Exploring the limits of nucleobase expansion: Computational design of naphthohomologated (xx-) purines and comparison to the natural and xDNA purines

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Supplementary Information (15 pages)

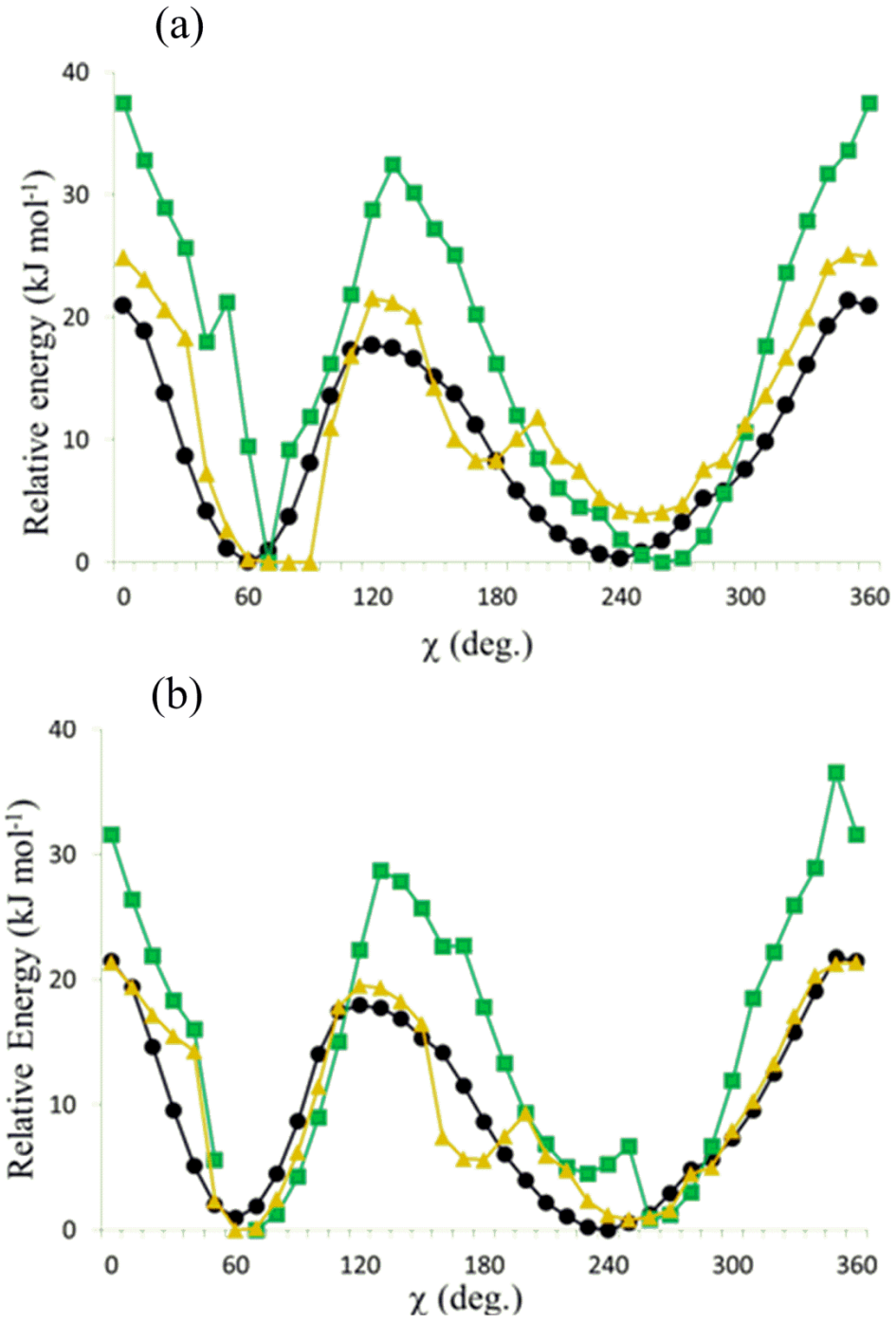

Figure S1. Comparison of the relative energy as a function of rotation about the glycosidic bond for (a) xx-adenine and (b) xx-guanine, using the nucleoside model (●, black), anionic phosphate nucleotide model (■, green) and the counterion added nucleotide model (▲, orange). χ (deg.) equals ∠(O4′C1′C3cC4c), and χ values between approximately 90 and 270° represent the *anti* orientation; see Figure 2 in the main manuscript).

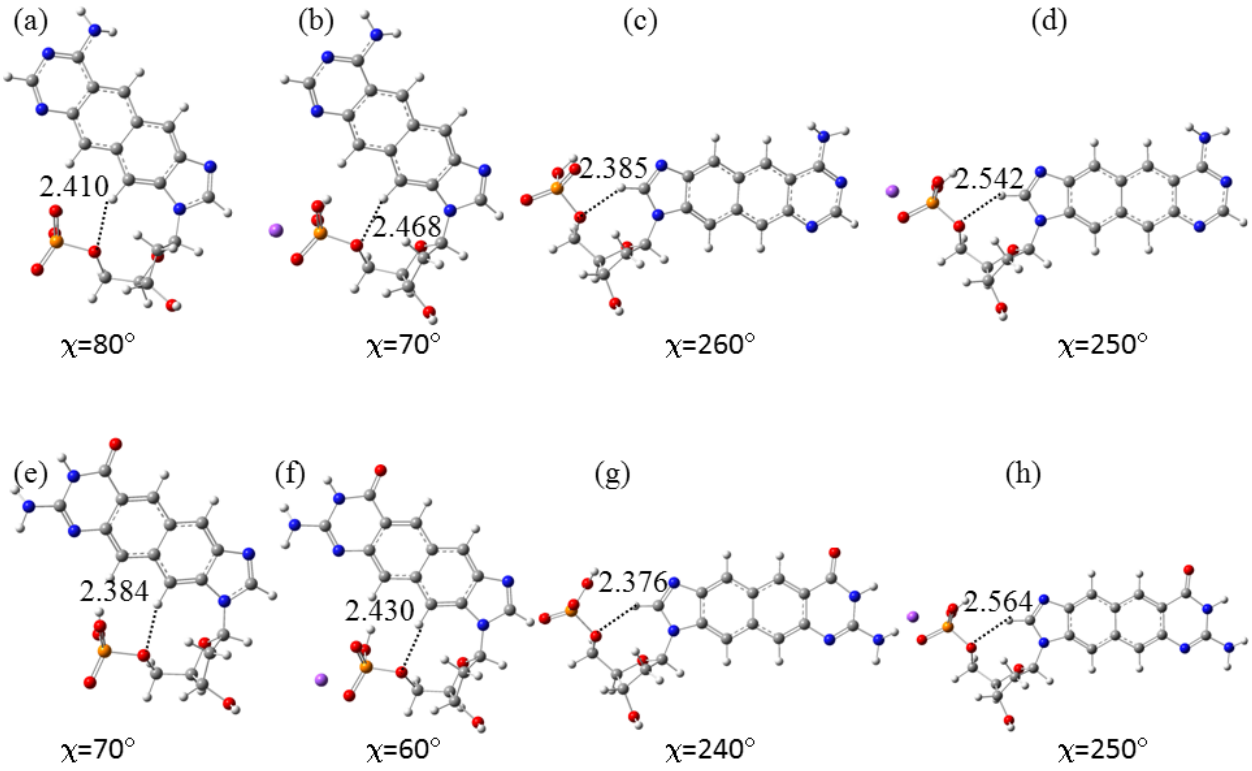

Figure S2. *anti* and *syn* minima for rotation about the glycosidic bond in xx-adenine (a-d) and xx-guanine (e-h)purines using the anionic phosphate model (a, b, e and f) and sodium counterion added phosphate model (c, d, g and h).

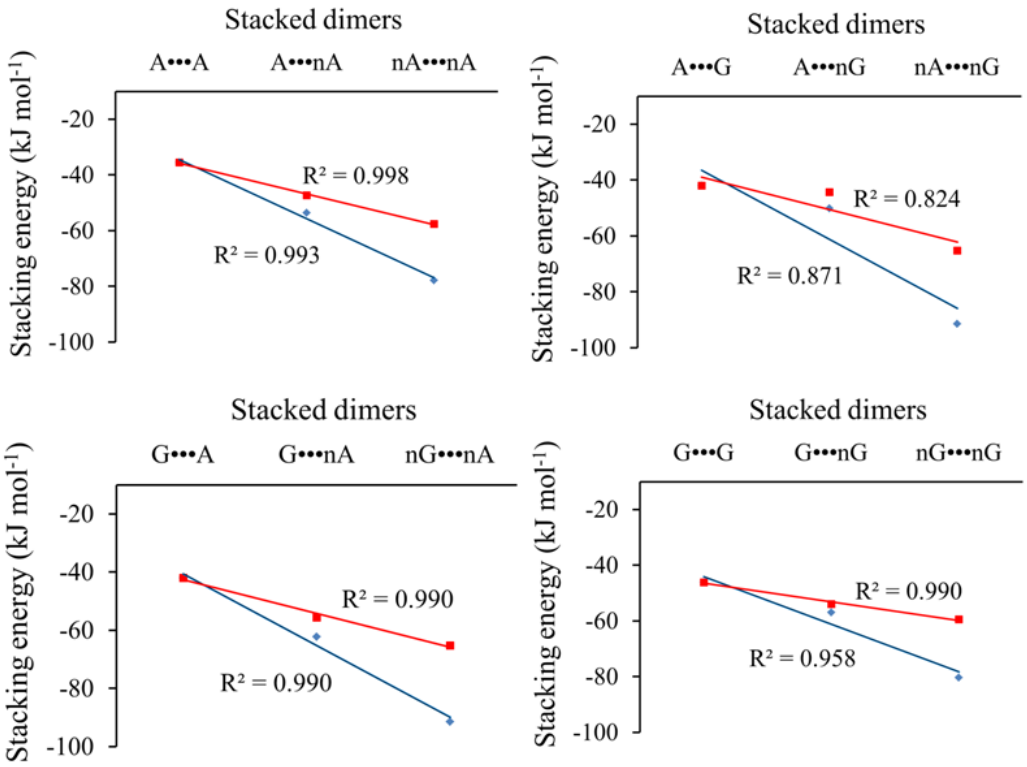

Figure S3. The stacking energy as a function of purine expansion for the x-purines (red, ■, n = x) and xx-purines (blue, ◆, n = xx).

Table S1. γ-torsions for the syn and anti minima for purines and expanded purines calculated from χ-scans on the nucleoside model.

purine	orientation	χ (deg)	γ (deg)
A	*anti*	230	51.2
xA	*anti*	240	50.3
xA	*syn*	60	44.4
xxA	*anti*	240	50.2
xxA	*syn*	60	45.9
G	*anti*	240	49.4
xG	*anti*	240	49.9
xG	*syn*	60	45.1
xxG	*anti*	240	49.9
xxG	*syn*	60	45.9

Table S2-S5.

Table S2. Cartesian coordinates for xA:T base pair.

Calculated energy (in Hartrees)= –1153.77282

atom	X	Y	Z
C	3.81890800	-1.28675100	-0.00111700
O	3.29327400	-2.39156100	-0.00249400
N	5.20911100	-1.10851700	0.00083800
N	3.09706900	-0.11055800	-0.00135300
H	2.05325100	-0.22215200	-0.00267400
C	3.59353800	1.18311200	0.00030100
C	5.04946100	1.29851700	0.00218200
C	5.76851900	0.15080400	0.00233500
H	6.85428900	0.16247100	0.00372000
O	2.83255500	2.15891100	0.00014200
C	5.66000500	2.66924400	0.00391400
H	5.33891300	3.24072400	-0.87323200
H	5.33712900	3.23931800	0.88132400
H	6.75220100	2.61725200	0.00499000
H	-4.05244000	-2.38817600	0.00238700
C	-3.78479500	-1.33766800	0.00124400
C	-2.41741800	-0.99059900	-0.00022700
C	-4.70422400	-0.30590700	0.00102400
C	-2.02332200	0.39224100	-0.00174600
N	-1.49602900	-2.01190300	-0.00027300
N	-6.08840900	-0.29191700	0.00209700
C	-4.32692300	1.07140200	-0.00069700
C	-0.59397700	0.63275700	-0.00283400
C	-2.98689600	1.41945400	-0.00212300
C	-0.23807500	-1.64989800	-0.00177900
C	-6.45623200	1.03976500	0.00100300
N	-5.45880000	1.88166100	-0.00071400
N	-0.07577600	1.87528000	-0.00411600
N	0.26579800	-0.38922800	-0.00297800
H	-2.71954900	2.47110400	-0.00375000
H	0.51687900	-2.43434100	-0.00200100
H	-7.50364800	1.31757800	0.00154600
H	0.94003700	2.00188400	-0.00319200
H	-0.66909300	2.68563000	-0.00108100
C	-6.96410300	-1.44698800	0.00410600
H	-6.79638000	-2.06316100	-0.88509300
H	-6.79575900	-2.06061500	0.89495000
H	-8.00126600	-1.10679100	0.00397300
C	6.06513000	-2.29407500	0.00098200
H	5.41464600	-3.16643700	0.00057700
H	6.69829000	-2.30954300	-0.89135000
H	6.69755900	-2.30974600	0.89381300

Table S3. Cartesian coordinates for xxA:T **base pair.**

Calculated energy (in Hartrees)= –1307.42852

atom	X	Y	Z
C	7.36752800	-2.05469200	-0.00476500
H	6.77779800	-2.96872400	-0.03426300
N	6.43361600	-0.92930200	-0.00522800
C	6.90712600	0.36452400	-0.00440600
H	7.98964800	0.44925800	-0.00685800
C	6.11232900	1.46121300	-0.00151500
C	6.62840700	2.87023900	-0.00167000
H	6.26659000	3.41826200	-0.87791300
H	6.26999500	3.41716800	0.87664800
H	7.72159600	2.89277800	-0.00378400
C	4.66778900	1.24773100	0.00136000
O	3.84369100	2.17146300	0.00368100
N	4.25885500	-0.07577400	0.00119700
H	3.22493400	-0.25794700	0.00343800
C	5.05849000	-1.20102200	-0.00090600
O	4.60838900	-2.33837600	0.00048600
H	7.98043300	-2.04506900	0.90181800
H	8.01903300	-2.01019600	-0.88260300
H	-8.79688200	1.29202300	-0.00400700
C	-7.73548300	1.07178100	-0.00308000
N	-7.29932000	-0.23946600	-0.00230100
N	-6.78892200	1.96784800	-0.00256000
C	-5.91357100	-0.18173000	-0.00121900
C	-8.11232600	-1.43809500	-0.00304300
C	-5.60885000	1.22341300	-0.00142800
C	-4.94941200	-1.16112100	-0.00021100
H	-7.91320700	-2.04350200	-0.89371300
H	-7.91252400	-2.04482200	0.88655800
H	-9.16624800	-1.15379900	-0.00238600
C	-4.29895400	1.64412700	-0.00051100
H	-5.19098600	-2.21935600	-0.00015300
C	-3.58721900	-0.74762200	0.00070900
H	-4.05867100	2.70269500	-0.00062200
C	-3.26350500	0.67014500	0.00057400
C	-2.53604900	-1.68399200	0.00172000
C	-1.90529400	1.04919200	0.00151700
C	-1.19995500	-1.29491900	0.00257400
H	-2.75072200	-2.74809700	0.00183900
C	-0.88218300	0.10970300	0.00246900
H	-1.68714500	2.11419400	0.00153100
N	-0.21734200	-2.26457700	0.00347100
C	0.53689900	0.43487400	0.00338000
C	1.01312200	-1.82901600	0.00419500
N	0.97655800	1.70576800	0.00349900
N	1.44862300	-0.53530700	0.00422800
H	1.81484200	-2.56566700	0.00479600
H	1.98354200	1.89592500	0.00370700
H	0.33354600	2.47746800	0.00201800

Table S4. Cartesian coordinates for xG:C **base pair.**

Calculated energy (in Hartrees)= –1169.83308

atom	X	Y	Z
N	-5.54700400	-0.41041400	0.06922100
C	-5.98132000	0.87914900	0.04906200
H	-7.05659000	1.02055200	0.07528900
C	-5.11394600	1.92313400	-0.00027800
H	-5.46988600	2.94518600	-0.01493400
C	-3.71117200	1.60692900	-0.03040900
N	-2.78809200	2.57512400	-0.07676800
H	-1.77992600	2.34261100	-0.07419200
H	-3.07164100	3.54093000	-0.07824600
N	-3.28607500	0.33880800	-0.01468300
C	-4.15786400	-0.70123300	0.03843100
O	-3.81657700	-1.88936300	0.06189000
O	-0.04362100	1.93670800	-0.04314800
C	0.41395100	0.77999000	-0.05052000
C	1.83389500	0.44890400	-0.02840500
N	-0.43273900	-0.30822300	-0.08100300
C	2.20364200	-0.93899600	-0.03471400
C	2.78612500	1.47661700	0.00215600
H	-1.44760400	-0.10837500	-0.07814600
C	0.01127000	-1.61823000	-0.09061900
N	1.27479400	-1.95667200	-0.06512200
C	3.56791700	-1.28597800	-0.00887400
H	2.46136400	2.51076500	0.00618200
C	4.12838600	1.12722500	0.02712900
N	-0.95666200	-2.56278100	-0.15010800
H	3.84285700	-2.33471800	-0.01401200
C	4.49205000	-0.25119200	0.02134800
N	5.26881500	1.92758500	0.06000400
H	-1.94815700	-2.34070900	-0.05298300
H	-0.64591300	-3.51685200	-0.07291800
N	5.87480500	-0.25146200	0.05132500
C	6.25854300	1.07873500	0.07290600
H	7.30889300	1.34400100	0.09836200
C	6.73804000	-1.41416700	0.05822500
H	6.54328800	-2.03908100	0.93618600
H	6.58643100	-2.01824700	-0.84255600
H	7.77858700	-1.08495800	0.08735800
C	-6.46729800	-1.54509400	0.12550600
H	-6.32082000	-2.18934800	-0.74380700
H	-6.27566800	-2.13891500	1.02167200
H	-7.49183500	-1.17012400	0.14108500

Table S5. Cartesian coordinates for xxG:C **base pair.**

Calculated energy (in Hartrees)= –1323.47500

atom	X	Y	Z
N	-7.12142000	-0.23139300	0.01769200
C	-7.57488800	1.07521700	0.02129700
H	-8.63904600	1.28172600	0.02725500
N	-6.63834900	1.98109500	0.01763900
C	0.67580200	0.59913800	-0.02167300
O	1.05113100	1.78372100	-0.02043600
N	1.58692800	-0.43125400	-0.02842500
H	2.58720900	-0.16866100	-0.02665200
C	1.22322600	-1.77253900	-0.02996400
N	2.25451500	-2.64677900	-0.04629000
H	3.23259300	-2.35762700	-0.01370200
H	2.01113000	-3.62268900	-0.02081900
N	-0.01295700	-2.19436200	-0.02295400
H	-4.99463000	-2.18813900	0.00400600
C	-4.76043400	-1.12799200	0.00391500
C	-3.40366200	-0.70349700	-0.00286100
C	-5.73622900	-0.15653000	0.01022500
C	-3.09905200	0.71781300	-0.00290200
C	-5.44907000	1.24928900	0.01024300
C	-4.14078200	1.68125900	0.00372300
H	-3.90643600	2.74115900	0.00367700
H	-2.55702700	-2.70007100	-0.00983500
C	-2.34169600	-1.63595200	-0.00961100
C	-1.00978100	-1.23964700	-0.01634400
C	-0.72392800	0.17223800	-0.01611300
C	-1.74112500	1.10701600	-0.00957500
H	-1.47783000	2.16050200	-0.00954500
N	3.75715000	2.60380300	-0.02717800
C	4.74036600	1.69519300	-0.00955400
H	2.76720900	2.30744100	-0.02795400
H	3.97859400	3.58566000	-0.02930100
C	6.12019700	2.09975900	0.00171800
N	4.39628500	0.40288700	-0.00315600
C	7.05267100	1.11227400	0.02086900
H	6.41049800	3.14243400	-0.00417100
C	5.33311100	-0.58037700	0.01682700
N	6.70124900	-0.20228500	0.02894900
H	8.11711500	1.32136800	0.03088200
O	5.06813700	-1.78785900	0.02536300
C	-7.91862900	-1.43926100	0.02082900
H	-7.71647700	-2.04306700	-0.87051800
H	-7.70729800	-2.04462400	0.90899600
H	-8.97633600	-1.16884300	0.02653100
C	7.69280100	-1.27646400	0.05057100
H	7.55370700	-1.89678600	0.93832400
H	7.57431800	-1.91351100	-0.82828900
H	8.69136100	-0.83676800	0.05804200

Table S6-S13. MP2/6-31G(d) optimized monomers used to build dimers for center-of-mass stacking calculations.

Table S6. Adenine (A)

Calculated energy (in Hartrees)= -465.94706

atom	X	Y	Z
N	-2.15072700	0.12906000	0.00000000
C	-1.90629800	1.47894600	0.00000000
H	-2.71140600	2.20310400	0.00000000
N	-0.61545400	1.78364100	0.00000000
C	0.00000000	0.54736400	0.00000000
C	1.35914600	0.17264500	0.00000000
N	2.35303400	1.09016300	0.00000000
H	3.31214000	0.77561900	0.00000000
H	2.13618400	2.07562900	0.00000000
N	1.67232800	-1.13335000	0.00000000
C	0.66248400	-2.03283700	0.00000000
H	0.97426900	-3.07513600	0.00000000
N	-0.65923100	-1.81786100	0.00000000
C	-0.92510300	-0.50063200	0.00000000
H	-3.05221200	-0.33370200	0.00000000

Table S7. x-adenine (xA)

Calculated energy (in Hartrees)= –619.09573

atom	X	Y	Z
C	0.00000000	0.88437500	0.00000000
C	0.22500700	2.31079300	0.00000000
N	-0.81499200	3.18520500	0.00000000
H	-0.59244100	4.17050000	0.00000000
H	-1.77892700	2.89745600	0.00000000
N	1.44147600	2.83790000	0.00000000
C	2.48572500	1.96185200	0.00000000
H	3.47112900	2.42599400	0.00000000
N	2.45118000	0.64730700	0.00000000
C	1.19282200	0.08450400	0.00000000
C	-1.27269400	0.28999500	0.00000000
C	1.11465500	-1.32011800	0.00000000
H	2.03805000	-1.89348600	0.00000000
H	-2.19831000	0.86052900	0.00000000
C	-0.15053700	-1.87993000	0.00000000

N	-2.46909300	-1.91178600	0.00000000
N	-0.60568700	-3.18585500	0.00000000
H	-0.03703100	-4.02340700	0.00000000
C	-1.97739100	-3.13453200	0.00000000
H	-2.57447300	-4.03922100	0.00000000
C	-1.34228300	-1.09823300	0.00000000

Table S8. xx-adenine (xxA)

Calculated energy (in Hartrees)= –772.24417

atom	X	Y	Z
N	-3.93579200	2.01803300	0.00000000
C	-3.65889200	3.36381100	0.00000000
H	-4.45530400	4.09968000	0.00000000
N	-2.37566900	3.65260100	0.00000000
C	1.76940700	-0.92644300	0.00000000
C	3.14672200	-1.37927600	0.00000000
N	4.17362900	-0.49090100	0.00000000
H	5.11218700	-0.86497700	0.00000000
H	4.04021500	0.50637900	0.00000000
N	3.46518100	-2.66219900	0.00000000
C	2.42503400	-3.55409100	0.00000000
H	2.72769400	-4.60048700	0.00000000
N	1.13601100	-3.31017200	0.00000000
C	0.78727000	-1.97201700	0.00000000
H	-4.85568700	1.59606900	0.00000000
C	-2.72019600	1.35419600	0.00000000
C	-1.75046900	2.40701100	0.00000000
C	-2.37951100	0.01865500	0.00000000
C	-0.39817900	2.11606000	0.00000000
H	-3.12165200	-0.77791600	0.00000000
H	0.33935800	2.91645700	0.00000000
C	-0.56412000	-1.63943500	0.00000000
C	-0.99799200	-0.30011400	0.00000000
C	0.00000000	0.75843000	0.00000000
C	1.36782000	0.40496900	0.00000000
H	2.09302500	1.21845900	0.00000000
H	-1.28473700	-2.45572600	0.00000000

Table S9. Guanine (G)

Calculated energy (in Hartrees)= -540.99346

Atom	X	Y	Z
N	-2.17314700	0.73436300	0.00000000
C	-1.83295800	2.06736500	0.00000000
H	-2.58196200	2.84872600	0.00000000
N	-0.52471700	2.26447100	0.00000000
C	0.00000000	0.98937000	0.00000000
C	1.37499700	0.56303300	0.00000000
O	2.42012800	1.20302100	0.00000000
N	1.42180900	-0.86801500	0.00000000
H	2.37168900	-1.23106700	0.00000000
C	0.35157100	-1.73014400	0.00000000
N	0.63350200	-3.06395200	0.00000000
H	1.57216900	-3.42861500	0.00000000
H	-0.14509800	-3.70474100	0.00000000
N	-0.90303500	-1.33902100	0.00000000
C	-1.00287800	0.02113100	0.00000000
H	-3.10309200	0.33208300	0.00000000

Table S10. x-guanine (xG)

Calculated energy (in Hartrees)= –694.15646

Atom	X	Y	Z
C	0.00000000	0.74715400	0.00000000
C	0.73578900	2.01549700	0.00000000
O	0.25060000	3.14599900	0.00000000
N	2.12310500	1.84388100	0.00000000
H	2.65329900	2.71093400	0.00000000
C	2.75275800	0.61301500	0.00000000
N	4.11784400	0.64246800	0.00000000
H	4.65303100	1.49496100	0.00000000
H	4.59859300	-0.24397200	0.00000000
N	2.12765800	-0.52565300	0.00000000
C	0.73502000	-0.47946100	0.00000000
C	-1.39432700	0.78415000	0.00000000
C	0.05185800	-1.70119500	0.00000000
H	0.62275300	-2.62616800	0.00000000
H	-1.91743300	1.73664200	0.00000000
C	-2.07299400	-0.43336600	0.00000000
C	-1.33760300	-1.65021800	0.00000000
N	-3.44009800	-0.67985200	0.00000000
N	-2.30908200	-2.63177300	0.00000000
H	-2.15665100	-3.63250100	0.00000000
C	-3.52700600	-1.99508100	0.00000000
H	-4.45535800	-2.55435300	0.00000000

Table S11. xx-guanine (xxG)

Calculated energy (in Hartrees)= –847.30805

atom	X	Y	Z
N	3.68903100	2.95274200	0.00000000
C	3.21133600	4.24126000	0.00000000
H	3.88643600	5.08968600	0.00000000
N	1.89863300	4.32995300	0.00000000
C	-2.83317100	-1.38718100	0.00000000
O	-3.88411900	-0.74887300	0.00000000
N	-2.84955400	-2.78242800	0.00000000
H	-3.77868900	-3.19387500	0.00000000
C	-1.70950400	-3.57377400	0.00000000
N	-1.93049400	-4.92096500	0.00000000
H	-2.84964800	-5.33192200	0.00000000
H	-1.11970600	-5.52064900	0.00000000
N	-0.49633900	-3.11313700	0.00000000
H	3.31455800	0.06710900	0.00000000
C	2.45675900	0.73778400	0.00000000
C	1.14397300	0.21047400	0.00000000
C	2.58852100	2.11220700	0.00000000
C	0.00000000	1.10449900	0.00000000
C	1.47127200	3.00379100	0.00000000
C	0.17901800	2.50503900	0.00000000
H	-0.67678400	3.17713600	0.00000000
H	4.66217600	2.67519200	0.00000000
H	1.76890100	-1.87387500	0.00000000
C	0.92349700	-1.18770100	0.00000000
C	-0.35234400	-1.72609500	0.00000000
C	-1.47153100	-0.83256400	0.00000000
C	-1.29718800	0.53584500	0.00000000
H	-2.17706800	1.17751000	0.00000000

Table 12. Cytosine (C).

Calculated energy (in Hartrees)= -393.76466

atom	X	Y	Z
N	-1.20108300	-0.98917800	0.00000000
C	-0.06095200	-1.72627900	0.00000000
H	-0.17406900	-2.80633000	0.00000000
C	1.14480600	-1.09954900	0.00000000
H	2.07294400	-1.65835900	0.00000000
C	1.10708900	0.33798200	0.00000000
N	2.27881800	1.02414500	0.00000000

H	2.23508000	2.03358800	0.00000000
H	3.17527400	0.56464200	0.00000000
N	0.00000000	1.05811100	0.00000000
C	-1.22732900	0.43056000	0.00000000
O	-2.31501300	0.99848200	0.00000000
H	-2.11496600	-1.42923500	0.00000000

Table S13. Thymine (T).

Calculated energy (in Hartrees)= -452.80602

atom	X	Y	Z
N	0.14415400	-1.66631700	0.00000000
C	-1.08610300	-1.04128900	0.00000000
H	-1.94395700	-1.70796900	0.00000000
C	-1.21462700	0.30706100	0.00000000
C	-2.52945400	1.02192800	0.00000000
H	-2.61589200	1.66653800	0.87905200
H	-2.61589200	1.66653800	-0.87905200
H	-3.36103700	0.31207600	0.00000000
C	0.00000000	1.12147500	0.00000000
O	0.02537700	2.35108200	0.00000000
N	1.19251000	0.38116700	0.00000000
H	2.05291600	0.92395400	0.00000000
C	1.35681800	-0.99517800	0.00000000
O	2.44355100	-1.56009500	0.00000000
H	0.21597900	-2.67696300	0.00000000