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Synthesis, Characterization, and Studies on DNA Binding of a New Mg(II) Complex with N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine

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Abstract—A new Mg(II) complex of $MgL(NO_3)_2$ (here L = N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine) has been synthesized and characterized. The interactions between the Mg(II) complex and calf thymus DNA has been investigated using UV spectra, fluorescent spectra, viscosity, thermal denaturation, and molecular modeling. The cleavage reaction on plasmid DNA has been monitored by agarose gel electrophoresis. The experimental results show that the mode of binding of the complex to DNA is non-classical electrostatic action and the complex can cleave pBR322 DNA.

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The design of small metal complexes that bind and react with DNA becomes increasingly important as we elucidate how genetic information is expressed. A more complete understanding of how such complexes interact with DNA will lead not only to novel chemotherapeutics but also to highly sensitive diagnostic agents [1]. Syntheses of DNA-binding molecules, such as triplex-forming oligonucleotide [2-5], peptide nucleic acid [6, 7], oligosaccharide [8], and oligopeptide [9, 10], have been exploited. These small molecules are stabilized in binding to DNA through a series of weak interactions, such as the π-stacking interactions associated with intercalation of a planar aromatic group between the base pairs, hydrogen bonding and van der Waals interactions of function groups bound along the groove of the DNA helix [11], and the electrostatic interaction of the cation with phosphate group of DNA [12]. Studies directed toward the design of site- and conformation-specific reagents provide rationales for new drug design as well as means to develop sensitive chemical probes of nucleic acid structure. Considerable attention has been given to polyamide complexes with metals due to their high affinity and specificity interactions to specific DNA regions [12-16]. Since these polyamides can permeate living cell membranes, they have the potential to control specific gene expression [17, 18].

Furthermore, many useful complexes can be created by polyamides coordinating with other various molecules. The complex $[Mg_2(diethylenetriamine)Cl(OH)]Cl_2 \cdot 2H_2O$ was found to have high cleavage activity toward DNA [19]. A polyamine complex with glucoses synthesized by Liu et al. has great potential in curing congenital genetic and acquired immunity disease because it can transfer nucleic acid medicines safely, innocuously, and highly efficiently [20, 21].

Up to now, study on the spin equilibrium [22], subchronic toxicity [23], and ion flotation [24] of triethylenetetramine–metal complexes have been reported, but there are few reports about the interaction between triethylenetetramine–metal complexes and DNA. We have studied the DNA-binding of the Cu(II) complex with N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethyl-

Abbreviations: CCC) supercoiled DNA form; DFT) density functional theory; DMF) dimethylformamide; DMSO) dimethyl sulfoxide; HRMS) high resolution mass spectrum; OC) open circular DNA form; TMS) tetramethyl silicon.

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enetetramine and found the Cu(II) complex to have a certain effect on cancer cells [25].

In this paper, a new Mg(II) metal complex with N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine has been synthesized and characterized. The interaction of the Mg(II) complex with calf thymus DNA has been investigated using UV spectra, fluorescent spectra, viscosity, thermal denaturation, and molecular modeling. The cleavage reaction on plasmid DNA has been monitored by agarose gel electrophoresis. The aim is to discover a new DNA-binding reagent. The results should be valuable in understanding the nature of the complex with DNA as well as laying a foundation for rational design of novel, powerful agents for probing and targeting nucleic acids. These can also provide valuable information for exploiting and developing drugs and their application in the field of molecular biology.

MATERIALS AND METHODS

Materials. Calf thymus DNA and plasmid DNA pBR322 were obtained from Sigma (USA). The ligand was synthesized according to a procedure described elsewhere [25]. Its purity was checked by mass spectrometry, elemental, FTIR, and NMR analyses. All other chemicals were of analytical reagent grade and used without further purification.

Carbon, nitrogen, and hydrogen analyses were determined using a Perkin-Elmer (USA) 240C elemental analyzer. ^{1}H-NMR and ^{13}C-NMR spectra were measured on a Bruker (Germany) DRX-300 spectrometer in dimethylsulfoxide (DMSO)-d_6 solution, with tetramethyl silicon (TMS) as the internal standard. IR spectra were recorded on a Shimadzu (Japan) FT-IR-8300 instrument using KBr discs in the 400-4000 cm. Absorbance spectra were recorded on a Hewlett-Packard (USA) HP-8453 Chemstation spectrometer, and the UV-Vis spectrometer was employed to check DNA purity ($A_{260}/A_{280} > 1.80$) and concentration ($\varepsilon = 6600\ M^{-1}\cdot cm^{-1}$ at 260 nm). Fluorescence measurements were made with a Perkin-Elmer Ls-50B spectrophotometer equipped with quartz curettes of 1 cm path length at room temperature. The excitation and emission slit widths were 10 nm. Plasmid DNA cleavage products were analyzed with a UVP GDS8000 complete gel documentation and analysis system. The conductance measurement was carried out on a DDS-307 conductivity gauge (Jingke Rex, China). Viscosity was measured using an Ubbelohde (Germany) viscosimeter maintained at 25.0 ± 0.1°C. Flow time was measured with a digital stopwatch; mean values of replicated measurements were used to evaluate the viscosity η of the samples. The data are reported as $(\eta/\eta_0)^{1/3}$ vs. the [ML]/[DNA] ratio (ML = Mg(II) complex with N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine), where η_0 is the viscosity of the DNA solution alone. The DNA melting experiments were carried out by controlling the temperature of the sample cell with a Shimadzu circulation bath, monitoring the absorbance at 260 nm.

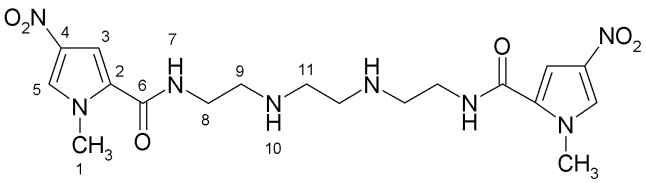

Fig. 1. The structure of the ligand N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine.

Synthesis of the ligand. The structure of N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine is shown in Fig. 1. It was synthesized according to the literature methods [25]. Yield solid, m.p. 174.6-175.2°C. *Anal.* Calculated for $C_{18}H_{26}N_8O_6$: C, 48.00; N, 24.88; H, 5.82. Found: C, 47.93; N, 24.81; H, 5.78. ^{1}H-NMR (300 MHz, DMSO-d_6, δ, ppm): 8.37 (t, J = 5.76 Hz, 2H, H7), 8.13 (d, J = 1.65 Hz, 2H, H5), 7.44 (d, J = 1.92 Hz, 2H, H3), 3.91 (s, 6H, H1), 3.28 (t, J = 6.32 Hz, 4H, H8), 2.65 (t, J = 6.31 Hz, 4H, H9), 2.60 (s, 4H, H11), 2.00 (m, J = 7.08 Hz, 2H, H10). ^{13}C-NMR (300 MHz, DMSO-d_6, δ, ppm), C6 160.8, C4 138.7, C5 132.7, C2 128.2, C3 118.6, C11 49.1, C9 48.6, C8 39.8, C1 31.5. IR (KBr): ν(N–H) 3386.5, ν(N–H) 3278.8, ν(Py C–H) 3128.3, ν(C–H) 2939.3, ν(C–H) 2839.0, ν(C=O) 1651.0, ν(N–H) 1558.4, ν(C=C) 1527.5, ν(C=C) 1504.4, ν(N–CH_3 N–C) 1419.5, ν(C–NO_2 C–N) 1315.4, ν(CO–NH C–N) 1276.8, ν(CH_2–NH C–N) 1068.5, ν(C–NO_2 C–N) 848.6, ν(N–H) 813.9, ν(N–H) 752.2, ν(NO_2) 705.9, ν(NO_2) 601.7. HRMS: calculated for $C_{18}H_{26}N_8O_6$ 450.4552; found 450.4556.

Synthesis of the complex. The ligand (0.4502 g, 1.0 mmol) was dissolved in dimethylformamide (DMF) (100 ml) with stirring and heated to 80°C. To this solution was added drop-wise $Mg(NO_3)_2\cdot 6H_2O$ (0.2564 g, 1.0 mmol) dissolved in DMF (30 ml) with stirring for 30 min, and the mixture was further stirred at 80°C for 4 h. The reaction mixture was evaporated to remove DMF in vacuum. The residue was dissolved in 25 ml of methanol and then the solution was filtered. The filtrate was placed in a refrigerator overnight, and yellow precipitate was formed. The precipitate was collected and washed three times with water. Recrystallization from hot methanol and further drying in vacuum afforded a yellow solid. *Anal.* Calculated for $ML(NO_3)_2$ (here L = N^1,N^8-bis(1-methyl-4-nitropyrrole-2-carbonyl)triethylenetetramine): C, 36.11; N, 23.39; H, 4.38. Found: C, 36.09; N, 23.36; H, 4.41. ^{1}H-NMR (300 MHz, DMSO-d_6, δ, ppm): 8.02 (d, J = 1.65 Hz, 2H, H5), 7.91 (t, J = 5.76 Hz, 2H, H7), 7.28 (d, J = 1.92 Hz, 2H, H3), 3.80 (s, 6H, H1), 3.24 (t, J = 6.32 Hz, 4H, H8), 2.85 (m, J = 7.08 Hz, 2H,

H10), 2.69 (t, J = 6.31 Hz, 4H, H9), 2.62 (s, 4H, H11). ^{13}C-NMR (300 MHz, DMSO-d_6, δ, ppm), C6 168.6, C4 138.8, C5 132.8, C2 131.4, C3 119.6, C11 53.1, C9 51.6, C8 42.8, C1 31.6. IR (KBr): ν(N–H) 3429.2, ν(N–H) 3319.3, ν(Py C–H) 3132.2, ν(C–H) 2941.2, ν(C–H) 2844.8, ν(C=O) 1652.9, ν(N–H) 1550.7, ν(C=C) 1525.6, ν(C=C) 1502.4, ν(N–CH_3 N–C) 1419.5, ν(C–NO_2 C–N) 1309.6, ν(CO–NH C–N) 1269.1, ν(CH_2–NH C–N) 1060.8, ν(C–NO_2 C–N) 850.5, ν(N–H) 812.0, ν(N–H) 750.3, ν(NO_2) 705.9, ν(NO_2) 590.2. HRMS: calculated for $C_{18}H_{26}MgN_{10}O_{12}$ 598.1582; found 598.1578. Conductance: $MgL(NO_3)_2$ (solvent DMF/H_2O = 3 : 2): 6 S·cm^2·mol^{-1}; $Mg(NO_3)_2$ (solvent DMF/H_2O = 3 : 2): 105 S·cm^2·mol^{-1}; solvent: (DMF/H_2O = 3 : 2): 5.9 S·cm^2·mol^{-1}.

The conclusion can be drawn from comparing the IR spectra of the ligand and the complex, which shows that the Mg(II) complex had been formed through Mg(II) coordinating two N atoms of NH groups and two O atoms of C=O groups. The complex is hard to dissolve in water, which indicates the complex may be electrically neutral coordination. It can be confirmed from comparing the conductance of $Mg(NO_3)_2$ and the $MgL(NO_3)_2$ complex that the $MgL(NO_3)_2$ complex should be an electrically neutral molecule. So the structure of the $MgL(NO_3)_2$ complex can be conferred as shown in Fig. 2.

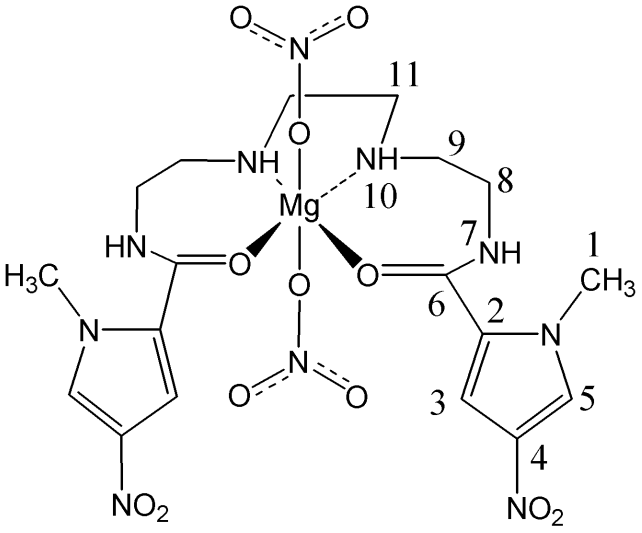

Fig. 2. The conferred structure of the complex based on the experimental results.

Computational details. The DFT (density functional theory) calculations were carried out by the restricted Hartree–Fock method using the Gaussian 03 system of programs [26]. The optimizations of various possible starting structures were carried out at B3LYP/3-21g [27-29] level and imaginary frequencies were analyzed at the same theoretical level. In accordance with the experimental results, only a nonsymmetrical structure (Fig. 3, see color insert) with hexacoordinate magnesium(II) center was confirmed to be a minimum during the calculation process. Other structures (such as those with tetracoordinate or pentacoordinate magnesium(II) center) were proved to be transition states or higher order saddle points. As shown in Fig. 3, the magnesium atom had a slightly distorted octahedron hexacoordination. The lengths of coordination bonds are labeled in the figure. It is worthy of note that the two pyrrole rings are arranged in a wedge-shaped structure, which would match the wedge-shaped cavity of DNA minor groove.

The complex–DNA interactions were also studied by molecular modeling. All calculations were performed in an SGI workstation with Insight II software package. The initial structure of the complex was that acquired by DFT calculation. Because the calf thymus DNA as well as pBR322 DNA used in the experimental work were too large for current computational resources to model, the structure of the DNA $d(CCGTCGACGG)_2$ (a familiar sequence used in oligodeoxynucleotide study) was constructed in the BIOPOLYMER Module of the Insight II package to study the DNA binding characters of the complex. The ESFF force field was used with its default parameters as it can deal with both DNA and metal complex. At the beginning of optimization, the Steepest Descent method was used until the root-mean-square derivation was less than 5 kcal/mol. Then it was switched to Conjugate Gradient method automatically by the DISCOVER 98 program. When the root-mean-square derivation was less than 0.5 kcal/mol, optimization was stopped. The DNA–complex interactions were examined by comparing the potential energy differences among different binding sites of both minor and major grooves. All interaction systems were dealt with periodic boundary conditions (usually in a parallelepiped that preserves the shape of the unit cell) and the corresponding summation method was the group-based cut-off. All systems containing DNA were calculated in aqueous solution, while other systems in vacuum.

Buffered aqueous solutions of DNA (0.6 mM) were prepared with water purified on a Millipore (France) apparatus. Phosphate (10 mM) buffer (pH 7.0) containing 1 mM EDTA was used. No added salt or support electrolyte was used. These solutions were dialyzed for three days with continuous agitation on a shaker bath at 30°C. Free complex concentrations were determined from the dialyzate by absorbance measurements at 279 nm (ε = 17,164 M^{-1}·cm^{-1}). Aqueous solution of the $MgL(NO_3)_2$ complex was prepared by dissolving in water at a concentration of $1.0\cdot10^{-4}$ M. The absorption titration was performed by keeping the concentration of calf thymus DNA ($1.18\cdot10^{-4}$ M) constant while varying the complex concentration (for $MgL(NO_3)_2$, (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0)·10^{-6} M). The absorption was recorded after each addition of the complex. The fluorescence spectra (λ_{ex} = 520 nm) were also recorded at room temperature. All

solutions were allowed to equilibrate thermally for about 30 min before measurements.

The cleavage of pBR322 DNA by Mg(II) complex was carried out with 10 μl of reaction mixture containing 10 mM Tris-HCl, pH 7.5, 5 mM NaCl, varying concentrations of complex, and 0.5 μl of pBR322 (0.5 μg/μl). After mixing, the DNA solutions were incubated at 37°C for 4 h. The reactions were quenched by the addition of EDTA and bromophenol blue. The gel was stained with ethidium bromide for 0.5 h after electrophoresis and then photographed.

RESULTS AND DISCUSSION

DNA binding studies are important for the rational design and construction of new and more efficient drugs targeted to DNA [30]. A variety of small molecules interact reversibly with double stranded DNA, primarily through three modes: (i) electrostatic interactions with the negatively charged nucleic sugar-phosphate structure, which are along the external DNA double helix and do not possess selectivity; (ii) binding interactions with two grooves of DNA double helix; and (iii) intercalation between the stacked base pairs of native DNA. Heterocyclic dyes, such as ethidium, anthracyclines, phenothiazines, and acridine derivatives interact through intercalation with the planar, aromatic group stacked between base pairs [31-33]. So as to explore the DNA binding and cleavage activity of the synthetic polyamide metal complex, the experiments as follow have been carried out.

Effect of the complex on UV spectra of DNA. "Hyperchromic effect" and "hypochromic effect" are the spectra features of DNA concerning its double-helix structure [34]. This spectral change reflects the corresponding changes of DNA in its conformation and structures after the drug binds to DNA. Hypochromism results from the contraction of DNA in the helix axis, as well as from the change in conformation on DNA; in contrast, hyperchromism derives from the damage of the DNA double-helix structure [34, 35]. As shown in Fig. 4, the absorption spectra of DNA decrease with increasing Mg(II) complex concentration. This is a typical "hypochromic effect". Therefore, the result indicates the interaction between Mg(II) complex and DNA is not the classical intercalation mode but the electrostatic mode, namely, the Mg(II) complex can not only make a contraction in the helix axis of DNA by electrostatic binding to the phosphate group of DNA backbone, but also result in changed conformation of DNA.

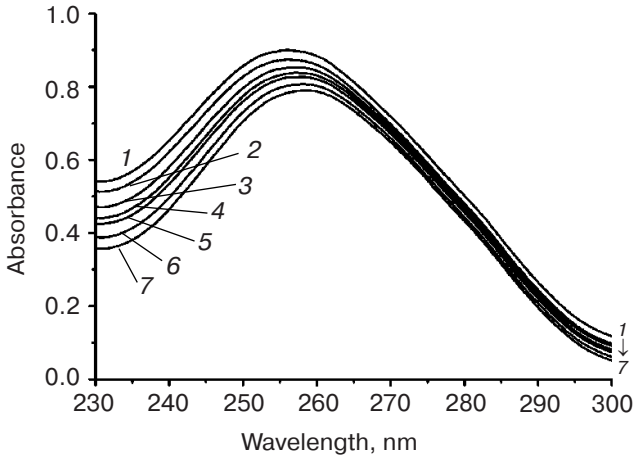

Fig. 4. Absorption spectra of calf thymus DNA ($1.18 \cdot 10^{-4}$ M) in Tris-HCl buffer (*1*) upon addition of MgL (($0.5, 1.0, 1.5, 2.0, 2.5, 3.0) \cdot 10^{-6}$ M) (*2-7*, respectively).

Effect of the complexes on the fluorescence spectra of DNA–ethidium bromide complex. To investigate the mode of binding of the Mg(II) complex to DNA, the competitive binding experiment has been carried out. The fluorescent emission of ethidium bromide (2 μM) bound to DNA (20 μM) in the absence and the presence of the complex was monitored. Ethidium bromide is a conjugated planar molecule. Its fluorescence intensity is very weak, but it is greatly increased when ethidium bromide is specifically intercalated into the base pairs of double-stranded DNA. When ethidium bromide is free from DNA, the fluorescence of DNA–ethidium bromide complex is evidently quenched. Therefore, ethidium bromide can be used as a probe for DNA structure detection [36]. $MgL(NO_3)_2$ itself does not show appreciable fluorescence in the spectral region studied, either free or bound to DNA, and does not quench the fluorescence of ethidium bromide in the absence of DNA under the conditions of our experiments. The emission band at 590 nm of the DNA–ethidium bromide system has almost no change in intensity on increasing the Mg(II) complex concentration. This indicates that the Mg(II) complex may cause a contraction in the helix axis of DNA by electrostatic binding to the phosphate group of the DNA backbone [37].

Scatchard plots. To get a better insight into the nature of complex–DNA binding, we have carried out a fluorescence study of ethidium bromide binding to DNA in the presence of a competing metal complex. The characteristics of the binding of ethidium bromide to DNA can be expressed by the Scatchard equation [36]:

$$r/C_f = K(n - r),$$

where r is the ratio of bound ethidium bromide to total nucleotide concentration, C_f is the concentration of free ethidium bromide, n is the number of binding sites per nucleic acid, and K is the intrinsic binding constant for ethidium bromide. Fluorescence Scatchard plots for the binding of ethidium bromide to calf thymus DNA

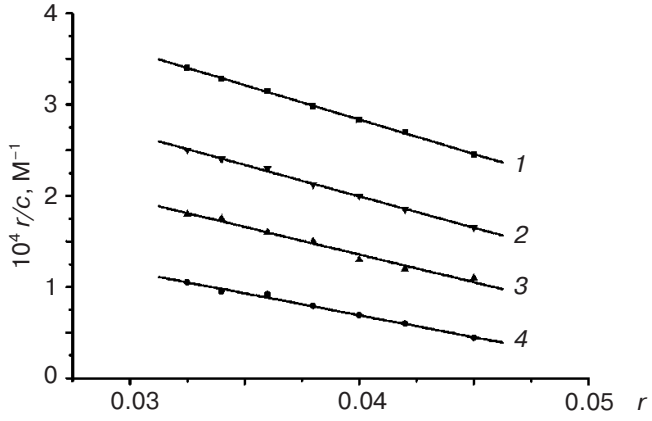

Fig. 5. Fluorescence Scatchard plots of the binding of ethidium bromide to calf thymus DNA in the absence (*1*) and the presence (*2-4*) of increasing concentrations of the complex ($C_{Mg(II)complex}/C_{DNA}$ = 0.25, 0.5, 1.0, respectively (from top to bottom)). $C_{DNA} = 1.18 \cdot 10^{-6}$ M.

($1.18 \cdot 10^{-6}$ M) in the absence and presence of the $MgL(NO_3)_2$ complex are given in Fig. 5. The value of *K* has nearly no change, as shown in Fig. 5, which indicates that the $MgL(NO_3)_2$ complex binds to DNA by a noncompetitive inhibition [30], namely, the interaction between the $MgL(NO_3)_2$ complex and DNA is through the electrostatic mode.

Viscosity study. Hydrodynamic methods, such as determination of viscosity, which is exquisitely sensitive to the change of length of DNA, may be the most effective means studying the binding mode of complexes to DNA in the absence of X-ray crystallographic or NMR structural data [38]. The viscosity measurement is based on the flow rate of a DNA solution through a capillary viscometer. The specific viscosity contribution (η) due to the DNA in the presence of a binding agent was obtained. The results indicate that the absence and the presence of the metal complex have a marked effect on the viscosity of the DNA. To further clarify the nature of the interaction between the complex and DNA, viscosity measurements were carried out. DNA is a polyanion. In solution, repulsion among negative charges makes the DNA molecule more extended. When the cation of a complex binds by electrostatic interaction to the phosphate group of DNA backbone, the negative charges of DNA are partially neutralized. This leads to the contraction of the DNA helix, shortening of the DNA molecule, and decrease of viscosity of the DNA solution. In Fig. 6, the specific viscosity of the DNA sample obviously decreases with the addition of the Mg(II) complex. Therefore, it can be confirmed that the binding between the Mg(II) complex and DNA is through electrostatic interaction with the phosphate group of the DNA backbone.

Thermal denaturation experiments. Other strong evidence for the binding mode between the complex and DNA was obtained from melting studies of the DNA. The intercalation of small molecules into the double helix is known to significantly increase the helix melting temperature, at which the double helix denatures into single-stranded DNA [39, 40]. The extinction coefficient of DNA bases at 260 nm in the double-helical form is much less than that in the single-stranded form [41, 42]; hence, the melting of the helix leads to an increase in the absorption at this wavelength. Thus, the helix-to-coil transition temperature can be determined by monitoring the absorbance of DNA bases at 260 nm as a function of temperature (T_m). However, the T_m will increase slightly ($T_m < 0.6$°C) when interaction of small molecules with DNA through nonspecific electrostatic interactions with the phosphate backbone of DNA occurs [43].

The DNA melting curves in the absence and presence of the Mg(II) complex are presented in Fig. 7. The

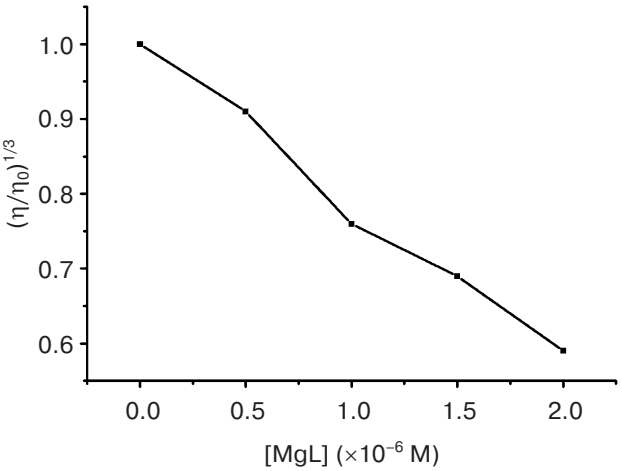

Fig. 6. Effect of increasing concentration of $MgL(NO_3)_2$ on the relative viscosity of DNA. $C_{Mg(II)complex}$ = (0, 0.5, 1.0, 1.5, 2.0)·10^{-3} mM.

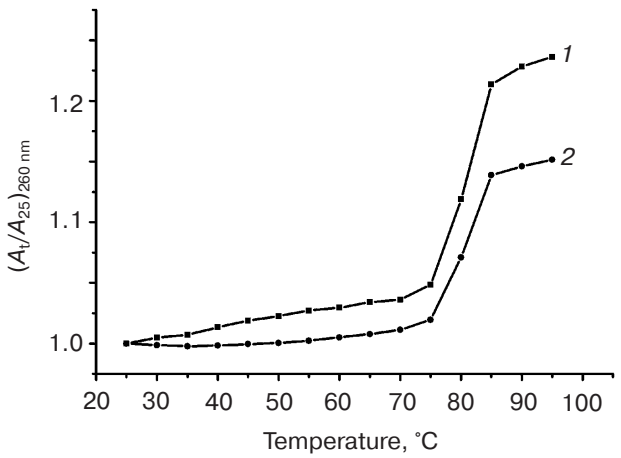

Fig. 7. Plot of the changes of absorbance at 260 nm of calf thymus DNA on heating in the absence (*1*) and presence (*2*) of the Mg(II) complex. $C_{DNA} = 1.18 \cdot 10^{-4}$ M and $C_{Mg(II)complex} = 1.2 \cdot 10^{-5}$ M in 10 mM Tris-HCl (pH 7.2) at 25°C.

T_m of DNA is 80°C in the absence of the Mg(II) complex and 80.3°C in the presence of the complex. Therefore, it can be concluded that Mg(II) complex interacts with DNA through nonspecific electrostatic interactions with the phosphate backbone of DNA.

Molecular modeling. The result reveals that the complex interacts with the DNA mainly through electrostatic groove surface binding, and the binding at the minor groove (3285.7 kcal/mol) is more preferential than that at the major groove (3303.3 kcal/mol). As shown in Fig. 8 (see color insert), the triethylenetetramine part of the complex locates in the bottom of the minor groove, while the two pyrrole parts and the Mg center interact with the DNA phosphate backbone, through which we could see the perfect match.

DNA cleavage experiments. The cleavage reaction of plasmid DNA can be monitored by agarose gel electrophoresis. When circular plasmid DNA is subject to electrophoresis, relatively fast migration will be observed for the intact supercoil form (form I, CCC form). If scission occurs on one strand (nicking), the supercoiled will relax to generate a slower-moving open circular form (form II, OC form). If both strands are cleaved, a linear form (form III) that migrates between form I and form II will be generated [44]. Figure 9 shows the results of cleaving superhelical pBR322 DNA in the presence of varying concentrations of the $MgL(NO_3)_2$. The results indicate that the CCC form of pBR322 DNA diminishes gradually, whereas the OC form increases with the increase of concentration of the $MgL(NO_3)_2$ and the linear form is also produced. When $C_{Mg(II)complex}/C_{DNA}$ is increased to 0.40 (lane *5*), the CCC form almost completely converts to the OC form and linear form. Therefore, the result here indicates that the $MgL(NO_3)_2$ can bind to and cleave DNA efficiently.

The DNA cleavage by the similar complex has been discussed in detail in our previous work [19]. The experiments indicated that the traces of Fe(II) contained in plasmid DNA had no effect on DNA cleavage. Furthermore, Fig. 9 shows that the cleavage effect is better with the increase in the Mg(II) complex concentration. If the DNA cleavage can be related with its ability to form chelates with Fe(II), the increase of the Mg(II) complex concentration will not affect cleavage effect because the concentration of Fe(II) is not changed in the reaction system and such little ligand can chelate Fe(II) completely.

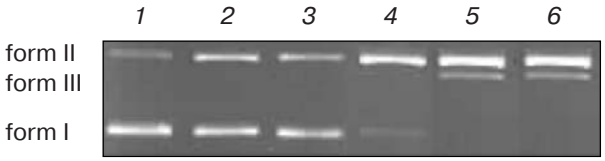

Fig. 9. Results of electrophoresis of pBR322 DNA in the presence of varying concentrations of $MgL(NO_3)_2$. $C_{Mg(II)complex}/C_{DNA}$: 0, 0.1, 0.2, 0.3, 0.4, 0.5 (*1-6*, respectively). Forms I-III are supercoiled DNA, nicked circular DNA, and linear DNA, respectively.

In summary, a new Mg(II) complex has been synthesized and characterized by elemental analyses, ^{1}H-NMR and ^{13}C-NMR, IR, HRMS, and molar conductivity. The experimentally postulated structure of the complex was confirmed by DFT calculations. The interactions between the complex and calf thymus DNA was first investigated using UV spectra, fluorescent spectra, thermal denaturation, and viscosity. Furthermore, the binding mode between the complex and DNA was studied by molecular modeling. The cleavage reaction on plasmid DNA has been investigated by agarose gel electrophoresis. Remarkably, the experimental results show that the complex is a new species that can bind DNA with electrostatic mode at the minor groove and can cleave DNA efficiently. The results should be valuable in understanding the mode of the complex with DNA as well as laying a foundation for the rational design of novel powerful agents for probing and targeting nucleic acids.

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