
Strong and weak hydrogen bonds in drug–DNA complexes: A statistical analysis

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A statistical analysis of strong and weak hydrogen bonds in the minor groove of DNA was carried out for a set of 70 drug–DNA complexes. The terms ‘strong’ and ‘weak’ pertain to the inherent strengths and weakness of the donor and acceptor fragments rather than to any energy considerations. The dataset was extracted from the protein data bank (PDB). The analysis was performed with an in-house software, hydrogen bond analysis tool (HBAT). In addition to strong hydrogen bonds such as O–H···O and N–H···O, the ubiquitous presence of weak hydrogen bonds such as C–H···O is implicated in molecular recognition. On an average, there are 1.4 weak hydrogen bonds for every strong hydrogen bond. For both categories of interaction, the N(3) of purine and the O(2) of pyrimidine are favoured acceptors. Donor multifurcation is common with the donors generally present in the drug molecules, and shared by hydrogen bond acceptors in the minor groove. Bifurcation and trifurcation are most commonly observed. The metrics for strong hydrogen bonds are consistent with established trends. The geometries are variable for weak hydrogen bonds. A database of recognition geometries for 26 literature amidinium-based inhibitors of Human African Trypanosomes (HAT) was generated with a docking study using seven inhibitors which occur in published crystal structures included in the list of 70 complexes mentioned above, and 19 inhibitors for which the drug–DNA complex crystal structures are unknown. The virtual geometries so generated correlate well with published activities for these 26 inhibitors, justifying our assumption that strong and weak hydrogen bonds are optimized in the active site.

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1. Introduction

DNA sequences, both Watson–Crick and mismatched base pairs, can be recognized with a variety of compounds that bind in the DNA minor groove (Neidle 2001; Lacy *et al* 2003; Tidwell *et al* 2003; Wilson *et al* 2005; Pindur *et al* 2005). These compounds can be broadly classified as those that bind without a significant increase in the groove width of the free DNA, and those that bind with a broadening of the groove. The former class is exemplified by ligands

containing aromatic rings and charged end-groups while the latter is typified by selective polyamide hairpin and related compounds such as distamycin and netropsin (Dervan and Edelson 2003). The forces that dominate small molecule minor groove-binding interactions are electrostatic, van der Waals, hydrophobic and hydrogen bonding. A crucial requirement for the ligand is a crescent shape that is complementary to the curvature of the minor groove.

Various aspects of minor groove drug–DNA recognition are revealed with the help of deposited X-ray structures in

Keywords. Docking; drug–DNA complexes; human African trypanosome; hydrogen bond; Protein Data Bank.

Abbreviations used: GA, genetic algorithm; HAT, Human African Trypanosomes; HBAT, hydrogen bond analysis tool; MGB, minor groove binder; NDB, nucleic acid data bank; PDB, protein data bank; RMSD, root mean square deviation; TBG, *Trypanosoma brucei gambiense*; TBR, *Trypanosoma brucei rhodesiense*.

the protein databank (PDB) and the nucleic acid databank (NDB) (Berman *et al* 2000). Experimental, comparative structural and molecular modelling studies suggest that sequence specificity is often linked to key hydrogen bonds between the base pairs and the small molecule (Kennard 1993; Taberero *et al* 1996; Dervan 2001; Morávek *et al* 2002; Rohs *et al* 2005).

The importance of weak C–H...O hydrogen bonds in macromolecules is a well-established phenomenon (Desiraju and Steiner 1999). We have earlier described their significance, as supporting interactions of stronger N–H...O and O–H...O bonds in protein–ligand complexation (Sarkhel and Desiraju 2004; Panigrahi and Desiraju 2007). Based on the assumption that strong hydrogen bonding in drug–receptor interactions are thus inherently assisted by weak hydrogen bonds (Aparna *et al* 2005), the aim of the present study is to analyse the importance of strong and weak hydrogen bonds in drug–DNA complexes.

1.1 Nomenclature

At this stage, and to avoid any possible linguistic misunderstanding, it is necessary to define the terms ‘strong’ and ‘weak’, as used in this paper, and by us elsewhere (Desiraju and Steiner 1999). The weak hydrogen bond is defined as *an interaction X–H...A wherein a hydrogen atom forms a bond between two structural moieties X and A, of which one or even both are only of moderate to low electronegativity*. There is no energetic implication in the definition of these terms ‘strong’ and ‘weak’. Hydrogen bonds cover a wide and continuous energy scale from around –0.5 to nearly –40 kcal/mol. The very weakest of hydrogen bonds (in energy terms) are barely distinguishable from van der Waals interactions while the strongest ones (in energy terms) are stronger than weak covalent bonds. Any energy cut-off between strong and weak bonds is arbitrary and therefore disputable. In principle, one could categorize hydrogen bonds as ‘weak’ and ‘strong’ according to an energetic criterion (an energy cut-off value), phenomenological criteria (distances or infrared] wave number shifts), or operational criteria (what they can do). The results of such alternative classifications are not necessarily consistent, because there are always cases where a hydrogen bond is, say ‘strong’ in terms of energy and ‘weak’ in terms of geometry, or the other way round. To avoid all confusion, therefore, we use a somewhat subjective, but undeniably unambiguous, definition. Hydrogen bonds formed by good donors (O–H, N–H) and good acceptors (N, O, halide) are labelled ‘strong’. Accordingly O–H...O, N–H...O, O–H...N and N–H...N hydrogen bonds will be termed ‘strong’ whatever be their energy stabilization, geometrical parameters or furcation status. Conversely, if either a poor

donor (C–H, S–H) or a poor acceptor is involved (–cloud, multiple bonds) (Nishio *et al* 1998), or both the donor and acceptor are poor (C–H...), the hydrogen bond is termed ‘weak’. There is substantial overlap between this definition and an energy-based definition but also some areas of difference. Notably, we do not consider as ‘weak’ very minor components of N–H...O bifurcated arrangements, which are frequently seen in biomolecules. Also, strongly bent O–H...O and N–H...O hydrogen bonds, which occur in sterically adverse situations, are not considered ‘weak’ by us.

Different terminologies have been employed by others. Jeffrey and Saenger (1991) have classified hydrogen bonds as ‘strong’ and ‘weak’ while Jeffrey (1997) has elaborated this further to ‘strong’, ‘moderate’ and ‘weak’. The reader will note that there is a near correspondence between the category we term ‘strong’ and Jeffrey calls ‘moderate’. Jeffrey’s terminology is in keeping with the biological literature where bonds such as O–H...O–H, and especially O_w–H...O_w–H, are not taken to be particularly ‘strong’, and N–H...O definitely veer towards what is understood as ‘weak’. Our bias in these definitions is of chemical origin. The reason we refer to Jeffrey’s middle category as ‘strong’ originates from supramolecular chemistry considerations. By ‘strong’ we mean hydrogen bonds that are able to control crystal and supramolecular structure effectively. This certainly includes O–H...O=C, N–H...O=C and O–H...O–H. By ‘weak’ we mean hydrogen bonds whose influence on crystal structure and packing is variable. In the end, though, all these discussions on nomenclature are semantic in nature. All kinds of hydrogen bonds are different and likewise, all kinds of weak hydrogen bonds are also different. Our definitions of ‘strong’ and ‘weak’ hydrogen bonds are certainly subject to debate and discussion, but they offer the advantages of consistency and lack of ambiguity. For a further classification of weak hydrogen bonds, the reader is advised to consult the book written by Desiraju and Steiner (1999).

1.2 Aims of this work

The first section of the present study deals with a comparative analysis of strong and weak hydrogen bonds in a database of 70 drug–DNA complex crystal structures. The second part deals with the molecular modelling applications of these results in a particular system. For the latter exercise, we have chosen a set of 26 amidinium derivatives targeted against Human African Trypanosomes (Athri *et al* 2006), *Trypanosoma brucei rhodesiense* (TBR) and *Trypanosoma brucei gambiense* (TBG). These organisms are responsible for Human African Trypanosomiasis (HAT) or sleeping sickness. The drugs currently used for the treatment of HAT are either toxic or difficult to use (Seed and Boykin 2001).

Only one drug for treating HAT is currently undergoing clinical trials (Boykin 2002; Wilson *et al* 2005). The orally available prodrug DB289 is converted systemically into another diamidine (DB75) that is active against the early-stage disease.

2. Materials and methods

2.1 Drug–DNA complexes from PDB

A set of 70 unique minor groove drug–DNA complexes was obtained from the PDB (table 1). The drug molecules present in these cases are berenil (3 complexes), furans and thiophenes (8), pentamidines (5), netropsin (12), distamycin (5), Hoechst drugs (16), benzimidazoles (14), DAPI (2), polyamide (3), pyridines (2). The therapeutic uses of the above-mentioned drugs are listed in table 2. H-atoms were added to the drug–DNA complexes, and then subjected to minimization keeping the heavy atoms rigid. This was carried out in MOE with the MMFFx force field (Halgren 1996; MOE 2006). The MOE optimized geometries were analysed with our in-house hydrogen bond analysis program, HBAT.

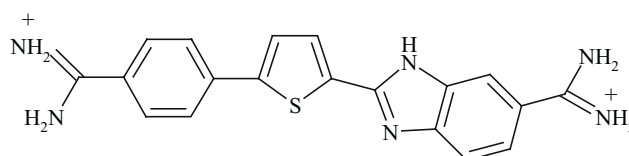
2.2 Hydrogen bond analysis tool

Strong and weak hydrogen bonds were analysed with an in-house developed program, HBAT (Tiwari *et al* 2006). Hydrogen bond analysis tool (HBAT) analyses and tabulates all hydrogen bonds present in a PDB file. The output file provides distance-angle distributions across various geometry ranges while tabulation of frequencies for each residue, ligand, water and nucleic acids is done easily for any kind of interaction. It is a user-friendly desktop tool, which operates both with default and user-selected parameters. The standard H-bonding criteria were set as d (H...A) 2.8 Å and $(X-H\cdots A)$ 90°. These liberal cut-offs were used, and this is common in statistical studies, because it is preferable to have some false-positives rather than a situation where genuine interactions get eliminated because of over-stringent cut-off limits.

2.3 Docking of HAT inhibitors

Molecule building, geometry optimizations and minimizations were carried out using the MMFFx force field in the MOE software. Docking was carried out with GOLD 3.0 (Cambridge Crystallographic Data Centre, Cambridge CB2 1EZ, UK). The amidinium inhibitors (26 compounds, table 3) were selected from the literature (Athri *et al* 2006). Of these, seven (furan-based compounds) are present in

the database of 70 experimental crystal structures analysed in the first section of this paper. Docking was performed for each of these 26 inhibitors into the DNA in eight experimental crystal structures; in other words, a total of 208 docking experiments were performed. Seven of these structures correspond to the seven furans mentioned above; the eighth corresponds to a thiophene-based inhibitor in structure ID-1VZK (Scheme I), which has been shown to be a good choice for docking for minor groove binders (Evans and Neidle 2006). This eighth structure is also contained in the earlier database of 70 structures. Significantly, the correlations observed for the docking geometries obtained from this eighth (thiophene-based) structure were significantly better than the others, and accordingly only results from this set of 26 docking experiments are discussed further. A region of 7.0 Å radius around the ligand was defined as the active site for each drug–DNA complex. Default-set parameters were used in the docking. For each of the 10 independent Genetic Algorithm (GA) runs, with a selection pressure 1.1, 100,000 GA operations were performed on a set of 5 islands. The population size of 200 individuals was specified. Default operator weights of 95, 95 and 10, respectively, were used for crossover, mutation and migration. To further speed up the calculation, the GA docking was stopped when the top three solutions were within 1.5 Å root mean square deviation (RMSD) of each other. The interaction analysis was carried out with HBAT as described above.



Scheme 1

3. Results and discussion

3.1 Overview of strong and weak hydrogen bonds in drug–DNA complexes

DNA contains a variety of strong and weak hydrogen bond functional groups (Scheme II). These groups are evenly exposed in the minor and major grooves. The ratio of the number of exposed donors to acceptors for AT and GC pairs in the major groove is 1:2, while it is 1:2 for GC and 0:2 for AT in the minor groove. The possible acceptors present in the major groove are $[A\{N(7)\}]$, $[G\{N(7)\}]$, $[G\{N(6)\}]$

Table 1. Minor groove drug–DNA complexes in this study: (a) berenil 1–3, (b) furans 4–11, (c) pentamidines 12–16, (d) netropsin 17–28, (e) distamycin 29–33, (f) Hoechst drugs 34–49, (g) benzimidazoles 50–63, (h) DAPI 64–65, (i) polyamides 66–68, (j) pyridines 69–70

SI No.	PDB ID	NDB ID	Resolution	Pubmed ID	Hetero group
1	1D63	GDL016	2	1640462	BRN
2	2DBE	GDL009	2.5	2323343	BRN
3	268D	GDLB42	2	n/a	BRN
4	289D	GDL045	2.2	8917643	D19
5	1VZK	-	1.7	n/a	D1B
6	1EEL	-	2.4	11128631	D24
7	1FMQ	DD0034	2	11128631	D34
8	1FMS	DD0035	1.9	11128631	D35
9	360D	GDL056	1.8	9611230	BPF
10	227D	GDL036	2.2	8639524	BGF
11	298D	GDL044	2.2	8917643	D18
12	1M6F	DD0052	1.7	12431090	CGQ
13	166D	GDL027	2.2	7813486	PET
14	1D64	GDL015	2.1	1643044	PNT
15	102D	GDL032	2.2	7608897	TNT
16	1PRP	GDL023	2.1	8268158	TNT
17	101D	GDLB31	2.2	7711020	NT
18	121D	GDL014	2.2	8395202	NT
19	195D	GDL030	2.3	n/a	NT
20	1D85	GDLB17	2.5	1332773	NT
21	1D86	GDL018	2.2	1332773	NT
22	1DNE	GDL004	2.4	2539859	NT
23	1DVL	DD0024	2.4	11914483	NT
24	261D	GDJ046	2.4	9125500	NT
25	358D	GDJB55	2.5	9826773	NT
26	375D	GDJ059	2.4	9826773	NT
27	474D	GDJB58	2.4	9826773	NT
28	6BNA	GDLB05	2.2	2991536	NT
29	267D	GDLB41	2	n/a	DMY
30	1JTL	DD0042	1.9	12071949	DMY
31	1K2Z	DD0046	2.4	12071949	DMY
32	2DND	GDL003	2.2	3479798	DMY
33	378D	GDH060	2.4	10089456	DMY
34	127D	GDL022	2	1371249	HT
35	128D	GDLB19	2.5	1371249	HT
36	129D	GDL021	2.2	1371249	HT
37	130D	GDLB20	2.5	1371249	HT
38	1D43	GDL010	2	1718416	HT
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40	1D45	GDL012	1.9	1718416	HT
41	1D46	GDL013	2	1718416	HT

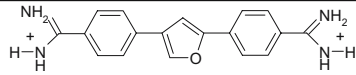
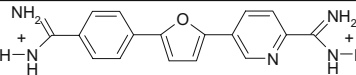
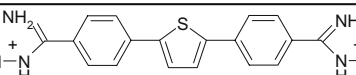
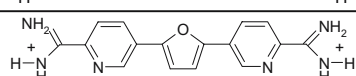
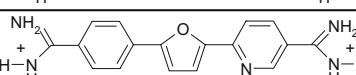
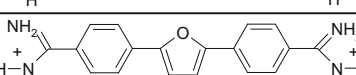
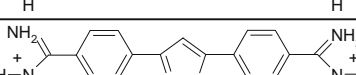
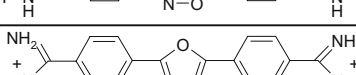
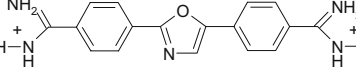
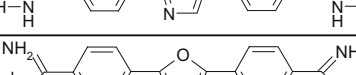
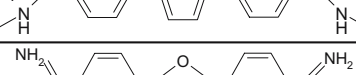
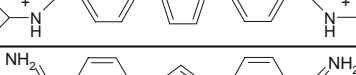
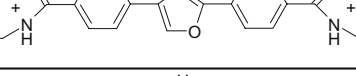
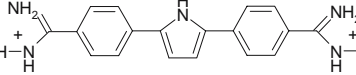
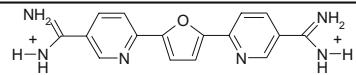
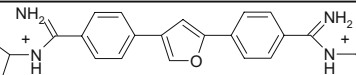
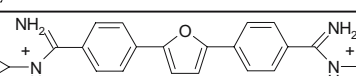
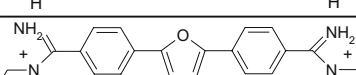
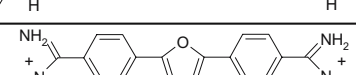
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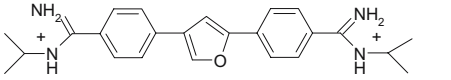
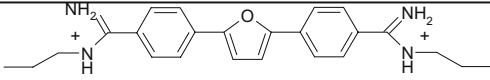
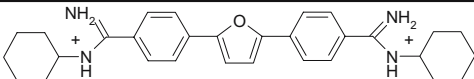
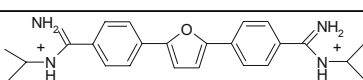
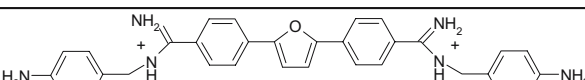
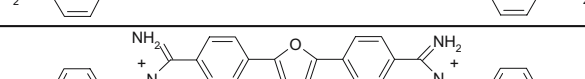
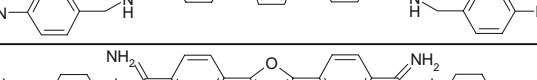
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43	264D	GDL026	2.4	7517864	HT
44	296D	GDL028	2.2	7515488	HT
45	8BNA	GDL006	2.2	2445998	HT
46	311D	GDL052	2.2	9162901	HT2
47	303D	GDL048	2.2	9017011	RO2
48	302D	GDL047	2.2	9017011	RO2
49	447D	DD0007	2.2	10666470	BBZ
50	263D	GDL039	2.2	8901516	TBZ
51	459D	DD0014	2.3	10373586	TBZ
52	1FTD	-	2	11170623	E97
53	403D	BDD001	1.4	9692982	HT1
54	443D	DD0004	1.6	10666470	IA
55	445D	DD0006	2.6	10666470	IA
56	449D	DD0009	2.1	10666470	IA
57	442D	DD0003	1.6	10666470	IB
58	444D	DD0005	2.4	10666470	IB
59	448D	DD0008	2.2	10666470	IB
60	109D	GDL033	2	n/a	IBB
61	1LEX	GDL037	2.2	8527438	IPL
62	1LEY	GDL038	2.2	8527438	IPL
63	269D	GDLB43	2.1	n/a	HT
64	1D30	GDL008	2.4	2627296	DAP
65	432D	DD0002	1.9	10600105	DAP
66	1CVX	DD0020	2.2	10623546	HP2
67	1CVY	DD0021	2.1	10623546	IPY
68	408D	BDD003	2.1	9756473	IPY
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70	328D	GDL053	2.6	9321660	SN7

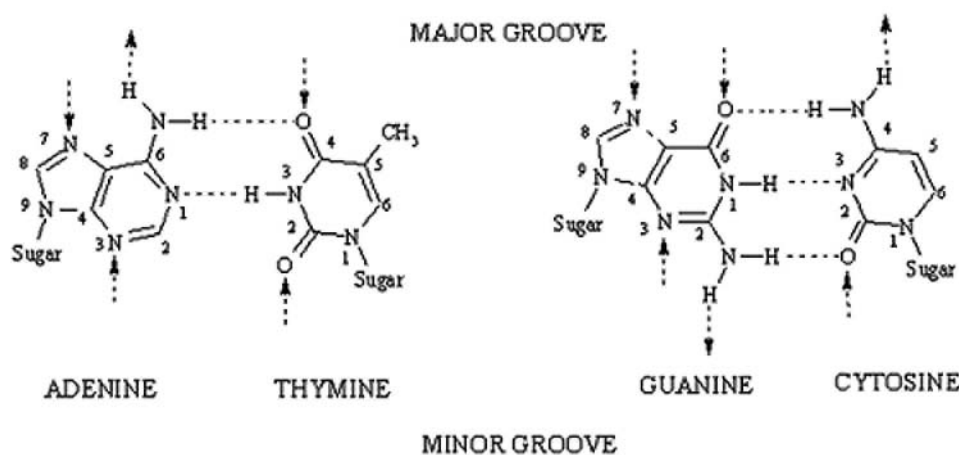
Table 2. Minor groove binders (MGB) and their respective therapeutic uses

Sl. No.	Drug	Therapeutic uses
1	Berenil	Antiprotozoal agents, intercalating agents trypanocidal agents
2	Furans	Antitrypanosomal, <i>Pneumocystis carinii</i>
3	Pentamidines	African trypanosomiasis and leishmaniasis, AIDS-related <i>P. carinii</i> pneumonia
4	Netropsin	Filaricides, antiviral agents, anticancer agents
5	Distamycin	Anticancer and antiviral agents
6	Hoechst drugs	Filaricides and antifungal agent
7	Benzimidazoles	Antiviral agents
8	DAPI	Trypanocidal agents
9	Polyamide	Anticancer agents
10	Pyridines	Anticancer agents

Table 3. Amidinium-based HAT inhibitors used in docking and their activities.

Sl. No.	Code	Structure	PIC ₅₀	IC ₅₀ (in μM)
1	DB690		8.79	0.0016
2	DB867		8.69	0.0020
3	DB351		8.51	0.00302
4	DB994		8.39	0.0040
5	DB820		8.31	0.0048
6	DB75		8.29	0.0051
7	1RJL164		8.28	0.0052
8	DB417		8.18	0.0066
9	DB484		8.15	0.0070
10	DB427		8	0.0100
11	DB313		7.97	0.0107
12	DB518		7.86	0.0138
13	DB262		7.85	0.0141
14	DB829		7.77	0.0169
15	DB481		7.72	0.0190
16	DB193		7.63	0.0234
17	DB312		7.63	0.0234
18	DB235		7.45	0.0354
19	DB244		7.45	0.0354

20	DB480		7.41	0.0389
21	DB240		7.35	0.0446
22	DB249		7.17	0.0676
23	DB181		7.16	0.0691
24	DB422		7.01	0.0977
25	DB421		6.99	0.1023
26	DB568		6.77	0.1698



Scheme 11

while donors belong to the amino groups in the [A{N(6)}] and [C{N(4)}] positions. In the minor groove, the acceptors are [A{N(3)}], [G{N(3)}], [T{O(2)}], [C{O(2)}] and the donor is the amino group of [G{N(2)}]. Several proteins of functional importance bind to the major groove, whereas non-covalently binding drugs bind to the minor groove. As discussed earlier, the MGB selectively bind to the AT-rich region. Therefore, acceptors present in the minor groove, notably N(3) of purine and C(2)=O of pyrimidine, are important sites for drug–DNA interaction. Apart from

nucleotides, phosphate groups and the ribose O-atoms are also acceptors.

3.2 Hydrogen bond analysis

Both strong and weak hydrogen bonds are observed in the minor groove of drug–DNA complexes. As expected, N(3) of purine and O(2) of pyrimidine are important (table 4). The exceptions are polyamides and DAPI drugs, which

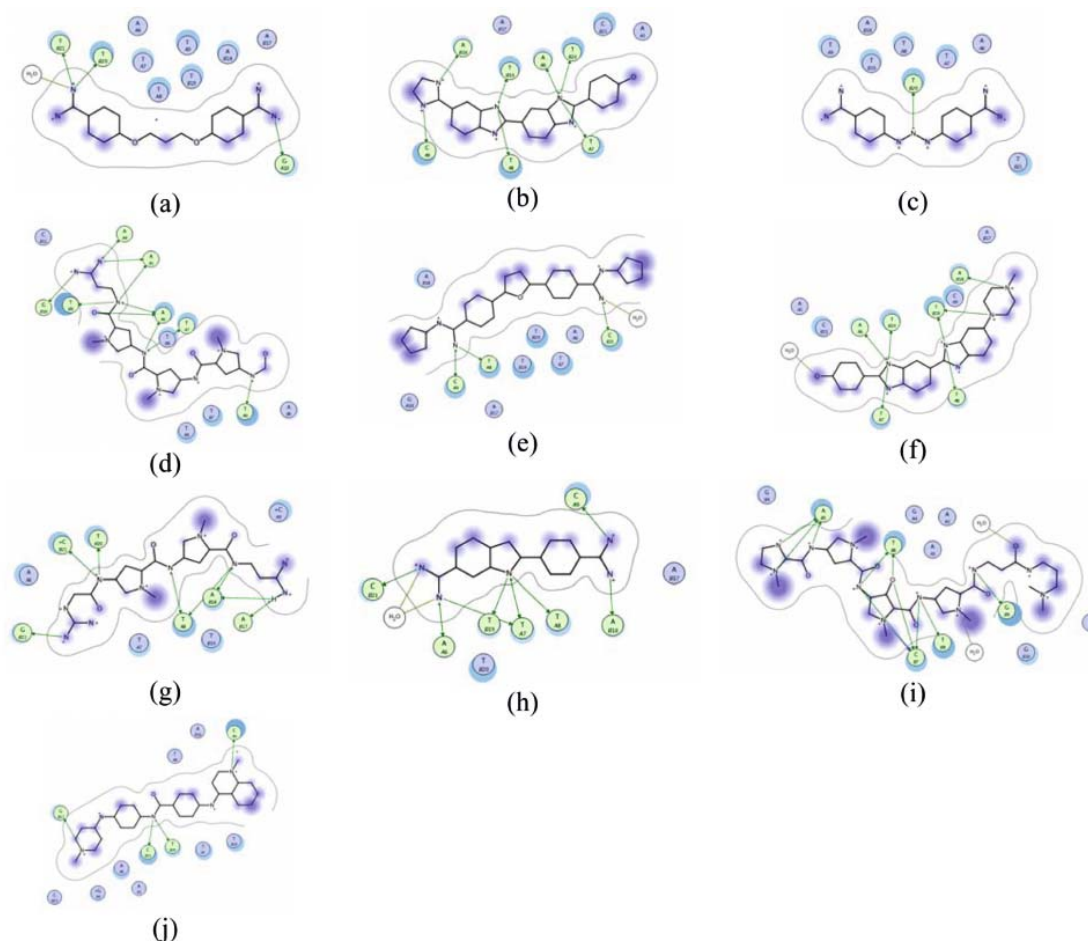


Figure 1. Schematic representation of minor groove binders in the minor groove. Strong hydrogen bonds are shown with green arrows, exposed ligand atoms in blue contours, and the nearest nucleotides as circles: (a) pentamidine, (b) benzimidazoles, (c) berenil, (d) distamycin, (e) furan, (f) Hoechst drugs, (g) netropsin, (h) DAPI, (i) polyamide, (j) pyridine.

interact with adenine N(3), guanine N(3), thymine O(2) and cytosine O(2). A schematic diagram for a typical inhibitor for each class is shown in figure 1. The types of strong and weak hydrogen bonds observed in the case of purine are N–H···N(3) and C–H···N(3), and for pyrimidine they are N–H···O(2) and C–H···O(2). Also observed clearly are N–H···O_w and C–H···O_w interactions between the drug and water. The distribution of types of strong and weak hydrogen bonds in a total of 835 interactions are: (a) purine C–H···N(3) 18%, N–H···N(3) 12%, (b) pyrimidine C–H···O(2) 18%, N–H···O(2) 18%, (c) C–H···O_w 21%, N–H···O_w 12% (figure 2a). The total number of C–H···N and C–H···O hydrogen bonds taken together is 481, while for N–H···N and N–H···O the total is 354. The present dataset contains 70 drug molecules. Thus, on average, each drug molecule interacts with DNA through seven weak interactions and five

strong interactions in the minor groove, which is effectively 1.4 weak hydrogen bonds for each strong hydrogen bond. Apart from nucleotides, drug molecules also interact with the sugar moiety, but they rarely interact with the phosphate group. The number of interactions observed between drug molecules and the deoxyribose sugar and phosphates taken together are 118. Among these interactions, deoxyribose sugar O4' of adenine and thymine have more hydrogen bonds (figure 2b).

3.3 Donor furcation

The specificity and affinity of minor groove-binding agents are sensitive to the local width of the groove. In AT-rich sequences, the minor groove is unusually narrow (0.3–0.4 nm). Due to the narrow width, a donor present

Table 4. Strong and weak hydrogen bonds in drug–DNA complexes.

	C–H...N [A{N(3)}]	C–H...N [G{N(3)}]	N–H...N [A{N(3)}]	N–H...N [G{N(3)}]	C–H...O (WATER)	N–H...O (WATER)	O–H...O (WATER)	C–H...O [T{O(2)}]	C–H...O [C{O(2)}]	N–H...O [T{O(2)}]	N–H...O [C{O(2)}]
Berenil	5		6	3	10			5	4		
Furans	15		3	44	18			14	14		
Pentamidines	14		6	8	11			18	3		
Netropsin	12		15	12	20			17	18		
Distamycin	14		19	10	8			11	16		
Hoechst drugs	33		15	45	13	3		39	34		
Benzimidazoles	29	2	20	19	8			33	40		
DAPI	1	1	2	1	5			3	5		
Polyamides	3	14	10	28	4	1			5	13	6
Pyridines	9			7	1			7	2		
TOTAL	135	17	96	177	98	4		147	5	149	6

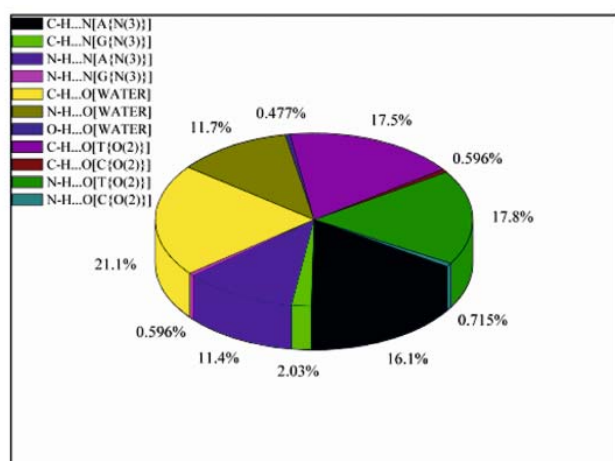
in a drug molecule possibly is hydrogen bonded to more than one acceptor on the wall of the groove. This type of situation, where a donor can interact with several acceptors simultaneously or an acceptor can interact simultaneously with many donors, is termed furcation. The most frequently observed furcated interactions in this study involve bifurcated and trifurcated donors. Figure 3 shows examples of bi- and trifurcated donors in the DB244–DNA complex in PDB ID 1EEL. Typically, a single donor from the ligand is shared by two or three acceptors of the minor groove. Table 5 shows a distribution of strong and weak hydrogen bonds at various levels of furcation. With an increase in furcation level, the numbers of weak hydrogen bonds increase. The numbers of donor-furcated cases are: (a) bifurcated, 205; (b) trifurcated, 41; (c) tetrafurcated, 7; (d) penta-furcated, 2.

3.4 Hydrogen bond geometry

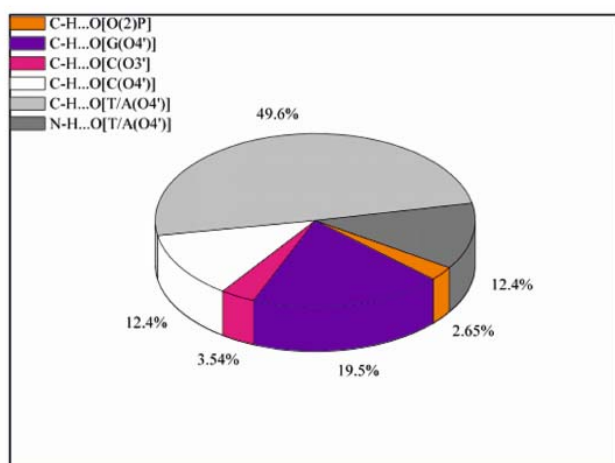
For strong hydrogen bonds of the type N–H...N and N–H...O, the median H...N/H...O distances, d , are less than 2.4 Å and 2.2 Å, respectively (figure 4). The cone-corrected angular distributions for N–H...N and N–H...O are similar with maxima in the range of 170–175°. The inverse length–angle correlations are also well-behaved in these cases. Strong N–H...N and N–H...O hydrogen bonds show better linearity compared with weak C–H...N and C–H...O hydrogen bonds. The weak C–H...N, C–H...O hydrogen bonds have variable geometry. The cone-corrected angular distributions of C–H...N and C–H...O interactions have maxima at 165–170° and 150–155°, respectively. To summarize, the geometries for strong and weak hydrogen bonds observed in the drug–DNA complexes are consistent and fall within acceptable limits.

3.5 Human African Trypanosomiasis (docking)

Molecular docking is a very useful technique in rational drug design. However, the purpose of using docking in the present context is different. Molecular docking was carried out to estimate the best drug–DNA geometries in cases where the crystal structures of the complex are unknown, assuming that strong and weak hydrogen bonds are optimized. Accordingly, we selected the best geometry (poses) for such complexes to obtain virtual crystal geometries for the 26 selected HAT inhibitors. The inhibitors were docked separately to each of the 8 drug–DNA complexes of the amidinium category. Each docking run was evaluated through regression analysis of experimental activities *versus* docking scores. The best correlation $r = 0.83$ was obtained in the case of PDB ID 1VZK, where molecules with higher activity show greater docking scores (figure 5),



(a)



(b)

Figure 2. Distribution of hydrogen bonds in drug–DNA complexes. Interactions of drug with (a) nucleotides and water, (b) sugar and phosphate.

showing that our assumption regarding optimization of hydrogen bonds is a valid one. The best poses for the inhibitors were exported to HBAT for hydrogen bond analysis. The docking solutions of molecule **DB690** and **DB568** are shown in figure 6.

Molecule **DB690** interacts with DNA through six weak and five strong hydrogen bonds. At one end, one amide group of the drug molecule is hydrogen-bonded to T(O2). Further, this amide is also hydrogen-bonded to a water molecule. The water molecule is again hydrogen-bonded to the phosphate group present at the opposite strand. The other amide group is hydrogen-bonded to C(O2). Between these two ends, the weak C–H...N and C–H...O hydrogen bonds

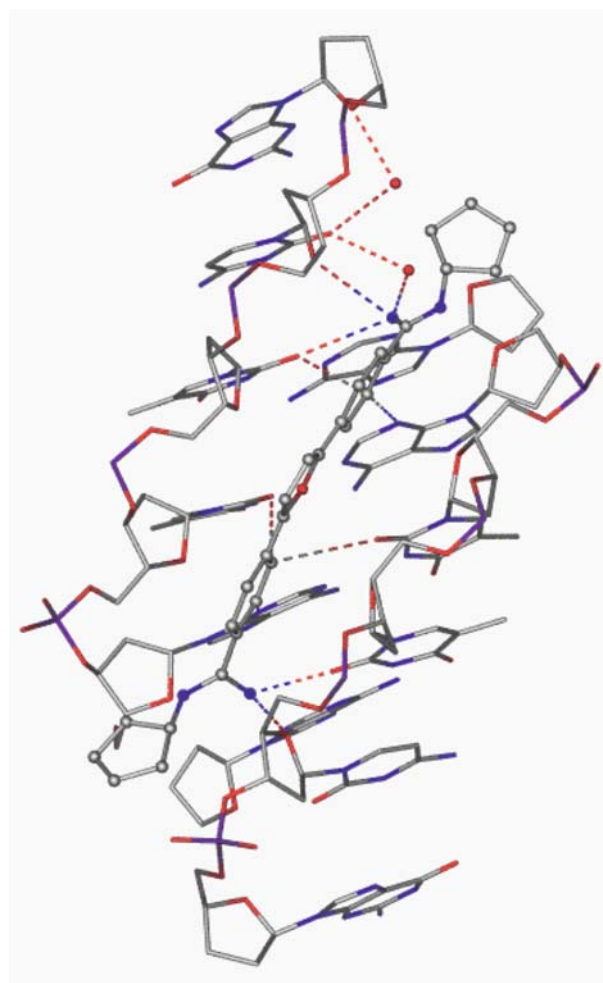
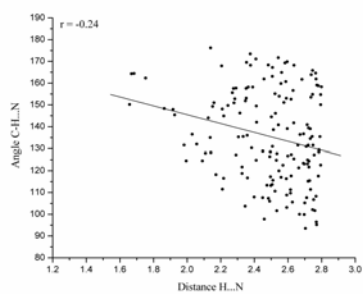


Figure 3. Bifurcated and trifurcated hydrogen bonds in DB244–DNA complex, PDB ID 1EEL.

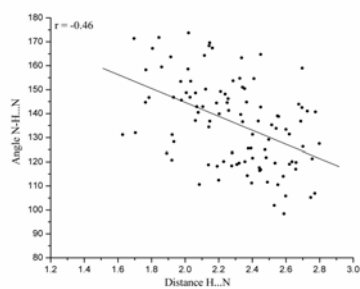
Table 5. Strong and weak hydrogen bonds at various levels of donor furcation.

Furcation level	C–H...N	N–H...N	C–H...O	N–H...O
Bifurcated	84	69	216	141
Trifurcated	20	20	52	31
Tetrafurcated	6	5	10	7
Pentafurcated	6	-	4	-

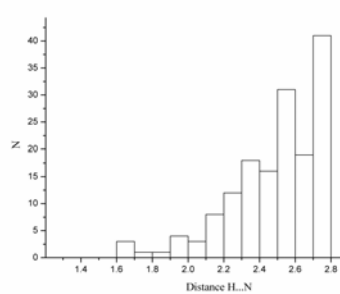
are present (figure 6a). The inactive molecule, **DB568** binds to DNA with six weak and four strong interactions (figure 6b). The interactions observed between molecule **DB690**, **DB568** and DNA are listed in table 6.



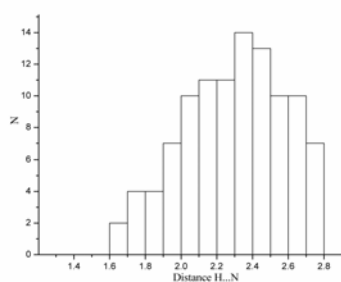
(a) C–H···N



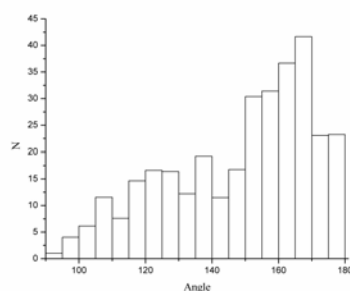
(b) N–H···N



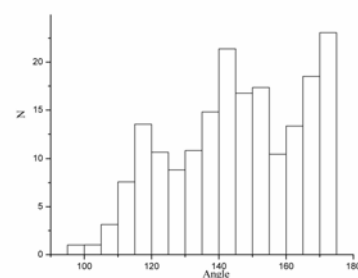
(c) C–H···N



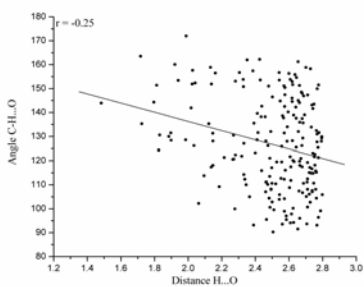
(d) N–H···N



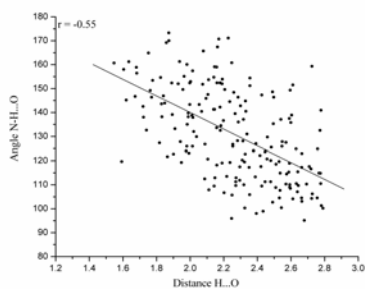
(e) C–H···N



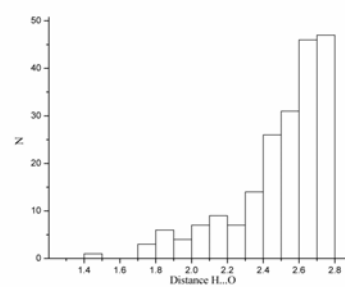
(f) N–H···N



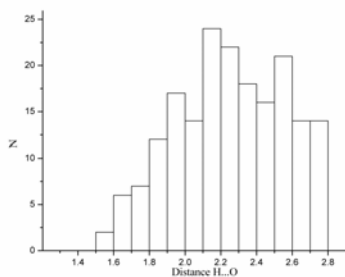
(g) C–H···O



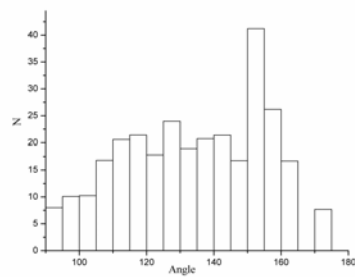
(h) N–H···O



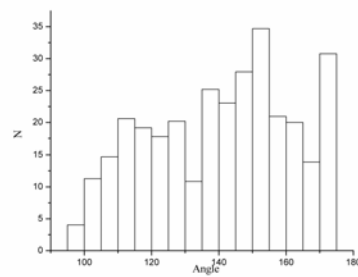
(i) C–H···O



(j) N–H···O



(k) C–H···O



(l) N–H···O

Figure 4. Hydrogen bond geometry for purine (a)–(f) and pyrimidine (g)–(l) acceptors. In each case, the inverse length–angle scatterplot is followed by histograms of distances and cone-corrected angular distributions.

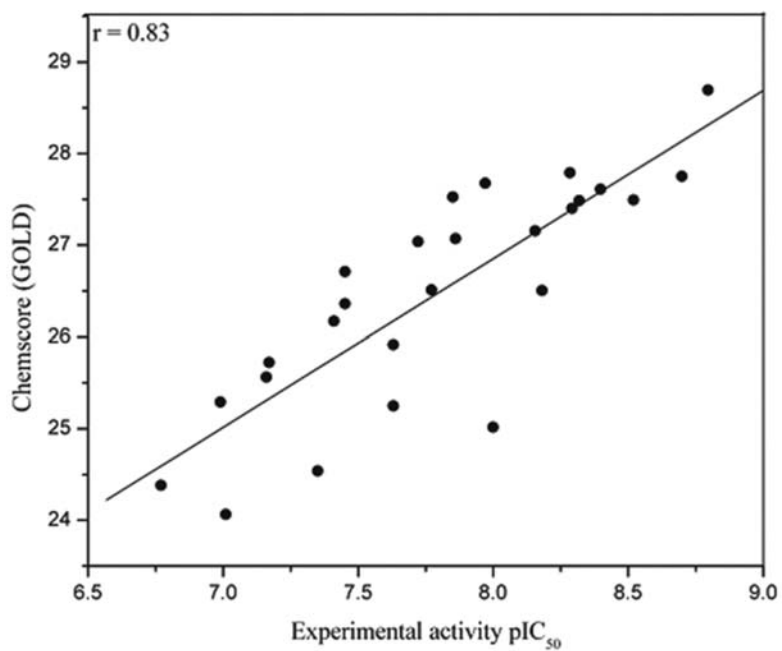
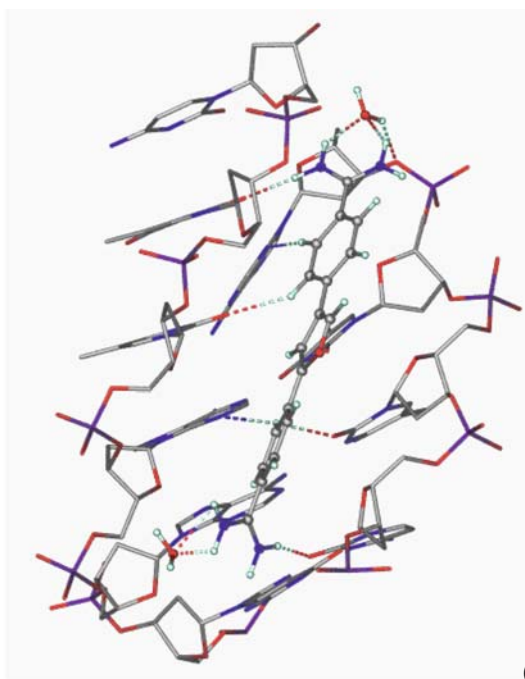
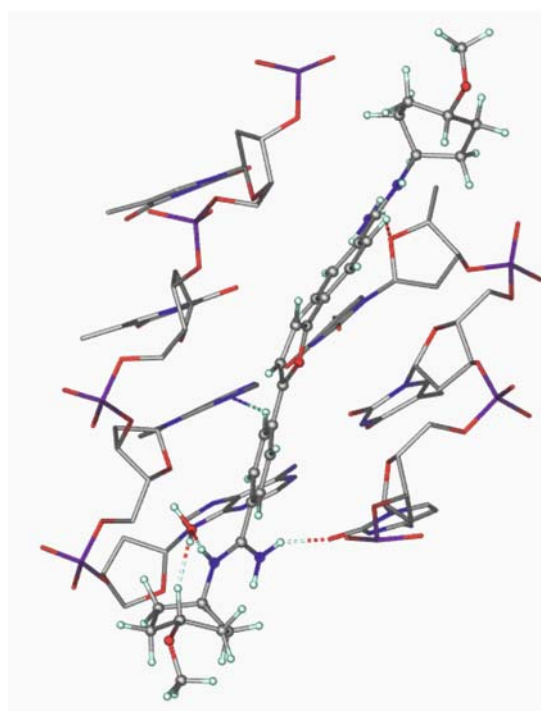


Figure 5. Fitness scores versus biological activities of HAT inhibitors.



(a)



(b)

Figure 6. Best docking solutions of (a) molecule DB690 and (b) molecule DB568 in the minor groove.

Table 6a. Hydrogen bonds in the molecule DB690–DNA complex

Type	Acceptor	Acceptor atom	Residue number	d (H···A)	D (X···A)	q (X–H···A)
C–H···N	A	N3	6	2.303	3.382	171.8
C–H···N	A	N3	18	2.602	3.378	127.5
C–H···O	T	O2	19	2.718	3.28	111.9
C–H···O	T	O2	19	2.449	3.284	132.4
C–H···O	T	O2	20	2.693	3.098	101.4
C–H···O	T	O2	8	2.43	3.053	114.8
N–H···O	C	O2	9	2.117	3.097	162.7
N–H···O	HOH	O	24	2.155	2.994	139.1
N–H···O	HOH	O	24	2.056	2.925	142.6
N–H···O	HOH	O	25	1.51	2.163	116.7
N–H···O	T	O2	20	2.135	3.085	155.7

Table 6b. Hydrogen bonds in the molecule DB568–DNA complex

Type	Acceptor	Acceptor atom	Residue number	d (H···A)	D (X···A)	q (X–H···A)
C–H···N	A	N3	18	2.775	3.654	137.5
C–H···O	A	O1P	18	2.767	3.299	109.4
C–H···O	A	O4'	18	2.694	3.071	99.67
C–H···O	HOH	O	25	2.076	3.122	158.1
C–H···O	T	O1P	8	2.599	3.222	115.1
C–H···O	T	O2	19	2.683	3.241	111.2
N–H···N	G	N2	16	2.667	3.146	108.8
N–H···O	C	O2	9	1.709	2.592	143.4
N–H···O	HOH	O	25	1.82	2.807	163.5
N–H···O	T	O4'	7	2.403	2.836	104.6

3.6 Hydrogen bonds in HAT inhibitors

The hydrogen bond geometry for C–H···O(2) and N–H···O(2) pyrimidine acceptors are discussed here as representatives of strong and weak hydrogen bonds. Figure 7 shows the C–H···O and N–H···O hydrogen bond geometries which involve DNA pyrimidine for the 26 selected HAT inhibitors. For N–H···O and C–H···O hydrogen bonds, the median H···O distances d are less than 2.1 Å and 2.8 Å, respectively. This is normal. The

inverse length–angle correlations are also consistent for both types of hydrogen bonds. The cone-corrected angular distribution for N–H···O has a maximum at 175–180°. For C–H···O interactions, the maximum lies at 140–145°. This too is as expected. Similarly, the hydrogen bond geometries obtained for both X-ray structures and the virtual complexes are consistent. Docking has produced a set of reasonable drug–DNA recognition geometries in the 19 cases where no crystal structure is available (virtual crystal structures).

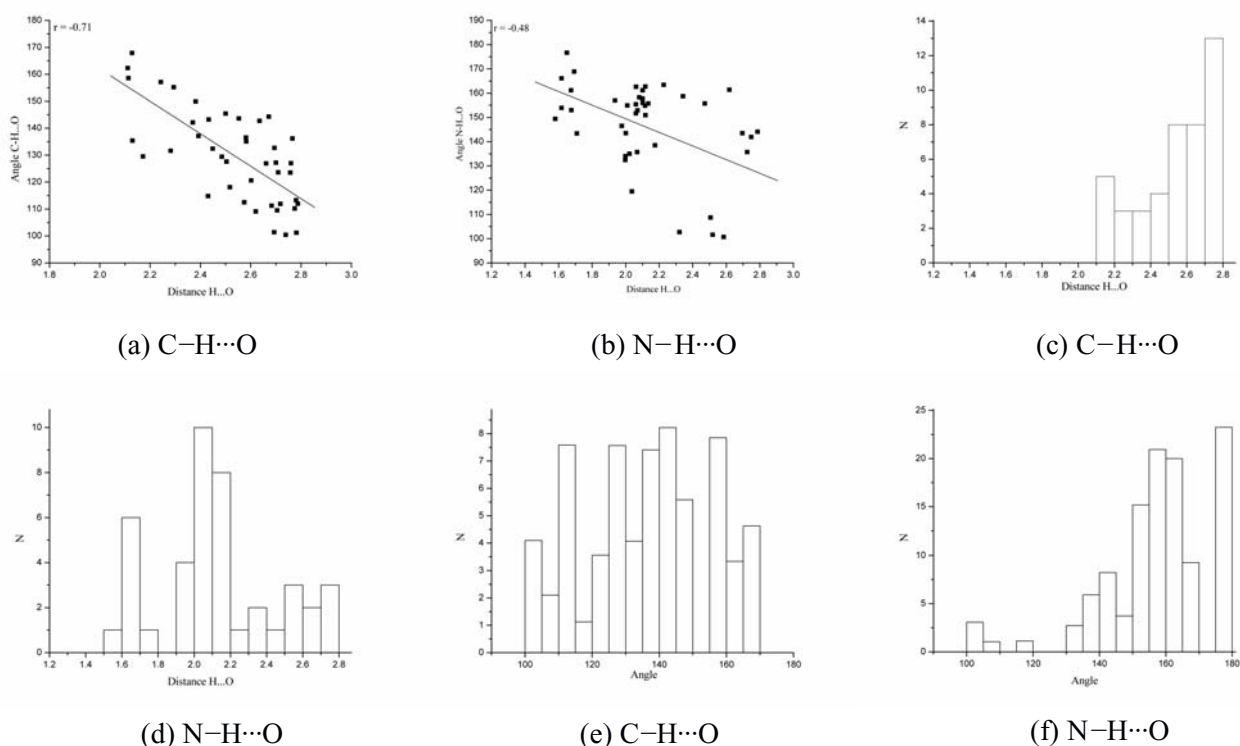


Figure 7. C-H...O and N-H...O hydrogen bond geometries for 26 amidinium derivatives. In all cases, pyrimidine O(2) is the acceptor.

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