Purine Nucleosides and Nucleotides Unequivocally in the *Syn* Conformation: Guanosine and 5′-GMP with 8-*tert*-Butyl and 8-(α-Hydroxyisopropyl) Substituents

Reynaldo Pless *+, Lech Dudycz *, Ryszard Stolarski ** and David Shugar *

Direct alkylation *via* a free radical reaction was utilized to prepare 8-*tert*-butylguanosine-5′-phosphate; this was dephosphorylated with alkaline phosphatase to give the parent nucleoside. The 8-(α-hydroxyisopropyl) derivatives of 5′-GMP and guanosine were prepared in an analogous manner.

The foregoing products, which are necessarily in the *syn* conformation about the glycosidic bond because of the bulky 8-substituents (van der Waals' radii 3.5-4 Å), were characterized by elementary analysis, UV spectra and ^{1}H NMR spectroscopy. The changes in chemical shifts of H(1′), H(2′) and H(3′) of each of the foregoing derivatives, relative to those for guanosine and 5′-GMP, were consistent with their being in the *syn* conformation and, furthermore, pointed to guanosine and 5′-GMP being predominantly *anti*, in aqueous medium or DMSO. They also demonstrated that, contrary to the prevailing opinion, 8-bromo-5′-GMP and 8-bromoguanosine are not necessarily exclusively in the *syn* conformation in solution.

While 8-bromoadenosine-5′-phosphate was slowly dephosphorylated by snake venom 5′-nucleotidase, the 8-*tert*-butyl and 8-(α-hydroxyisopropyl) derivatives of 5′-GMP were fully resistant to this enzyme.

One of the important conformational parameters of purine nucleosides and nucleotides is the orientation of the heterocyclic base about the glycosidic bond. The significance of this parameter has been clearly delineated in a number of enzymatic reactions *e. g.* binding of dehydrogenase inhibitor analogues of NAD or its components is conditional on these being in the *anti* conformation [1]. Differences in activation of glycogen phosphorylase b by various nucleotides have been ascribed to differences in the glycosyl torsion angles of the latter when bound to the enzyme [2]. Numerous additional illustrations are extant [3 4]. Conversion of purine nucleotide residues to the *syn* conformation at the polymer level has also been proposed as a source of spontaneous mutations [4], and could well be a factor in some cases of induced mutagenesis.

* Institute of Biochemistry and Biophysics, Academy of Sciences, Warszawa and
** Department of Biophysics, Institute of Experimental Physics, University of Warsaw, Warszawa

+ *Present address:* The Johns Hopkins University, McCollum-Pratt Institute, Charles and 33rd Streets, Baltimore, Md. 21218 (USA).

Requests for reprints should be sent to D. Shugar, Institute of Biochemistry and Biophysics, Academy of Sciences, 36 Rakowiecka St., 02-532 Warszawa, Poland.

Abbreviations: UV, ultraviolet; NMR, nuclear magnetic resonance; DMSO, dimethyl sulfoxide; DSS, sodium 2,2-dimethyl-2-silapentane sulfonate; TMS, tetramethylsilane.

It is consequently desirable to have available model purine nucleosides fixed in the *syn* or *anti* conformation. Typical models of the former have been considered to be 8-substituted nucleosides [1, 5, 6], but serious doubt now exist as to the presumed exclusive *syn* conformation of 8-bromopurine nucleosides [7]. This led to the synthesis of 8-(α-hydroxyisopropyl) adenosine, which is *syn* in the solid state [8], and would also be expected to be exclusively *syn* in solution because of the large effective van der Waals' radius of the hydroxyisopropyl substituent, 3.5 − 4 Å, as compared to about 2 Å for a bromo substituent.

We have elsewhere [9] described the solution conformation, by ^{1}H NMR spectroscopy, of 8-(α-hydroxyisopropyl)-adenosine which, with the aid of several model compounds, was shown to be exclusively *syn*. We here report on the syntheses, and conformation about the glycosidic bond, of 8-(α-hydroxyisopropyl)-guanosine and its 5′phosphate, as well as 8-*tert*-butylguanosine and 8-*tert*-butyl-5′GMP, in which the *tert*-butyl substituent is even more bulky than hydroxyisopropyl.

Synthetic Procedures

The required 8-subtituted derivatives of guanosine were prepared initially as the 5′-monophosphates by the direct addition of the *tert*-butyl and α-hydroxyisopropyl radials to 5′-GMP.

The synthesis of 8-*tert*-butyl-5'-GMP was based on a homolytic alkylation reaction. The alkyl radical was generated from pivalyl aldehyde (trimethylacetaldehyde) in the presence of potassium persulphate and $Fe(NH_4)_2(SO_4)_2$. These are conditions which normally lead to formation of reactive acyl radicals from the aldehyde by cleavage of a hydrogen from the carbonyl carbon. However, it was previously noted that the use of isobutyryl aldehyde for the homolytic acylation of cyclic 3',5'-GMP yielded, in addition to 8-acyl derivatives, appreciable proportions of the 8-isopropyl derivatives [10], most likely as a result of partial decarbonylation of the acyl radical. When we employed pivalyl aldehyde in this reaction, the main product was the alkyl derivative, with only traces $(1-2\%)$ of the acyl derivative. This indicated that the tendency of the acyl radical to undergo cleavage to CO and the corresponding alkyl radical increases as one proceeds from a carbonyl bonded primary alkyl, *via* a secondary alkyl, to a tertiary alkyl. The stabilities of the alkyl radicals increase in the same order. The *tert*-butyl radical is one of the more stable alkyl radicals, while the isopropyl radical is slightly less stable, so that the presence of the alkyl radicals is a consequence of the conversion of the less stable acyl radical to the more stable alkyl radical.

The reaction is highly sensitive to the presence of oxygen and, in the absence of flushing the reaction mixture with nitrogen, the maximal attainable yield of alkylated product is reduced 4 to 5-fold.

The corresponding 8-*tert*-butylguanosine was obtained by quantitave dephosphorylation of the nucleotide with *E. coli* alkaline phosphatase. The nucleoside was then isolated by chromatography on silica gel and crystallized from water. The product gave a satisfactory elemental analysis and was further idendified by means of UV and ¹H NMR spectroscopy. This also provided evidence for the identification of the nucleotide.

The synthesis of 8-(α-hydroxyisopropyl)-5'-GMP was based on the di-*tert*-butylperoxide sensitized photoaddition of isopropanol to 5'-GMP, essentially as previously applied by Elad *et al.* [11]. The starting substance in this case was the tri-*n*-butylamine salt of 5'-GMP, because of its improved solubility in the aqueous isopropanol solvent employed. The yield of desired product, following purification, was more than 25%. Enzymatic dephosphorylation of the 8-substituted nucleotide yielded the corresponding nucleoside, obtained in crystalline form, identical with that previously reported by Elad *et al.* [12].

Both 8-*tert*-butyl- and 8-(α-hydroxyisopropyl)-5'-GMP, as well as 8-(α-hydroxyisopropyl)-5'-AMP, proved fully resistant to Russell viper venom, which is a rich source of 5'-nucleotidase. It is of interest that, under identical conditions, 8-bromo-5'-AMP was slowly dephosphorylated by the snake venom, at a rate about 40-fold lower than the parent AMP. A plausible interpretation of these findings is that the enzyme requires the *anti* form of the substrate. However, the foregoing observations do not enable us to exclude possible steric effects in the case of the bulky 8-alkyl substituents.

¹H NMR Spectral Analyses

¹H NMR spectral data for the compounds are presented in Tables I and II.

The conformations of the sugar rings, calculated from the proton-proton vicinal coupling constants with the aid of the two-state model of Altona and

Table I. Values of chemical shifts (in ppm *vs* internal DSS) and vicinal coupling constants (in Hz) for the sugar protons of 5'-GMP, and two of its alkyl derivatives, at concentrations of 0.05 M in ^2H_2O at pD 8 [a].

Compound	H(1')	H(2')	H(3')	H(4')	H(5')	H(5'')	CH_3	$J(1',2)$	$J(2',3)$	$J(3',4)$
5'-GMP	5.90	4.75	4.49	4.34	.... 4.0 [b]		—	5.5	5.0	4.0
8-*tert*-butyl-5'-GMP	6.24	5.35	4.66	.... 4.2 [b]			1.47	5.7	6.0	~4.0 [c]
8-(α-hydroxyisopropyl)-5'-GMP	6.65	5.26	4.65	.... 4.2 [b]			1.70	5.4	5.8	~4.0 [c]

[a] Spectra obtained without decoupling of 5'-P.
[b] Band center.
[c] H(3') partially overlapped by water signal.

Table II. Chemical shifts (in ppm *vs* internal TMS) and vicinal proton-proton coupling constants (in Hz) for 8-*tert*-butylguanosine in DMSO [a], and comparative values of chemical shifts for guanosine (0.05 M at 22 °C).

Nucleoside	H(1')	H(2')	H(3')	H(4')	H(5')	H(5'')	CH_3	NH	NH_2	OH(2')	OH(3')	OH(5')
8-*tert*-butylguanosine	5.95	5.06	4.17	3.87	3.68	3.54	1.39	10.58	6.19	5.33	4.97	5.06
guanosine	5.65	4.41	4.10	3.88	3.58 [b]	....	....	10.60	6.42	....	c	....
	J(1',2')	J(2',3')	J(3',4')	J(4',5')	J(4',5'')	J(5',5'')	J(2',2OH)	J(3',3OH)		J(5',5OH)	J(5'',5OH)	J(4',5OH)
8-*tert*-butylguanosine	6.1	5.8	3.2	4.2	5.0	-12.3	6.3	5.3		4.2	7.0	-0.4

a Assignments of individual signals established by decoupling experiments, and parameters verified by simulation (LAOCOON III Programme).
b Band center.
c Signals overlap.

Sundaralingam [13], correspond to a $C(2')$ *endo* $\rightleftharpoons$ $C(3')$ *endo* equilibrium. The $C(2')$ endo populations for the nucleotides are about 60%; for 8-*tert*-butyl-guanosine it is about 65%.

The exocyclic $5'\text{-}CH_2OH$ classical conformations in 8-*tert*-butylguanosine are 40% *gauche-gauche*, 30% *gauche-trans* and 30% *trans-gauche*.

A comparison of the chemical shifts for the various compounds shows characteristic changes in chemical shifts of $H(1')$, $H(2')$ and $H(3')$ relative to the parent guanosine and 5'-GMP (Tables I and II). These amount to +0.34 ppm, +0.60 ppm and +0.17 ppm for 8-*tert*-butyl-5'-GMP: +0.75 ppm, +0.55 ppm and +0.16 ppm for 8-(α-hydroxyiso-propyl)-5'-GMP; and +0.30 ppm, +0.65 ppm and +0.60 ppm for 8-*tert*-buytlguanosine. These changes in chemical shifts are clearly due to a change in orientation of the base with respect to the glycosidic bond towards a very pronounced preference for, if not exclusively, the form *syn*. The changes in chemical shifts of $H(2')$ and $H(3')$, similar for all three compounds, result from the anisotropic influence of the ring $N(3)$ and the ring currents of the pyrimidine moiety in the conformation *syn*, and are not directly affected by the nature of the 8-substituent. The changes in chemical shifts of $H(1')$, by contrast, are due to anisotropic interaction with the 8-substituent, since these are close to each other in the conformation *syn*; and, in accordance with expectations, would depend on the nature of the 8-substituent. The results also indicate that both guanosine and 5'GMP are preferentially *anti*, but do not necessarily exclude the presence of a certain proportion in the conformation *syn*.

Similar changes in chemical shifts of the sugar protons have been observed for other derivatives of guanosine with bulky 8-substituents, *e. g.* 8-bromo- and 8-dimethylamino-guanosines [14]. These exhibit the characteristic strong deshielding of $H(2')$, by 0.51 ppm and 0.57 ppm, respectively, relative to guanosine, and a small change in the chemical shift of $H(1')$, which depends on the nature of the 8-substituent. These effects testify to a constrained preference of the conformation *syn* by the 8-substituents. It may be assumed, as in the case of the corresponding adenosine derivatives [9], that the magnitude of the change in chemical shift of $H(2')$ reflects the changes in populations of the *syn* and *anti* conformers (in equilibrium with each other), the glycoside torsion angles remaining unchanged.

The change in chemical shifts of H(2′) for 8-bromoguanosine (0.51 ppm) is 0.14 ppm lower than that for the fully *syn* 8- *tert*-butylguanosine (0.65 ppm), suggesting that 8-bromoguanosine is partly in the form *anti*. For 8-dimethylaminoguanosine the change in chemical shift of H(2′) relative to guanosine is 0.57 ppm, hence closer to that for 8-*tert*-butylguanosine, indicative of a higher population of the form *syn*, but still not to the extent of 100%.

The changes in chemical shifts of H(2′) for 8-*tert*-butyl-5′-GMP and 8-(α-hydroxyisopropyl)-5′-GMP, relative to 5′-GMP, differ by 0.1 ppm. Since the 8-substituents in these instances are comparable in size, and sufficiently bulky to ensure a 100% *syn* population, the unequal changes in chemical shifts must be due to differences in the glycosidic torsion angles. An analogous situation probably prevails for 8-bromo- and 8-dimethylamino-guanosines.

Under conditions of chemical exchange involving the *syn* ⇌ *anti* equilibrium, the chemical shifts of H(2′) would be a linear function of the relative populations. The change in chemical shift of H(2′) for a change in conformation from *anti* to *syn* should be about 0.65 ppm (this is the difference in shift between the fully *syn* 8-*tert*-butylguanosine and the preferentially *anti* guanosine). From the chemical shift of H(2′) for 8-bromoguanosine, which is 0.14 ppm less than that for 8-*tert*-butylguanosine, it may be inferred that 8-bromoguanosine should have a population *anti* of about 15%. Bearing in mind possible differences in glycosidic torsion angles, it is more likely that the *anti* population of 8-bromo-guanosine is somewhat lower than 15%. In addition there is an observed dependence of the *anti* population of 8-substituted guanosines on the bulkiness of the substituent which constrains the conformation to *syn*: the greater the bulkiness of the substituent, the greater the population of the *syn* conformer.

Experimental

Guanosine-5′-phosphate was obtained from Calbiochem (Los Angeles, Calif.) and Reanal (Budapest). Trimethyl acetaldehyde was a product of K & K Laboratories (California, U.S.A.). Di-*tert*-butylperoxide was purchased from Merck-Schu-

chart (Hohenbrunn, Munchen, GFR). Desalting was carried out with Sigma (St. Louis, Mo., U.S.A.) charcoal and celite 501 from Vulcascot.

Melting points (uncorr.) were measured on a Boetius microscope hot stage. Elementary analyses were run on a Perkin-Elmer 240 instrument. UV spectra were obtained with a Zeiss (Jena, GDR) VSU-2P manual spectrophotometer, and a Specord (Zeiss) UV-VIS recording instrument.

^{1}H NMR spectra were recorded on a Bruker-90 instrument, operating in the Fourier transform mode, at room temperature (22 °C), using 0.05 M solutions in ^2H_2O (Merck, Darmstadt, GFR, 99.7 mol % ^{2}H) adjusted to pD 8, with DDS as internal standard; or in DMSO-d_6 (Merck, 99.5 mol % ^{2}H), with TMS as internal standard.

E. coli alkaline phosphatase was a product of Sigma (St. Louis, Mo., U.S.A.), while *Russell viper* venom was used as a source of 5′-nucleotidase.

8-tert-butylguanosine-5′-phosphate. To a solution of 2.08 g (4.7 mmol) of 5′-GMP·Na_2·2 H_2O in 160 ml of 50% aqueous acetic acid at 10 °C was added 25 ml of 3 N aqueous H_2SO_4 and 19 ml (210 mmol) of pivalyl aldehyde. The solution was purged with nitrogen, and solutions of 14.5 g (37 mmol) of $Fe(NH_4)_2(SO_4)_2$·6 H_2O in 60 ml H_2O, and 10 g (37 mmol) of $K_2S_2O_8$ in 100 ml H_2O, were added simultaneously, dropwise, with constant stirring over the course of 1 h, the solution being maintained at 10° − 15 °C. The reaction mixture was stirred for an additional hour at room temperature, diluted by addition of 300 ml H_2O, and percolated through a mixture of 60 g charcoal and 30 g Celite. The charcoal bed was washed with 2.5 l of H_2O, followed by 2.2 l of EtOH-H_2O-conc. NH_4OH (10 : 10 : 1, v/v). The ammoniacal alcohol eluate was concentrated to 25 ml under presure and applied to a 80×2.8 cm column of 200 − 400 mesh AG 50 W-X 2 (H^+). The column was eluted with H_2O at a flow rate of 220 ml/h. Material with absorption maxima at 279 nm and 330 nm (presumably 8-pivalyl-5′GMP) eluted at 370 ml, unreacted GMP at 640 − 2100 ml, and the desired product from 2100 − 3100 ml (10,000 OD$_{256}$ units, 0.62 mmol). 3,000 OD$_{256}$ units of the eluate, concentrated to small volume under reduced pressure, were deposited as a band on Whatman 3 MM paper, which was developed with *n*-BuOH-H_2O-CH_3COOH (5 : 3 : 2, v/v). The band with $R_f = 0.4$ was eluted with water. Aqueous ammonia was added and the

solution concentrated to a gum. The residue was taken up in 0.5 ml water, and the product precipitated by addition of ethanol, and dried over P_2O_5 under vacuum. Yield, 92 mg (14.0%). UV absorption, in aqueous medium: pH 2: λ_{max} 263.5 nm (ε_{max} 15.1×10³), λ_{min} 230 nm (ε_{min} 2.7×10³); pH 7: λ_{max} 255.5 nm (ε_{max} 16.2×10³), λ_{min} 223 nm (ε_{min} 3.9×10³); pH 12: λ_{max} 260.5 nm (ε_{max} 14.7×10³); λ_{min} 229 nm (ε_{min} 4.7×10³).

8-tert-butylguanosine. 7,000 OD_{256} units of 8-*tert*-butylguanosine-5′-phosphate (column eluate, without further purification) were brought to dryness under reduced pressure. The residue was taken up in dilute aqueous ammonia and again taken to dryness. The residue was taken up in 6 ml of 0.1 M Tris-HCl pH 8.0 containing 0.002 M $MgCl_2$. To this was added 25 units of *E. coli* alkaline phosphatase and the mixture incubated at 37 °C for three days. The enzymatic digest was then chromatographed on three 20×20 cm plates of silica gel with chloroform-methanol (4:1, v/v). The band at $R_f = 0.3$ was eluted with chloroform-methanol (3:2, v/v). The eluated was brought to dryness and the residue crystallized from 5 ml hot water. The crystals were dried over P_2O_5 under vacuum to yield 97 mg, m. p. 213–215 °. Concentration of the mother liquors yielded a second crop, 11 mg, m. p. 213–215 °C, and then a third, 12 mg, m. p. 213–215 °C (total yield 120 mg, 82%). UV spectral characteristics, identical with those for the nucleotide. Elem. analysis: C, 46.94%; H, 6.25%; N, 19.40%; calcd. for $C_{14}H_{21}N_5O_5 \cdot H_2O$: C, 47.06%; H, 6.44%; N, 19.60%.

8-(α-Hydroxyisopropyl)guanosine-5′-phosphate. To a solution of 443 mg (1.0 mmol) of 5′-GMP·Na_2·2 H_2O, 1.2 mmol HCl and 2.1 mmol (0.50 ml) of tri-*n*-butylamine in 60 ml of H_2O–2-propanol (5:4, v/v) was added 2 ml of *tert*-butyl peroxide. The mixture was irradiated in a photochemical reactor with a 700-watt medium pressure mercury lamp, the radiation from which was filtered through a 5-mm layer of 0.015 M adenine in dimethylforma-

mide, which cuts off at about 270 n. After 28 h the reaction mixture was applied to a 4.5×2.5 cm column of 200–400 mesh Dowex 1 X-4 (formate form). The column was washed with 300 ml water, 300 ml 0.5 M aqueous formic acid, 100 ml of 0.5 M formic acid in 50% aqueous ethanol, and finally with 120 ml of 4 M aqueous formic acid. The eluate from the final wash was brought to dryness under reduced pressure and the residue taken up in aqueous ammonia. The solution was concentrated to small volume, and methanol added to give a precipitate which was subjected to chromatography on Whatman 3 MM paper with *n*-propanol–conc. NH_4OH–water (20:20:3, v/v). The band with $R_f = 0.54$ was eluted with water and concentrated under reduced pressure to a glass, 123 mg (27%) after drying under vacuum over P_2O_5.

8-(α-hydroxyisopropyl)guanosine. To 64 mg of 8-(α-hydroxyisopropyl)guanosine-5′-phosphate in 3 ml of 0.1 M Tris-HCl buffer pH 8.0, containing 0.002 M $MgCl_2$, was added 14 units of *E. coli* alkaline phosphatase and the mixture incubated at 37 °C for 24 h. The digest was then subjected to chromatography on two 20×20 cm silica gel thick layer plates with chloroform-methanol (7:3, v/v). The band at $R_f = 0.4$ was eluted with chloroform-methanol (3:2, v/v), the eluate brought to dryness and the residue crystallized from 1.5 ml hot water. The crystals were washed with ice-cold water and dried under vacuum over P_2O_5, yield 25 mg, m. p. 212–214 °C. Concentration of the mother liquors to 0.5 ml yielded an additional 3 mg (total 28 mg, 54%), m. p. 214–215 °C (Elad *et al.* give 211–213 °C). Elem. analysis: C, 43.56%; H, 5.56%; N. 19.38%; calcd. for $C_{13}H_{18}N_5O_6$ H_2O: C, 43.58%; H, 5.59%; N, 19.55%.

[1] F. E. Evans and N. O. Kaplan, J. Biol. Chem. **251**, 6791–6797 (1976).
[2] M. Morange, A. Kolb, H. Buc, C. Chachaty, and G. Langlet, Europ. J. Biochem. **74**, 99–106 (1977).
[3] a. A. Hampton, P. J. Harper, and T. Sakai, Biochemistry **11**, 4965–4969 (1972).
b. A. Matsuda, M. Tezuka, and T. Ueda, Nucleic Acids Res., Spec. Publ. No **2**, 13–16 (1976).
c. J. Zemlicka, J. Am. Chem. Soc. **97**, 5896–5903 (1975).
[4] D. C. Ward and E. Reich, Annu. Rep. Med. Chem. **1969**, 272–281.
[5] R. H. Sarma, Che-Hung Lee, F. E. Evans, N. Yathindra, and M. Sundaralingam, J. Am. Chem. Soc. **96**, 7337–7348 (1974).
[6] S. Uesugi and M. Ikehara, J. Am. Chem. Soc. **99**, 3250–3253 (1977).
[7] M. A. Abdallah, J. F. Biellmann, B. Nordström, and C. I. Bränden, Eur. J. Biochem. **50**, 475–481 (1975).

[8] G. I. Birnbaum and D. Shugar, Biochim. Biophys. Acta **517**, 500−510 (1978).

[9] L. Dudycz, R. Stolarski, R. Pless, and D. Shugar, in preparation.

[10] L. F. Christensen, R. B. Meyer, Jr., J. P. Miller, L. N. Simon, and R. K. Robins, Biochemistry **14**, 1490−1496 (1975).

[11] J. Salomon and D. Elad, J. Org. Chem. **38**, 3420−3421 (1973).

[12] M. Steinmaus, J. Rosenthal, and D. Elad, J. Org. Chem. **36**, 3594−3598 (1971).

[13] C. Altona and M. Sundaralingam, J. Am. Chem. Soc. **95**, 2333−2344 (1973).

[14] F. Jordan and H. Niv, Biochim. Biophys. Acta **476**, 265−271 (1977).