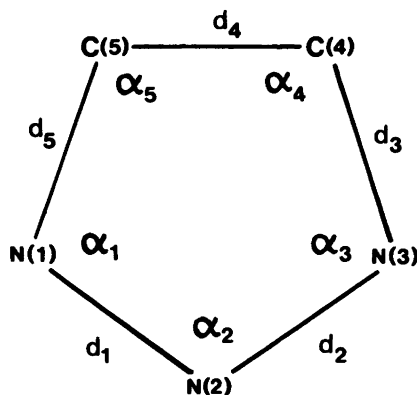
C(5) ——— d_4 ——— C(4)

α_5 α_4

d_5 d_3

N(1) α_1 α_3 N(3)

d_1 α_2 d_2

N(2)

Fig. 1. Labelling and numbering of the atoms, distances and angles in the triazole ring. The direction of numbering is chosen such that $d_1 > d_2$.

THE *N*-SUBSTITUENTS

Of the 35 compounds there are 22 compounds comprising 29 exocyclic N–C bonds. Of these 7 involve a phenyl carbon atom. In the remaining N–C bonds the carbon atom is aliphatic in nature. The N–C(aliphatic) bond lengths range from 1.447 to 1.482 Å, with an average value of 1.457(2) Å, which is of the expected order of magnitude for a N–C single bond.[31] The N–C(phenyl) distances range from 1.418 to 1.442 Å. Although the angles between the normals to the triazole and the phenyl rings lie between 1.6 and 57.8°, this seems to have no significant effect on the C–N distances. The average value of 1.427(4) Å indicates some degree of conjugation. In terms of bond orders, this distance corresponds to a value of 1.2.[31] An examination of the effect of interchanging methyl and phenyl groups has been carried out in Refs. 3 and 4, with the conclusion that this has an insignificant effect on the geometry of the triazole ring, the only effect, as found by CNDO-calculations, being a small redistribution of charge on the nitrogen atoms. Neither has it been possible, within the present material, to correlate any distance or angle in the triazole ring to the nature of the carbon atoms. Furthermore, this lack of correlation can be extended to include also hydrogen atoms. There seem to be no differences in the effects induced on the geometry of the triazole ring by the different *N*-substituent.

This last observation is in contrast to what has been observed in substituted phenyl rings (Refs. 32–34 and references therein), where substitution of a hydrogen atom by a methyl or a phenyl group decreases the endocyclic angle about 2°. Another illustration of the differences in the behaviour of the phenyl and the triazole rings is provided by benzotriazole-1-oxide, which is 1,3-substituted and 1-hydroxybenzotriazole, which is 1-substituted.[35] In 1-hydroxybenzotriazole the angle at the oxygen substituted nitrogen atom is 113.2(2)°, which may be compared to the average of α_1 (110.2°) for the 1-substituted compounds. The difference of 3.0° is ten times larger than found in hydroxybenzenes. When the corresponding angle in benzotriazole-1-oxide (112.3°) is compared to the averages of α_1 and α_2 for the 1,3-substituted compounds [113.6 and 113.3°] the decrease due to oxygen substitution is ~5 times smaller than observed in benzene derivatives.[32–34]

When analyzing the angles at the *ipso* carbon atoms in the phenyl groups substituted onto the triazole rings, one observes that the angles in all cases are larger than 120°. The deformations range from 0.9 to 2.3°. According to the results from analyses of deformations in phenyl rings, the 1,2,3-triazole group falls in the group consisting of OH, SO_3^-, Cl, NH_3^+, F

and NO_2, which act as σ-acceptors and π-donors and are highly electronegative.[32-34] This possibly accounts for the behaviour mentioned above.

As a result of these considerations, the present analyses are based on the assumption that the origin of the geometrical differences between the triazole groups of the present material primarily are due to differences in the C-substituents and differences in the positions of the N-substituents.

HYBRIDIZATION RATIOS

An immediate effect on the nitrogen atoms caused by substitution is a change in hybridization. A parameter, which may express this effect, is the p/s-hybridization ratio, λ, for the $N-C$ and $N-N$ bonds as calculated from the angles around the nitrogen atom. If the valence electrons of an sp^2 hybridized nitrogen atom form σ-bonds in directions specified by the angles γ_1, γ_2 and γ_3 between adjacent bonds, the requirement of orthogonality between the three wave functions results in a p/s-hybridization ratio, λ_i, of the bond opposite γ_i of $(-\cos \gamma_j \cos \gamma_k/\cos \gamma_i)^{-\frac{1}{2}}$; i, j, k being permutations of the numbers 1, 2 and 3.[36]

From the formula for the hybridization ratio it is seen that the smaller γ_i the smaller the p-character of the orbital opposite γ_i, and the larger the total p-character of the two other orbitals. In the triazole ring, where the endocyclic angles are below $120°$, the valence orbitals in the ring have a much larger p-character than the orbitals directed towards the substituents. Especially the valence orbitals of nitrogen not involved in σ-bonding have a low p-character. On substitution, the hybridization will tend towards the ideal sp^2-hybridization, $i.e.$ an increase in p-character of the exocyclic orbital, and a decrease in p-character of the ring orbitals.

When examining the angular configuration around the carbon substituted nitrogen atoms, it is noticed that for the 1- or 3-substituted compounds, the $C-N-C$(exocyclic) angles range from 127.0 to 131.5°, whereas the $N-N-C$(exocyclic) angles range from 118.5 to 124.0°. The difference between the two angles, which is in agreement with the larger van der Waals radius for carbon compared to nitrogen,[37] has only a small influence on the hybridization ratio of the exocyclic valence orbitals. In the 2-substituted compounds (B and D) the two $N-N-C$(exocyclic) angles range from 120.0 to 125.7°, but for the B-compounds there is a large variation in α_2 leading to a larger variation in the hybridization ratio of the exocyclic orbital. This larger variation in α_2 may partly be attributed to differences in the C-substituents, since it may be shown that if these substituents together with the triazole ring form a condensed ring system, the value of α_2 increases.[38] One might therefore expect that the average value of the hybridization ratio for the exocyclic orbital, as listed in Table 2, is a little too high for the N(2) atom.

Table 2. Mean hybridization ratios, λ_i, of the exocyclic valence orbitals of the substituted nitrogen atoms. The index, i, refers to the nitrogen atom.

Substitution site(s)	λ_1	λ_2	λ_3
1	1.02	–	–
2	–	1.30	–
1,3	1.17	–	1.18
1,2	0.97	1.07	–

Table 3. Changes, $\Delta\alpha_i$, in the endocyclic angles for the benzotriazole compounds as compared to the benzotriazolate ion. The values given are in degrees.

Compound	Substitution site(s)	$\Delta\alpha_1$	$\Delta\alpha_2$	$\Delta\alpha_3$	$\Delta\alpha_4$	$\Delta\alpha_5$	$\sigma(\Delta\alpha)$
A2	1	5.4	−5.0	3.4	0.4	−4.1	0.6
A3	1	4.8	−4.1	2.5	0.6	−3.7	0.6
A5	1	5.9	−5.3	3.6	0.2	−4.3	1.1
B6	2	−3.1	4.4	−2.9	0.6	1.1	0.6
B7	2	−2.9	3.2	−2.1	0.3	1.7	0.6
B9	2	−2.9	4.6	−2.8	0.2	1.0	1.0
C6	1,3	7.2	−8.6	8.1	−4.0	−2.9	0.6
C7	1,3	7.3	−7.9	7.5	−3.2	−3.6	0.9

Since the atomic radius increases with increasing *p*-character,[36,39] it should be expected that the N−C(aliphatic) distance increases with λ. However, this distance also depends on the hybridization of the carbon atom, but the mean values within each type of substituted compound to a certain degree show this pattern of behaviour. Thus the N−C(aliphatic) average distances for the 1,3- and 2-substituted compounds [1.468(3) and 1.461(4) Å] are larger than the distances for the 1- and 1,2-substituted compounds [1.455(3) and 1.448(2) Å].

Changes in hybridization of one atom in the ring are compensated for by changes in hybridization of the neighbouring atoms in the opposite direction.[38] Thus one observed an oscillating behaviour of the changes in the endocyclic angles due to *N*-substitution, changes that fade out with the distance from the substitution site. Table 3 contains an example of these changes for the benzotriazole compounds as compared to the benzotriazolate ion. For the 1- and 2-substituted compounds (A and B) one observes that the changes at the substitution site and at the neighbouring atoms depend on the values of the angles in the benzotriazolate ion. The increase in α_1 for the A-compounds is larger than the increase in α_2 for the B-compounds. In the benzotriazolate ion the two angles are 105.5 and 113.0°, respectively. When comparing $\Delta\alpha_2$ and $\Delta\alpha_5$ for the A-compounds, it is observed that he larger the decrease of an angle the larger the corresponding angle in the benzotriazolate ion (α_5 is 108.1°). Thus it seems as if changes directed away from an angle of about 108° are damped. In the C-compounds the decrease in α_2 is less than twice the decrease in α_2 for the 1-substituted compounds, and the increases in α_1 and α_3 are less than the sum of the increases in α_1 and α_3 for the A-compounds. The small changes in α_4 for the A-compound seem to be due to an increase induced by the changes in hybridization at C(5) and a decrease induced by the changes at N(3). A similar feature is found for the B- and C-compounds.

OVERALL ANGULAR RELATIONS

From Table 3 it is also apparent that the change in angle at a nitrogen atom is approximately linearly related to the sum of the changes at the neighbouring atoms. Including also the benzotriazolate ion in the regression analysis, the linear equations for the benzotriazole subset become

$$\alpha_i = k_i(\alpha_{i-1} + \alpha_{i+1}) + c_i; \quad i = 1,2,3$$

Table 4. Results from least-squares calculations of the lines $a_i=k_i(a_{i-1}+a_{i+1})+c_i$ and the subsequent normal probability plots for the benzotriazole subset. E.s.d.'s are given in parentheses. The last five lines refer to the results of the normal probability plot.

	$i=1$	$i=2$	$i=3$
k_i	$-0.608(9)$	$-0.591(13)$	$-0.640(7)$
c_i(deg.)	240.0(1.9)	238.1(2.8)	247.(1.6)
r.m.s.(deg.)	0.17	0.30	0.13
Slope	0.522	0.894	0.383
Intercept	0.003	0.012	0.009
Corr. coeff.	0.974	0.956	0.962
5 % rejection level	0.912	0.912	0.912
$\text{Max}|\delta/\sigma(a_i)|$	0.92	1.30	0.70

The correlation coefficients for the three relations are -0.9992, -0.9983 and -0.9996, respectively. Table 4 summarizes the results of the least-squares analyses together with a normal probability plot of the weighted residuals.[40] The fits to the least-squares lines are almost perfect, the maximum deviation of a_i from the lines being $1.3\times\sigma(a_i)$. However, because of the C_{2v} symmetry of the triazole skeleton, one might expect that $k_1=k_3$ and $c_1=c_3$. A subsequent calculation of the lines for a_1 and a_3, with these constraints included, gave $k_1=k_3=-0.623(7)$ and $c_1=c_3=243.2(1.5)°$. The overall root mean square deviation (r.m.s.) was $0.19°$, and the maximum deviation from the lines was $1.3\times\sigma(a)$. When performing an R-ratio test of the two models,[41] the hypothesis that $k_1=k_3$ and $c_1=c_3$ can be rejected at a 5 % level, but not at a 1 % level. Taking into account also the fact that the change in the r.m.s. takes place in the second decimal, and that the angles are given with only one decimal, it is dangerous to reject the hypothesis on this basis. Thus the relations for a_1 and a_3 are possibly identical.

On this assumption, the three relations are not independent. Adding the equations for a_1 and a_3 and using the relation $\Sigma a_i=540°$, results in an equation for a_2, where $k_2=(1+k_1)/k_1=-0.606(18)$ and $c_2=-2c_1/k_1-540=241.3(9.8)°$, values that are not significantly different from those obtained from the least-squares line of a_2. Finally it should be remarked that the asymmetry of the 2-substituted benzotriazoles possibly is an artifact due to the numbering convention, since d_1 and d_2 are insignificantly different.

Table 5. Results from the least-squares calculations of the lines $a_i=k_i(a_{i-1}+a_{i+1})+c_i$ and the subsequent normal probability plots for all compounds. E.s.d.'s are given in parentheses. The last five lines refer to the results of the normal probability plot.

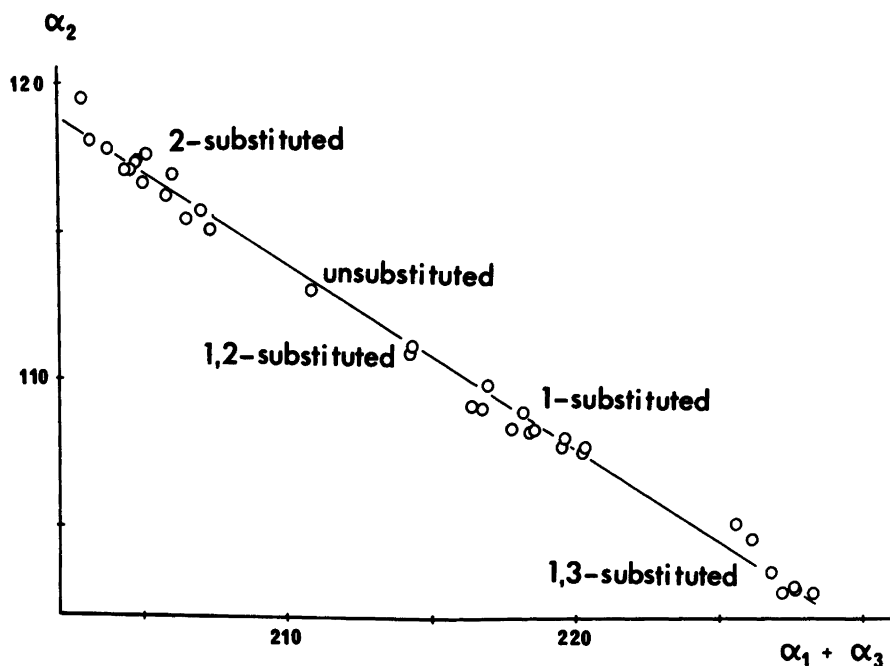|	$i=1$	$i=2$	$i=3$
k_i	$-0.562(9)$	$-0.623(9)$	$-0.650(13)$
C_i(deg.)	229.5(1.9)	244.7(2.0)	249.5(2.8)
r.m.s.(deg.)	0.39	0.43	0.41
Slope	1.668	1.818	1.707
Intercept	0.029	0.065	-0.043
Corr. coeff.	0.984	0.961	0.945
5 % rejection level	0.968	0.968	0.968
$\text{Max}|\Delta/\sigma(a_i)|$	4.33	6.09	5.16

Fig. 2. α_2 as a function of $\alpha_1+\alpha_3$ for the triazole compounds. The values are in degrees.

Whereas the C-substituents in the benzotriazole subset are very similar, the full set of compounds shows very large differences in the substituents. This is also reflected in the results of the least-squares calculations of the three lines (Table 5). The correlation coefficients are -0.996, -0.996 and -0.994, respectively. In Fig. 2 α_2 is depicted as a function of $\alpha_1+\alpha_3$ for all 35 compounds. The different types of compounds group together in the order $\alpha_2(B) > \alpha_2(E) > \alpha_2(D) > \alpha_2(A) > \alpha_2(C)$. The high values of the r.m.s. ($\sim 0.4°$) indicate that these relations are only approximate. This is also illustrated by the least-squares calculation of α_2 as a function of $\alpha_4+\alpha_5$, which, because of the relation $\Sigma\alpha_i=540°$, ought to give an equally good description.

However, the r.m.s. is $1.2°$, and the maximum deviation of α_2 from the line is $17.9\times\sigma(\alpha_2)$. Similar results are obtained for the other two equations. Furthermore, there is a substantial asymmetry in the lines for α_1 and α_3. These effects are probably due to differences in the C-substituents, and the better agreement of the line for α_2 as a function of $\alpha_1+\alpha_3$ is probably obtained because the substituent effects to a certain degree cancel at the nitrogen atoms.

One implication of the identical lines for α_1 and α_3, obtained for the benzotriazole subset, is recognized for the 2-substituted compounds. Subtraction of the two equations results in $\alpha_1-\alpha_3=k(\alpha_5-\alpha_4)$, and the actual least-squares calculation gives $k=-0.537(78)$, and a constant term equal to $-0.20(11)$, values not significantly different from -0.623 and zero, respectively.

If the type of relations analysed in this section may be explained by changes in hybridization, they should be expected to hold also for oxygen substituted compounds. In Table 6 the constrained relations, obtained on the benzotriazole subset, are used on

Table 6. The endocyclic angles (°) at the nitrogen atoms as calculated from the sum of the angles at the neighbouring atoms for benzotriazole-1-oxide and 1-hydroxybenzotriazole.

Angle	Benzotriazole-1-oxide		1-Hydroxybenzotriazole	
	obs.	calc.	obs.	calc.
α_1	111.8	112.0	109.2	109.7
α_2	105.2	105.6	106.6	106.6
α_3	112.3	112.3	113.2	112.7
$\sigma(\alpha_i)$	0.3		0.3	

benzotriazole-1-oxide and 1-hydroxybenzotriazole. The relations hold reasonably well, the maximum deviation being $1.7 \times \sigma(\alpha)$.

ANALYSIS OF THE SUM OF THE ANGLES AT THE CARBON ATOMS

Within each type of substituted compound, the sum, $\Sigma = \alpha_4 + \alpha_5$, is almost constant. Table 7 shows the average values, $\langle \Sigma \rangle$, and the maximum value of the individual residuals, δ, divided by $2^{1/2}$ times the average standard deviation, σ, of the angles in the ring. Information on the subsequent normal probability plots is also given.

The present model is contradicted by the overall linear relation between α_2 and $\alpha_1 + \alpha_3$, since constancy of $\alpha_4 + \alpha_5$ implies a slope of -1 in the former relation. However, since α_2, depicted as a function of $\alpha_4 + \alpha_5$, gave a poorer result, it is likely that different effects cancel in the two models, and one has to give both of them equal credibility.

A closer examination of the deviations from constancy, shows that the deviation for the A-compounds depends on the C–C distance, d_4 (Fig. 3). The correlation coefficient is -0.82, and the r.m.s. of the least-squares line is 0.004 Å, a value of the same order of magnitude as the standard deviations of the individual C–C bond lengths. The B- and C-compounds, where the fluctuations in d_4 are much smaller, show the same tendency. The explanation of this dependence is possibly that the more double bond character the C–C bond possesses, the larger the sum of the endocyclic angles at the carbon atoms, because of a more ideal sp^2-hybridization of the carbon atoms.

The change in $\alpha_4 + \alpha_5$, due to substitution at a particular site, seems to be independent of whether the other positions are substituted or not. In Table 8 the changes, Δ_1 and Δ_2, due to

Table 7. Analysis of the sum, Σ, of the endocyclic angles at C(4) and C(5). Standard deviations and the 5 % rejection level are given in parentheses. The first two columns are in degrees.

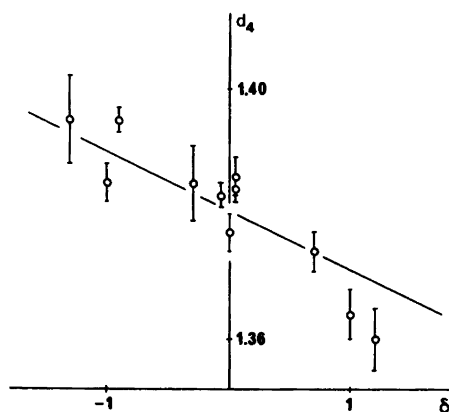| Group	$\langle \Sigma \rangle$	Max$|\delta|$	Max$|\delta/2^{1/2}\sigma|$	Sample size	Results from normal probability plots	
					Slope	Median corr. coeff.
A	213.30(17)	1.30	3.54	11	2.063	0.974(0.922)
B	218.02(12)	0.82	2.88	14	1.349	0.977(0.934)
C	209.43(10)	0.62	1.18	7	0.770	0.960(0.899)
D	214.62(17)	0.28	0.65	2		

Fig. 3. The C–C distance as a function of the deviations, δ, from $\langle a_4 + a_5 \rangle$ for the A-compounds. The values are in Å and degrees, respectively.

1- or 3-substitution and 2-substitution, are estimated from the average values of Σ. The agreement is reasonably good, and the signs and magnitudes of Δ_1 and Δ_2 qualitatively agree with what is expected from the discussion on hybridization, *i.e.* opposite signs of Δ_1 and Δ_2 due to substitution on neighbouring atoms, and a smaller magnitude of Δ_2 due to a more distant substitution site.

EFFECTS ON DISTANCES

Whereas the changes in the endocyclic angles seem to be dictated by changes in hybridization, the distances are heavily affected by changes in the distribution of the π-electrons. This results in difficulties in extracting the effect of N-substitution. The only significant effect that has been detected, is the dependence of d_4 and d_5 on whether the compound is 2-substituted or not.

The analysis is performed in the following way: The 35 compounds are divided into two classes. Class I consists of the 16 compounds (B and D) with a substituent bonded to N(2), and class II consists of the remaining 19 compounds (A, C and E). Within each class the joint probability funtion for d_4 and d_5 is approximated by a two-dimensional Gaussian density function, and the mean values and the variance-covariance matrix are estimated from the compounds in the class.[42] If $P(d_4,d_5|I)$ and $P(d_4,d_5|II)$ denote the joint probability functions of d_4 and d_5 for class I and II, respectively, one may, by means of Bayes' theorem,[41] estimate $P(I|d_4,d_5)$, *i.e.* the probability that a substituent is bonded to N(2), given the two distances d_4 and d_5:

Table 8. Analysis of the changes in $\langle \Sigma \rangle$ as a function of substitution site. The values are in degrees.[a]

Compounds	Equation	Weight	Deviation
A	$213.30 = \Sigma_o + \Delta_1$	0.17^{-2}	0.21
B	$218.02 = \Sigma_o + \Delta_2$	0.12^{-2}	−0.06
C	$209.43 = \Sigma_o + 2\Delta_1$	0.10^{-2}	−0.05
D	$214.62 = \Sigma_o + \Delta_1 + \Delta_2$	0.18^{-2}	0.15
E	$216.10 = \Sigma_o$	0.71^{-2}	0.60

[a] Result of least-squares calculation: $\Sigma_o = 216.70(33)$, $\Delta_1 = -3.61(18)$, $\Delta_2 = 1.38(31)$.

$$P(I|d_4,d_5)=\frac{P(I)P(d_4,d_5|I)}{P(I)P(d_4,d_5|I)+P(II)P(d_4,d_5|II)}$$

Here $P(I)$ and $P(II)$ denote the probability that a compound belongs to class I and II, respectively. Since $P(I)$ and $P(II)$ cannot be known, they are assigned equal probability, $P(I)=P(II)=\frac{1}{2}$, and with these values the probability of $N(2)$-substitution is calculated from d_4 and d_5 for all 35 compounds. For the compounds belonging to class I (B and D), the minimum probability is 0.871, and for class II compounds the maximum probability is 0.043. This type of calculation has been performed for any triple and pair of distances. The best result, with as few distances as possible, was obtained for d_4 and d_5.

The mean value of d_4 for class I [1.399(2) Å] is larger than for class II [1.382(2) Å], and the mean value of d_5 for class I [1.399(4) Å] is smaller than for class II [1.3581(21) Å]. For the A- and B-compounds this is in agreement with the features that may be derived from the most important Kekulé structure. For the C- and E-compounds it confirms the findings from bond order calculations.[1,29,30]

Although some distances in the compounds have values in better agreement with the wrong class averages, the joint distribution of the two distances is sufficient to determine the class property, *i.e.* to determine whether the compound is 2-substituted or not.

TEST ON IMIDAZOLE COMPOUNDS

The results, obtained on the triazole compounds, have been applied to a set of 29 imidazole groups.[43-67] A more rigorous analysis of the correlations in the imidazole groups is in progress. The labelling of the imidazole group is equivalent to the labelling of the triazole group (Fig. 1). Instead of using the equations for α_1 and α_3 as listed in Table 5, the constrained equations, with $k_1=k_3=-0.576$, and $c_1=c_3=232.9°$, have been applied. The root mean square deviations of the angles from the three lines are 0.47, 0.54 and 0.24°, respectively, and these values are of the same order of magnitude as obtained for the triazole groups. However, for α_2 most of the points lie below the line obtained from the triazole compounds (Fig. 4). In contrast to the triazole groups, the C–C distances in the imidazole groups show large fluctuations. The distances range from 1.329 to 1.414 Å, and the deviation from the line may be partly correlated to the C–C distance. In Table 9 the average C–C

Table 9. Dependence of the average, $\langle \Delta\alpha_2 \rangle$, of the deviation of α_2 from the least-squares line on the average, $\langle d_4 \rangle$, of the C–C distance for the imidazole derivatives.

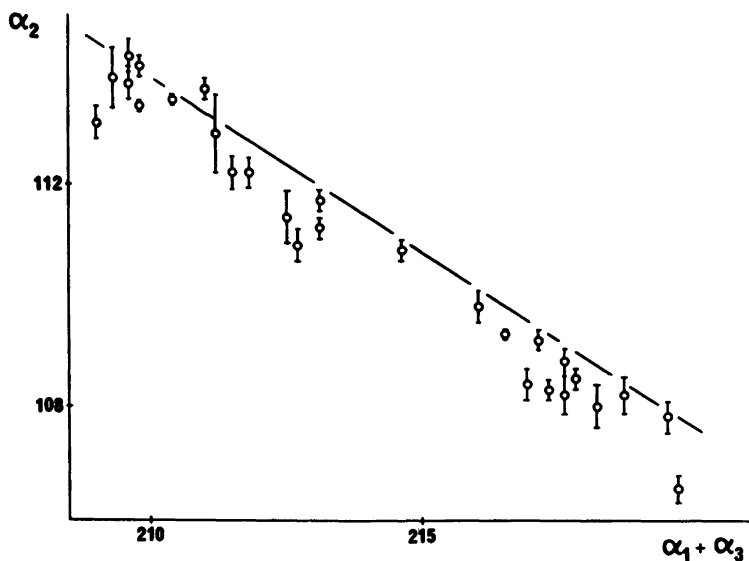| Interval (Å)	Number of compounds	$\langle d_4 \rangle$ (Å)	$\langle \Delta\alpha_2 \rangle$ (deg.)
1.329–1.34	6	1.331	−0.65
1.33–1.35	9	1.334	−0.60
1.34–1.36	8	1.350	−0.44
1.35–1.37	8	1.358	−0.39
1.36–1.38	7	1.370	−0.41
1.37–1.39	6	1.375	−0.37
1.38–1.40	6	1.395	−0.12
1.39–1.414	5	1.398	−0.04

Fig. 4. α_2 as a function of $\alpha_1+\alpha_3$ for the imidazole compounds. The line depicted is the least-squares line obtained for the triazole compounds. The values are in degrees.

distance and the average deviation from the line, within narrow intervals of the C−C distance, are listed. It is seen that other quantities affecting the deviations cancel to a certain degree, and the values clearly show the C−C dependence. Zero deviation occurs at a C−C distance of ~1.41 Å, not far from the C−C distance commonly observed in triazole groups. The dependence may possibly be explained by a more ideal sp^2-hybridization of the carbon atoms in groups with a C−C bond length close to the value of a C−C double bond. An increase in the endocyclic angles at the carbon atoms then induces a decrease in the angles at the nitrogen atoms and a smaller increase in α_2 with the result that the point lies below the triazole line.

The sum, $\alpha_4+\alpha_5$, exhibits a similar behaviour as observed for the triazole compounds. The average, values, $\langle\alpha_4+\alpha_5\rangle$, are $216.32(15)°$ and $213.95(15)°$ for the 1- and 1,3-substituted compounds, respectively. The difference $[-2.37(21)°]$ in $\langle\alpha_4+\alpha_5\rangle$ between the 1- and 1,3-substituted compounds is, however, somewhat different from Δ_1 $[-3.61°]$ for the triazole compounds. The sum, $\alpha_4+\alpha_5$, also shows some dependence on the C−C distance. The fluctuations are, however, much larger than observed for the triazole compounds.

CONCLUSION

The angular changes due to N-substitution have been related qualitatively to changes in hybridization. Apart from smaller deviations, primarily due to differences in the C−C distances, the same relations hold for the imidazole compounds, and possibly other nitrogen-containing 5-membered rings may show a similar behaviour. A more quantitative analysis of the hybridization effect will involve quantum mechanical calculations on model systems, and will be the subject of further investigations.

In the analysis of $\alpha_4 + \alpha_5$ two compounds have been omitted from the calculations on the imidazole groups. Both compounds are 1,3-substituted, but one of the substituents is a metal ion [Cu^{2+} and Cd^{2+}].[52,46] For the Cu-complex $\alpha_4 + \alpha_5$ is 215.4°, slightly lower than the average value for the 1-substituted imidazole compounds. For the Cd-complex the value of $\alpha_4 + \alpha_5$ [216.3°] is identical to the average value of the 1-substituted compounds. If the changes in the angles are related to changes in hybridization, the value of $\alpha_4 + \alpha_5$ may possibly express the degree of σ-character of the nitrogen-metal bond. Similar features are found in benzotriazole complexes of various metal ions,[28,62–72] and an analysis of these aspects is in progress.

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