Synthesis of [Ru(phen)₂dppz]²⁺-Tethered Oligo-DNA and Studies on the Metallointercalation Mode into the DNA Duplex

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Received November 16, 2000

Abstract: To explore the binding properties of [Ru(phen)₂dppz]²⁺ complex (phen = 1,10-phenanthroline, dppz = dipyrido[3,2-α:2′,3′-ε]phenazine) in a sequence-specific manner in DNA duplex, it was tethered through the dppz ligand to a central position as well as both at the 3′- and 5′-ends of oligodeoxyribonucleotide (ODN). The middle [Ru(phen)₂dppz]²⁺-ODN tethered was resolved and isolated as four pure diastereomers, while the 3′- or 5′-[Ru(phen)₂dppz]²⁺-ODNs were inseparable on RP-HPLC. Thermal stability of the (Ru²⁺-ODN)-DNA duplexes is found to increase considerably (ΔT_m = 12.8–23.4 °C), depending upon the site of the covalent attachment of the tethered [Ru(phen)₂dppz]²⁺ complex, or the chirality of the [Ru(phen)₂dppz]²⁺-linker tethered at the middle of the ODN, compared to the unlabeled counterpart. Gross differences in CD between the [Ru(phen)₂dppz]²⁺-tethered and the native DNA duplexes showed that the global duplex conformation of the former has considerably altered from the B-type, but is still recognized by DNase I. The thermal melting studies, CD measurements, as well as DNase I digestion data, are interpreted as a result of intercalation of the dppz moiety, which is realized by threading of the Ru(phen)₂ complex part through the DNA duplex core. DNase I footprinting with four diastereomerically pure middle ([Ru(phen)₂dppz]²⁺-ODN)-DNA duplexes furthermore showed that the tethered [Ru(phen)₂dppz]²⁺-linker chirality dictates the stereochemical accessibility of various phosphodiester moieties (around the intercalation site) toward the cleavage reaction by the enzyme. The diastereomerically pure ruthenium-modified duplexes, with the well-defined π-stack, will be useful to explore stereochemistry-dependent energy- and electron-transfer chemistry to understand oxidative damage to the DNA double helix as well as the long-range energy- and electron-transfer processes with DNA as a reactant.

Introduction

Polypyridyl Ru²⁺ complexes are useful nonradioactive probes for structure elucidation of nucleic acids. They have been found to be valuable as luminescent reporters, ¹ DNA/RNA cleaving² or cross-linking³ agents, and also for the study of the long-range energy- and electron-transfer processes through the DNA.⁴ The most attractive way to evaluate the binding properties of Ru²⁺ metal complexes with nucleic acids in a sequence-specific manner is to covalently incorporate Ru²⁺ metal complexes into ODNs with a spacer, ensuring a well-defined donor–acceptor distance and geometry. This can be achieved by varying both the attachment site to the ligand of the Ru²⁺ metal complex as well as the linker length, thereby opening the possibility to engineer the mobility as well as the delivery of the Ru²⁺ complex in a stereospecific manner along the double-helical core.

To date, the preparation of Ru²⁺-containing ODNs is based on either (i) modifying the nucleic acid single-strand after the solid-phase synthesis or (ii) synthesizing the Ru²⁺ complex-derivatized phosphoramidite and its subsequent incorporation into the nucleic acid strand during the solid-phase synthesis protocol.

(1) Sigel, A.; Sigel, H.; Probing of Nucleic Acids by Metal Ion Complexes of Small Molecules; Marcel Dekker Inc.: New York, 1996; Vol. 33, p 678.
enormous flexibility for rapid and straightforward introduction of the Ru$^{2+}$ complex at various sites of ODN.13–16

Among the various types of Ru$^{2+}$ complexes studied so far, [Ru(phen)$_2$dpzp]$_{2}^{2+}$ is probably the most interesting because it binds extremely strongly to double-stranded DNA ($K = 10^{8}$ M$^{-1}$) through intercalation of its elongated planar dpzp moiety, displaying intense photoluminescence (molecular “light switch”).9,18 Postsynthetic covariant 5′-attachment of [Ru-(phen)dpzp]$_{2}^{2+}$ to an ODN has been accomplished by Barton and co-workers,9,10 and Giese et al.12 and Barton and co-workers have subsequently used this as specific fluorescent probes8,12 and cleaving agents (“artificial nucleases”)10 as well as to study long-range electron transfer through a [Ru(phen)dpzp]$_{2}^{2+}$-tethered 15mer DNA duplex.19 The use of [Ru(phen)dpzp]$_{2}^{2+}$-DNA and [Ru(dimine)$_3$]$_{2}^{2+}$-DNA conjugates, in general, has enabled exploration of different photochemical properties of Ru$^{2+}$ complexes at the target ODN sequences.20 In all of these conjugation works on tethered [Ru(phen)dpzp]$_{2}^{2+}$, the linker was attached to one of the phen ligands, thereby giving precise preferences to a certain geometry of intercalation vis-à-vis the DNA duplex helix. This unfortunately resulted in only a $T_m$ rise of 3–8 °C.10,12

In this study, we have synthesized [Ru(phen)$_2$dpzp]$_{2}^{2+}$-tethered ODNs (as in the 5′-, 3′-, and the middle-modified oligos, 10, 11, and 12, respectively), in which the dpzp moiety has been used to tether to the ODN. Thus, we have compared the stabilities and the binding geometries of tethered [Ru(phen)$_2$-dpzp]$_{2}^{2+}$ in the duplexes formed with 10, 11, or 12 with the target ODN 9 and compared them with the dpzp-tethered counterparts (as in 10′, 11′, and 12′).21 We here show that the change of the ODN-spacer attachment site in the tethered [Ru(phen)dpzp]$_{2}^{2+}$ complex from phen to the dpzp moiety indeed plays an important role in the recognition of the tethered Ru$^{2+}$ complex by the DNA double helix in that we observe a dramatic $T_m$ rise of the DNA-DNA duplexes, with $\Delta T_m$ varying from 13 to 23 °C, depending upon whether the Ru$^{2+}$ complex was tethered at the 5′-, in the middle, or at the 5′-end of the 9mer 9.

The [Ru(phen)$_2$dpzp]$_{2}^{2+}$-labeled ODNs have been prepared using the phosphoramidite chemistry.17 The [Ru(phen)$_2$dpzp]$_{2}^{2+}$ derivatized building block 5 was constructed such that it could be introduced at the 3′-, 5′-, or at the interior of the 9mer ODN strand by choice, basing on a non-nucleosic $sn$-glycerol-tri-(ethylene glycol) fused linker. The comparison of the CD data of the single-stranded Ru$^{2+}$-ODN and the double-stranded (Ru$^{2+}$-ODN)-DNA duplex, along with the comparison of $T_m$ and $\Delta G^\circ$ and the results of digestion by DNaI of the latter showed the extent and location of structural distortions caused by interaction of Ru$^{2+}$ complex within the DNA duplex framework.


Results and Discussion

(1) Synthesis of Ru$^{2+}$-Labeled Oligodeoxyribonucleotides.
Preparation of the synthetic ODNs with tethered metal complex by standard solid-state synthesis required the development of a bifunctional linker in which one of the functional groups can be protected while the other is activated. We chose $sn$-glycerol-tri-(ethylene glycol) fused linker21–23 for this purpose because of its hydrophilic and flexible character, permitting the incorporation of the metal complex either between the two phosphodiester residues of the ODN or into the 3′- or 5′-terminal of the ODN chain.

The [Ru(phen)$_2$dpzp]$_{2}^{2+}$ derivatized building block 5 was synthesized as follows in five steps, $1^{24} \rightarrow 2^{18} \rightarrow 3^{26} \rightarrow 5$ (Figure 1): The precursor acidic complex 3 was previously obtained18 in two steps starting from Ru(phen)$_2$Cl$_2$ 1 which was complexed with 1,10-phenanthroline-5,6-dione11 to give the racemic ($\Delta\Lambda$) [Ru(phen)$_2$Cl(phendione)][PF$_6$] 2. It was then condensed with 3,4-diaminobenzoic acid to give the desired -COOH group in [Ru(phen)$_2$dpzp-COOH][PF$_6$]$_2$ 3 (dpzp-COOH = dipyrindophenazine-11-carboxylic acid) in a straightforward manner. Activation of the racemic mixture of $\Delta\Lambda$- and $\Lambda\Lambda$-enantiomeric carboxylic acids 3 with 1,1′-carbonylbis[1H-imidazole] and the treatment of intermediate complex with $sn$-glycerol derivatized amine 4 in pyridine at room temperature gave the key amide 5 (59%). It is important to note that using racemic ($\Delta\Lambda$)-mixture of metallocomplex 3 and ($R/S$ from $sn$-glycerol)-mixture of the linker 4 gives four possible isomers of compound 5 (5$R$, $\Delta\Lambda$, $\Lambda\Lambda$, and $\Lambda\Lambda$) ($\Delta\Lambda/\Lambda\Lambda$ and ($\Delta\Lambda/\Lambda\Lambda$ are two pairs of enantiomers). As a consequence, all subsequent derivatives of compound 5 (including the ODN conjugates) described in this paper should exist in four isomeric forms. Complex 5 as well as the precursors 2 and 3 were isolated as the PF$_n$ salts, which ensured their solubility in organic solvents for subsequent use in the automated DNA/RNA synthesizer. In the final step, the compound 5 was converted in the usual manner25 to the corresponding phosphomodiphosphate 6 (94%) for incorporation of the [Ru(phen)$_2$dpzp]$_{2}^{2+}$-derivatized monomer unit into the 5′-end or in the middle of an ODN. Compound 5 was also treated with succinic anhydride and DMAP in CH$_2$Cl$_2$ to give the corresponding succinate block 7 (86%) which was then immobilized onto aminopropyl-CPG support26 and was used for incorporation of the [Ru(phen)$_2$dpzp]$_{2}^{2+}$-tethered building block at the 3′-terminus of the ODN.

In this study, we prepared three [Ru(phen)$_2$dpzp]$_{2}^{2+}$-tethered ODNs 10–12 (Table 1) by the phosphoramidite methodology27 on a commercially available DNA/RNA synthesizer. The model nucleotide sequence chosen in the above oligos was identical to the dpzp-ODN conjugates used in our previous study,21 thereby allowing us to compare the present data with those published. Removal of the finished 9mer ODNs from the solid support using concentrated ammonium hydroxide was followed by incubation at 55 °C for 17 h to afford the deprotected ODNs.

which were purified by reverse-phase HPLC with a gradient of 5–50% CH$_3$CN containing 0.1 M triethylammonium acetate, pH 7.0.

The HPLC separation (Figure 2A) of the middle Ru$_2^{2+}$-labeled ODN 12 gave well-resolved two pure ε-isomers (R and S) 12a, 12b, and two pure δ-isomers (R and S) 12c, 12d, according to the CD analysis (see below) (R and S cannot however be assigned for 12a–d). The 5′-Ru$_2^{2+}$-modified ODN 10 could only be resolved into two fractions (Figure 2B). The 3′-Ru$_2^{2+}$-modified oligo 11, exhibited an unresolved single peak, by our attempts to separate them with various eluents and gradient systems. Satisfactory separation of the constituent stereoisomers of the middle Ru$_2^{2+}$-labeled ODNs 12a–d might be a consequence of different chemospecific interactions of the Ru$_2^{2+}$ ligands (δ and ε) with the chiral environment of the single-stranded ODN. Analytical gel electrophoresis of the purified diastereomers of the middle Ru$_2^{2+}$-modified ODN 12a–d is shown in Figure 3.

The ODN-conjugates synthesized have been characterized by matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF-MS). The calculated mass for all conjugates is 3720.8 (C$_{139}$H$_{154}$N$_{42}$O$_{58}$PuRu including $^{102}$Ru isotope), and the observed $m/z$ was respectively found at 3720.6 for oligo 10, 3720.4 for 11, 3720.8 for 12b, and 3720.3 for a 12c/12d mixture. From these data one can conclude all substances are indeed the desired conjugates. Further structural evidence showing the correct incorporation site of the [Ru-(phen)$_2$dpzp$^2$]$_2^{2+}$ moiety at the middle of ODN (i.e., between 4A and 5A, see Figure 8A for numbering) came from the partial digestion of 12a–d with snake venom phosphodiesterase (SVP), a 3′-exonuclease, and spleen phosphodiesterase, a 5′-exonuclease, followed by MALDI-TOF MS of the digest. The MS measurement after 5 min of SVP degradation in pure water showed a mixture consisting of the molecular ion at $m/z$ 3722.17, and products corresponding to loss of 9 T residue at $m/z$ 3417.97, followed by loss of 8 A residue ($m/z = 3104.7$), 7 C residue ($m/z = 2815.45$), and 6 A residue ($m/z = 2502.2$). Then the digestion stops at 5 A. A similar partial digestion study by the spleen phosphodiesterase for 5 min, followed by MALDI-TOF showed no molecular ion at $m/z$ 3722.17, but the products.
from the digestion consisted of a peak at \( m/z = 3419.6 \) owing to the loss of 1 T residue and a peak at \( m/z = 3130.3 \) due to the loss of 2 C residue, and then the digestion stopped finally at 4 A residue after the loss of 3 C (\( m/z = 2840.8 \)). These partial exonuclease digestion studies both from the 3′- and 5′-ends showed that 4 A and 5 A residues are resistant to both exonucleases, which supports that the tethered \([\text{Ru(phen)}_2\text{dppz}]^{2+}\) moiety have been indeed introduced between the 4 A and 5 A residues.

\[(\text{II})\] CD Spectroscopy of Ru\(^{2+}\)-labeled ODNs and the (Ru\(^{2+}\)-ODN)-DNA Duplexes. As it has been mentioned above, the preparative HPLC chromatogram of the middle-modified 9mer ODN consisted of four product peaks of nearly equal intensity (Figure 2A), which were collected separately in ascending order of their retention times (12a, 12b, 12c, and 12d). The electrophoretic mobilities of these fractions were the same (Figure 3), while their CD spectra (Figure 4A) argued that they belong to different isomers of the middle Ru\(^{2+}\)-labeled 9mer ODN. Comparison of our CD spectra with those of the literature data for free \([\text{Ru(phen)}_2\text{dppz}]^{2+}\) complex or tethered to the 5′-termini of ODN 12 has led us to assign 12a and 12b with the tethered Ru\(^{2+}\) complex in two possible \( \lambda \)-configurations (S and R), and assign 12c and 12d in the two mirrored \( \lambda \)-configurations. On the basis of equal and opposite relationship of the CD spectra as well as equal intensity of all four HPLC peaks (Figure 2A), one can conclude that none of the diastereomers was formed preferentially. In contradistinction, the CD spectra of two fractions obtained in the course of HPLC purification of 5′-Ru\(^{2+}\)-modified ODN 10 (Figure 2B) showed the corresponding bands of opposite signs but different intensity (Figure 4B), which did not allow us to clearly assign the distribution of four diastereomers in the two fractions 10a and 10b.

![Diagram](image1.png)

![Diagram](image2.png)

**Table 1.** Synthetic Ru\(^{2+}\)-Labeled ODN Conjugates (Modification Is Designated as \( \text{X} \)) and Their Target Oligo-DNA and Oligo-RNA

<table>
<thead>
<tr>
<th>oligos</th>
<th>compd</th>
</tr>
</thead>
<tbody>
<tr>
<td>natural</td>
<td>5′-d(TCCAAACAT)</td>
</tr>
<tr>
<td>9mers</td>
<td>5′-modified</td>
</tr>
<tr>
<td></td>
<td>5′-modified</td>
</tr>
<tr>
<td></td>
<td>middle</td>
</tr>
<tr>
<td></td>
<td>middle</td>
</tr>
<tr>
<td>11mers</td>
<td>single strand</td>
</tr>
<tr>
<td>targets</td>
<td>5′-r(CAUUUUGGAC)</td>
</tr>
</tbody>
</table>

\(^a\) For comparison the dppz-tethered ODNs (modification is designated as \( \text{Y} \)) are entered

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The structural changes in the enantiomerically pure Ru\(^{2+}\)-ODN conjugates (12a-d) upon its hybridization with the DNA target have also been explored. The CD spectra of (Ru\(^{2+}\)-ODN)-DNA duplexes 12a-13 and 12b-13 are different from 11a-13. They altogether differ from the B-form of DNA,\(^{30}\) and have features that are reminiscent of the A-type helix.\(^{31}\)

The positive band is centered near \(\lambda = 260\) nm and the negative band centered near \(\lambda = 232.5\) nm which is shifted by 7.5 nm from the corresponding native maximum (267.5 nm) and minimum (240 nm) to the short wave area. The CD crossover of 5'- and the middle-modified duplexes 10-13 is centered near \(\lambda = 246.3\) nm which is shifted by 5 nm from the native counterpart (251.3 nm) to the short wave area. The CD spectra of 3'-modified duplex 11-13 exhibits features which are characteristic for the natural duplex: i.e. the same negative band minimum (240 nm) and a shoulder at 267.5 nm which coincides with the native duplex positive band. It also shows the same crossover point (246.3 nm) and shifted main positive band as in the 5'- and middle modified duplexes 10-13 and 12-13. These features suggest that the global conformation of 10-13 and 12-13 are different from 11-13. They altogether differ from the B-form of DNA,\(^{30}\) and have features that are reminiscent of the A-type helix.\(^{31}\)

The structural changes in the enantiomerically pure Ru\(^{2+}\)-ODN conjugates (12a-d) upon its hybridization with the DNA target have also been explored. The CD spectra of (Ru\(^{2+}\)-ODN)-DNA duplexes 12a-13, 12b-13, 12c-13, and 12d-13 (Figure 6) were compared to the CD spectra of enantiomerically pure single-stranded Ru\(^{2+}\)-ODNs recorded at 5 °C. For the middle-modified \(\Delta\)-isomers 12c and 12d the intensity of the short (246 nm) wavelength band essentially increases upon hybridization, while the corresponding band for the \(\Delta\)-isomers duplexes 12a-13 and 12b-13 increases very little. Additionally, the long wavelength band at 262 nm is notably broadened upon hybridization of the \(\Delta\)-isomers 12c and 12d in contrast with the \(\Delta\)-isomers 12a-13 and 12b-13, which exhibit sharp 262 nm band in the duplex form. Taken together, these facts denote somewhat different binding geometries for \(\Delta\) and \(\Delta\)-diastereoisomers of the Ru\(^{2+}\) complex tethered at the middle of the 9mer DNA in the duplex form compared to the single-stranded counterpart, which is also evident from their relative thermodynamic stabilities as well as recognition and cleavage by DNase I (see below).

(II) Thermal Melting Study of Intermolecular Ru\(^{2+}\) Complexes and DNA-DNA Duplex. Prior to the metaling of (Ru\(^{2+}\)-ODN)-DNA and (Ru\(^{2+}\)-ODN)-RNA hybrids, we have examined the influence of some nonconjugated ruthenium complexes on the stability of natural DNA-DNA duplex 9-13 (ruthenium complex (1-5 \(\mu\)M) added to the native duplex 9-13 (1 \(\mu\)M) in 20 mM PO\(_4\)\(^{3-}\), 0.1 M NaCl buffer at pH 7.3). In this study, [Ru(phen)\(_2\)dpdz][PF\(_6\)] and [Ru(phen)\(_3\)][PF\(_6\)] were compared to the [Ru(phen)\(_2\)(dpdz-CONH(CH\(_2\)CH\(_2\)O\(_3\)CH\(_2\)-OH)(CH\(_2\)OH)](PF\(_6\))\(_2\) to examine the effect of the linker in the Ru\(^{2+}\)-labeled ODNs 10-12. It has been earlier shown that most polypyridyl Ru\(^{2+}\) complexes are positively charged, and may thus bind electrostatically to the single- or double-stranded (ds) DNA at low ionic strength.\(^{22,33}\) In dsDNA, they may also undergo partial intercalation between two DNA base pairs,\(^{33-35}\) when one of the ligands is an extended polyazaaromatic planar system. Another feasible binding mode of such complexes with dsDNA is a groove-bound interaction.\(^{36}\) Various methods, including fluorescence quenching,\(^{37}\) flow linear dichroism,\(^{17}\) NMR spectroscopy,\(^{38}\) and topoisomerase unwinding assay\(^{37,39}\) have confirmed that [Ru(phen)\(_2\)dpdz][PF\(_6\)] is a typical metallointercalator, while for [Ru(phen)\(_3\)][PF\(_6\)] both intercalative and surface binding modes can be accepted.

It can be seen from Figure 7 that two types of behavior are observed for the complexes selected. For [Ru(phen)\(_2\)dpdz][PF\(_6\)] and the new complex 8, \(T_m\) increases sharply with an increase of the amount of the complex added to the DNA-DNA duplex 9-13. In this case temperature curves have strongly marked kink points ([ruthenium]/[DNA phosphate] or D/P = 0.15–0.2; i.e. 3–4 equiv of ruthenium complex per 9mer + 11mer duplex 13-19), after which \(T_m\) increase becomes slow. On the other hand, growing amount of [Ru(phen)\(_3\)][PF\(_6\)] does not practically result in the duplex stabilization. This observation is in agreement with the earlier study on some polypyridyl Ru\(^{2+}\) complexes as DNA binders.\(^{40}\) Since the plot of \(T_m\) versus D/P for [Ru(phen)\(_2\)dpdz]-[PF\(_6\)] and the new complex 8 are very similar and since the former stabilizes DNA duplex by intercalating with the dpdz moiety, we conclude that our complex 8 intercalates in a very


similar way, despite the fact that the dppz ligand in the latter is sterically hindered by covalent attachment of the linker arm. This assumption can be supported by the fact that \([\text{Ru}(\text{phen})_2\text{dppz}]^2\) – \((\text{PF}_6)_2\), which interacts with DNA by only its phenanthroline ligands, showed very small stabilization and shallow \(T_m\) rises with \(D/P\).

Another factor which demonstrated intercalative character for both \([\text{Ru}(\text{phen})_2\text{dppz}]^2\) – \((\text{PF}_6)_2\), which interacts with DNA by only its phenanthroline ligands, showed very small stabilization and shallow \(T_m\) rises with \(D/P\).

Figure 5. CD spectra of racemic \((\text{Ru}^{2+}\text{-DNA})\)–DNA duplexes as a function of wavelength (nm): 10–13 (–), 11–13 (•••), 12–13 (– – –). CD spectra of nonmodified DNA–DNA duplex 9–13 (– • –) is shown for comparison.

Figure 6. CD spectra of diastereomers of \(\text{Ru}^{2+}\) middle-modified ODN 12 (dotted curves) and their corresponding duplex spectra (full curves). concentration because the stabilization near the binding sites is greater than for the base pairs distant from the bound complexes.\(^{35}\)

(IV) Thermal Melting Study of (Ru\(^{2+}\)-ODN)-DNA Duplexes. The (Ru\(^{2+}\)-ODN)–DNA duplexes (entries 2–8 in Table 2) were generated by hybridization of the Ru\(^{2+}\)-ODNs 10–12 with the target 11mer ODN 13 in a 1:1 ratio (1 \(\mu\)M of each strand in 20 mM PO\(_4\)^{3–}, 0.1 M NaCl buffer at pH 7.3). All of the melting curves of these duplexes showed a monophasic dissociation, and Table 2 shows the melting temperatures, which leads to the following conclusions: Tethering the \([\text{Ru}(\text{phen})_2\text{dppz}]^2\) – \((\text{PF}_6)_2\) through the dppz moiety at all positions of the 9mer strand (3′- or 5′-termini or at the middle) leads to the dramatic
rigid ligand configuration at the Ru²⁺ center of the complex plays an essential role for the DNA hybridization. For the enantio-merically pure middle modified ODNs, for example, one can see that A-Ru²⁺ complex gives higher stabilization (ΔTm = 19.4 °C and 16.4 °C for two possible orientation of the tri(ethylene glycol) spacer at the tertiary sn-glycitol carbon). On the other hand, the corresponding Δ-Ru²⁺ complex gives relatively poorer stabilization (ΔTm = 14.3 and 13.6 °C). The same tendency is observed for the 5’-(Ru²⁺-ODN)-DNA duplexes: 10a-Ru²⁺ is more stable (ΔTm = 23.4 °C) than 10b-Ru²⁺ (ΔTm = 21.6 °C). Finally, 3’-Ru²⁺-conjugation gives the least stabilization (ΔTm = 12.8 °C). Thus the strength of duplex stabilization for various site-specific Ru²⁺ incorporations into ODN are as follows: 5’-Ru²⁺→ middle Ru²⁺→ 3’-Ru²⁺-modified duplex.

(V) Thermodynamics of DNA-DNA Duplex Formation.

Melting curves with a series of DNA concentrations (2, 4, 6, 8, and 10 μM of total strand concentration) were recorded for (Ru²⁺-ODN)-DNA duplexes including natural duplex and dppz-conjugated analogues for comparison. Thermodynamic parameters were calculated according to an “all-or none” two-state model, and are listed in Table 4. As seen from this Table, the introduction of a Ru²⁺ complex in a duplex gives a more negative ΔG° (i.e., stabilization increases by 9.3–17.1 kJ/mol) compared to the unmodified counterpart (ΔG° = −37.8 kJ/mol), which is in accordance with the enhanced thermal stability of ruthenated duplexes. There is also a correlation between the difference in the free energy (ΔΔG°) and the change of melting temperature (ΔTm): 5’-(Ru²⁺-ODN)-DNA (ΔTm = 23.4–21.6 °C, ΔΔG° = −17.1/−13.8 kJ/mol) > middle-(Ru²⁺-ODN)-DNA (ΔTm = 19.4–13.6 °C, ΔΔG° = −11.4/−9.4 kJ/mol) > 3’-(Ru²⁺-ODN)-DNA (ΔTm = 12.8 °C, ΔΔG° = −9.3 kJ/mol) > natural duplexes.

Differences found in the thermodynamic data for the most of the Ru²⁺-modified DNA–DNA duplexes and the natural counterpart are of the same order of magnitude as their calculated errors (±3–9%). This simply did not allow us to identify a clear trend of competing enthalpy and entropy contribution in the observed ΔG° of stabilization of the duplexes, in general.

(VI) Mechanism of the Stabilization of (Ru²⁺-ODN)-DNA Duplexes.

The high stability observed for (Ru²⁺-ODN)-DNA duplexes is presumably owing to the intercalation of the dppz subunit between stacked base pairs in a very similar way found for bis-ruthenium complex.31 This intercalative interaction is energetically optimal because of the large π-stacking area available for the dppz moiety (distance between Ru²⁺ and e-C of dppz is 9.93 Å, Figure 1) with the adjacent base pairs (the distance across two distal atoms of a base pair is being ~9.9 Å).
which clearly is not possible for the phen group to cover (4.77 Å being the distance between two distal atoms). For our tethered [Ru(phen)2dppz]2+−ODN, the dppz intercalation can be realized if the Ru(phen)2 moiety passes through the DNA strands to reach their final position, or the linker has to sling itself around the opened base pairs. This threading through DNA should produce a very rigid structure in which covalently attached complex acts as a staple,41 holding the DNA-DNA duplex bases tightly stacked together near the intercalation site promoting a conformational reorganization with a net free-energy gain, which is also consistent with the CD properties.

With the above scenario, the decrease of DNA-DNA duplex stability from 5′ > middle > 3′-modified duplex can be explained by the following model: For the most stabilized 5′-modified duplex 10-13 and middle-modified duplex 12-13 the tethered [Ru(phen)2dppz]2+−complex threads through the duplex core ensuring the dppz intercalation between two base pairs. The bulged abasic site between 4-ÂT and 5-ÂT doublets as well as neighboring sites are accessible for such threading in the middle-modified duplex 12-13 (Figure 8A), while in 5′-modified duplex 10-13 the dppz ligand intercalates between 1-ÂT and 2-ÂG or perhaps between 2-ÂG and 3-ÂG base pairs (Figure 8B). In the 3′-modified duplex 11-13 the metallo-intercalator covers only terminal base pair 3′-T-2′A (Figure 8C) which should be less effective in terms of net stabilization of the duplex.

(VII) Thermal Melting Study of (Ru2+−ODN)-RNA Duplexes. The hybrid duplexes (Ru2+−ODN)-RNA (entries 10−14 in Table 2) were generated by hybridization of the Ru2+-tethered 9mers 10−12 with the target 11mer RNA 14 in a 1:1 ratio (1 μM of each strand in 20 mM PO43−, 0.1 M NaCl buffer at pH 7.3). Thermal denaturation study on the internally modified (Ru2+−ODN)-RNA duplexes showed no stabilization for any of the diastereoisomers (entries 12−14 in Table 2) in contrast with the (Ru2+−ODN)-DNA counterpart. The 5′- and 3′-conjugated (Ru2+−ODN)-RNA duplexes are, however, found to be more stable than the natural counterpart (∆Tm = 9.1 °C and 7.9 °C respectively, entries 10−11 in Table 2). It is likely that the 5′- and 3′-conjugated (Ru2+−ODN)-RNA duplexes are stabilized in a manner similar to that of the corresponding (3′-Ru2+−ODN)-DNA duplexes (compare Figure 8C with 8E and 8F). On the other hand, the reason for lack of stabilization of the middle-modified (Ru2+−ODN)-RNA duplexes is not clear. One possible reason could be that the relative width size of the major groove (varies from 7.6 to 9.6 Å) and the minor groove (8.9−10.2 Å) of the DNA-RNA are different from DNA-DNA duplexes (10.5−11.5 Å and 3.4−7.4 Å, respectively).42 This may mean two things: (i) The Ru2+ complex with ∼10 Å diameter is bulky and cannot place itself in the minor or in the major groove of the DNA-RNA duplexes. (ii) On the other hand, DNA-RNA has a minor groove width larger than the DNA-DNA duplex; still the Ru2+ complex does not bind there, and the likely reason is most probably that it is a major groove binder. This is indirectly supported by Barton’s NMR work38 in which she showed that the intercalation site of the [Ru(phen)2dppz]2+ complex is indeed in the major groove of DNA-DNA duplex.

(VIII) DNase I Footprinting of (Ru2+−ODN)-DNA Duplexes. The 5′-end of the target DNA strand 13 was 5′-32P-labeled by γ-32P-ATP and T4 polynucleotide kinase. Typical DNase I digestion patterns for all (Ru2+−ODN)-DNA duplexes were compared with the middle-modified (dppz-ODN)-DNA 12-13 and the native DNA-DNA duplexes (Figures 9−11). The information provided by DNase I digestion are two-fold: (i) The comparison of cleavage yields showed how the structures of (Ru2+−ODN)-DNA duplexes are different from the native unmodified counterpart. (ii) The comparison of the cleavage sites showed where the [Ru(phen)2dppz]2+ complex is intercalated. The ability of the native and (Ru2+−ODN)-DNA duplexes to be a substrate for DNase I decreases from the native (97%) > 3′-Ru2+-modified (98%) > middle-Ru2+-modified (48%) > 5′-Ru2+-modified (38%) duplex, which are correlated in the opposite order with their thermal stabilities. The extent of the cleavage reflects how deeply (Ru2+−ODN)-DNA duplex structure is altered from the B-form duplex, which is ideal for DNase I recognition.43 Two main conclusions can be made from this observation: (i) all (Ru2+−ODN)-DNA duplexes are substrates for DNase I, which means that their global duplex conformation is more similar to the B-type DNA-DNA duplex,

and the fact that (ii) the 5'- and middle-Ru²⁺-conjugated duplexes are least degraded (38% and 48%, respectively) suggests that they have undergone major conformational reorganization and distortion from the B-type DNA duplex structure, caused by metallocomplex moiety.

DNase I is known to bind at least 4bp to the 5'-end and 6bp to the 3'-end from the scissile phosphodiester bond of the substrate duplex. Inspection of the cleavage pattern of the 11mer in the native duplex leads us to conclude that the whole duplex should be covered by DNase I. Digestion of the native duplex...
Figure 11. DNase I digestion of duplexes formed from 5′-32P-labeled 11mer 13 with the native 9mer 9 or different diastereomers of Ru2+-modified ODNs 12a–12d. Time in minutes after the addition of the enzyme is shown at the top of each lane. The length and sequence of 5′-32P-labeled ODNs formed upon cleavage are shown on the extreme left and right sides of the gel, and the main cleavage sites after 30 min of reaction are also shown by arrows on the duplex sequence.

Conclusions

(1) The novel type of attachment through the dppz moiety of [Ru(phen)2dppz]2+ complex has been implemented. The complex was covalently linked to the non-nucleosidic sn-glycerol-tri(ethylene glycol) fused linker through the dppz ligand, allowing us to prepare ruthenium phosphoramide 6 and CPG-anchored Ru2+ for the multiple machine incorporation of the metal complex to the ODN strand.

(2) All four diastereomers (two Λ- and two Δ-stereoisomers) of internally Ru2+-labeled ODN 12 were separated by means of reversed-phase HPLC. They were subsequently used for spectroscopic and enzymatic studies to understand the modes of intercalation in the DNA duplexes along with 3′- and 5′-ruthenated counterparts.

(3) The 5′-, 3′-, and middle-modified ODNs form duplexes with 11mer DNA target, which are significantly stabilized (ΔTm = 12.8–23.4 °C) compared with the natural DNA-DNA duplex. The 3′- and 5′-modified ODNs also formed stable hybrid duplexes with complementary RNA, but the middle-modified (Ru2+-ODN)-RNA duplex did not show any improved stability compared to the natural counterpart.

(4) DNase I digestion of pure diastereoisomers of the middle-modified (Ru2+-ODN)-DNA duplexes showed unique diasterospecificity of DNase I recognition between R- and S-isomers in both Λ and Δ series (12a–d). Comparison of the digestion results of diastereomerically pure ΛR-, ΛS-, ΔR-, and ΔS-isomers showed the relative degree of protection from the DNase I, which the complex confer to the neighboring phosphodiester residues in the duplex. The comparison of the relative cleavage pattern with four pure middle-modified diastereomers showed that both steric and the conformational change in the octahedral [Ru(phen)2dppz]2+ complex have profound influence in the way the DNase I can approach the duplex for the cleavage reaction.
Implication
Synthesis of middle Ru2+-incorporated ODNs using Ru(bpy)3 (bpy = 2,2’-bipyridine),14 Ru(bpy):phen,13 and Ru(tap):dip (tap = 1,4,5,8-tetraazaacenaphthene, dip = 4,7-diphenylphenantroline)11 have so far resulted into no stabilization or destabilization of the duplexes, suggesting that such ruthenium complexes are not simply intercalated in DNA double helix. This is the first report of four diastereomerically pure middle Ru2+ -incorporated ODNs and their duplexes, which showed considerable stabilization. These diastereomerically pure Ru2+-modifed duplexes have been found to have different well-defined stereochemistry with respect to DNA minor and major grooves. This means that the study of their stereochemistry-dependent energy- and electron-transfer chemistry will be useful in understanding oxidative damage to the DNA double helix. It will be also interesting to probe if the diastereospecific interactions between the tethered Ru2+ complex and the DNA double helix actually have any influence in the long-range energy- and electron-transfer processes with DNA as a reactant. These diastereomerically pure Ru2+-modified duplexes have also the potential to be useful to understand donor–acceptor properties via luminescence and transient absorption spectroscopies.

Experimental Section
[Ru(phen)(dppz)(PF6)]2 (4). Compound 5 (15 mg, 0.14 mmol) was coevaporated with dry CH2CN twice and dissolved in dry CH2CN (3.4 mL) and kept under N2. Then dry diisopropylethylamine (87 mg, 0.68 mmol) was added, followed by addition of 2-cyanonitrodiisopropylphosphoramide (108 mg, 0.46 mmol) under vigorous stirring, which was continued for a further period of 3 h. The reaction mixture was worked up with aqueous saturated NaHCO3, dried over MgSO4 and coevaporated with toluene and then CH2Cl2 to afford the ruthenium phosphoramidite 6 (226 mg, 94%), which was then directly dissolved in 1 mL of anhydrous CH2CN for immediate synthesis use. Rf: 0.34 (A); 13C NMR (CDCl3): +149.51 and 149.44 ppm.

Preparation of the Ru2+-Functionalized Support. CH2Cl2 (0.93 mL) solution of diisopropylethylamine (19 mg, 149.0 µmol) was added to squacate block 7 (132 mg, 78.4 µmol), followed by addition of CH2Cl2 solution (0.37 mL) of isobutyl chloroformate (10.7 mg, 78.4 µmol). After stirring for 2 h, a solution of DPEA (0.34 mL) in dry CH2Cl2 (0.87 mL) and 3-aminophenol-CNP (364 mg) were added to the reaction mixture. The suspension was stirred for 2 h and then filtered and thoroughly washed with CH2Cl2 (four times) and diethyl ether (four times). The product was then suspended in dry pyridine (2.9 mL), 4(dimethylamino)pyridine (59 mg) and acetic anhydride (0.26 mL) were added, and the suspension was shaken for 2 h, after which the suspension was filtered and thoroughly washed with pyridine, CH2Cl2 (four times) and diethyl ether (four times) and then vacuum-dried over P2O5. DMR reference with acid and measurement at 498 nm showed the loading of 20.9 µmol per 1 g of CPG.

Bis(1,10-phenanthroline)(11,12-dihydroxy-6,9-dioxo(11H)-pyridino)(2,3-a:2’,3’-c)phenazine-11-carboxamide ruthenium(II) Bis(hexafluorophosphate) (8). Compound 5 (71 mg, 0.05 mmol) was dissolved in CH2Cl2 (1 mL), and 80% acetic acid (4 mL) was added to the solution. The mixture was shaken for 10 min and evaporated to dryness. The residue was suspended in water and neutralized with triethylamine. The product was isolated by silica gel column chromatography, eluting with 10–50% EtOH in CH2Cl2. Yield 132 mg, 86%. Rf: 0.46 (C). 1H NMR (acetone-d6): 9.81, 9.80 (2H, 2d, H4, J4 = 8.2), 9.23 (1H, br t, NCNO), 9.17 (1H, d, H8, J8 = 1.2), 8.93, 8.91 (4H, 2d, H4, J4(7,9) = 7.8), 7.83–8.67 (4H, m, H3, H5, H7, H8), 8.63 (2H, d, H2, J2 = 5.2), 8.54 (4H, s, Hs), 8.50 (2H, d, H6, J6 = 5.2), 8.07 (2H, d, H6, J6 = 8.2, J8 = 5.2), 7.98–7.90 (4H, m, Hs), 4.25 (1H, quintet, HOCH2CH, J = 4.2), 3.83–3.64 (16H, overlapping m). 13C NMR (acetone-d6): 167.80 (CONH), 154.85 and 154.73 (C13), 153.59 (C15), 151.18 (C15), 151.65 and 151.48, 148.06, 147.32, 141.91, 141.61, 141.31, 137.22 (C14), 136.34, 133.95 and 133.78 (C17), 131.24, 130.71, 130.38 and 130.16 (C15), 129.58 (C18), 128.32 (C9), 127.72 and 127.61 (C10), 126.36 (C12), 73.70, 72.20, 70.55, 70.21 (HOCH2CH), 69.98 and 69.90 and 69.87 (CH2OCH2OCH2OCH2O), 63.92. The proton and carbon assignments have been made on the basis of 1H–13C correlation spectra. MS calculated for C92H92N20Ru2P2F4 (including 102Ru isotope): 1283.0. Found: 1283.4 ± 0.2.

Synthesis, Deprotection, and Purification of Oligonucleotides. All ODNs were synthesized on 1.0 µmol scale with an 8-channel Applied Biosystems 392 DNA/RNA synthesizer using conventional 2-cyanonitrodiisopropylphosphoramide chemistry. Modified oligonucleotide 11 was synthesized on modified support containing [Ru(phen)(dppz)]2+ chromeophore tethered to glycerol residue through the linker of 12-atoms length. Other ODNs were obtained using standard CPG dT-support. The preparation
of target ODNs 13 and 14 involved the use of standard CPG dC or C-supports. Phosphoramidite block 6 was dissolved in dry acetonitrile with a final concentration of 0.15 M and used after filtration for solid-phase synthesis with a coupling time of 10 min (25 s for standard nucleoside amides).

After each synthesis of the protected oligomers, the solid support was transferred directly out from the cassette to a 50 mL RB flask containing 20 mL of concentrated aqueous NH₄, and was shaken for 2 h at 20 °C. After removal of CPG by filtration and evaporation of the filtrate, the residue was redissolved in concentrated aqueous NH₄ and stirred at 55 °C for 17 h. The crude ODNs were purified by reversed-phase HPLC (C18 column) eluting with the following gradient systems: A (0.1 M triethylammonium acetate, 5% MeCN, pH 7.0) and B (0.1 M triethylammonium acetate, 50% MeCN, pH 7.0) and the purity of Ru²⁺-ODN conjugates were checked by analytical reversed-phase HPLC and denaturing 20% polyacrylamide gel electrophoresis. UV-visible spectrum of each collected Ru²⁺-ODNs showed the characteristic MLCT absorption band of the complex [Ru(phen)₂dppz]²⁺ at 438 nm and IL transition band at 381 nm. The detritylated oligomers were evaporated and coevaporated with water five times and then directly lyophilized (5 x 1 mL H₂O) to dryness. All ODNs were subsequently sodium exchanged through a column of Dowex-50 Na⁺ form.

Concentrations of Ru²⁺-ODNs were determined, accounting for the contribution to the absorbance at 260 nm from the [Ru(phen)₂dppz]²⁺ moiety itself. This was done by taking the ratio of the area under the UV curve for compound 8 at 238–335 nm to that at 335–580 nm. The absorption of the Ru²⁺-labeled oligomers at 260 nm was then corrected for metal complex absorption at this wavelength by using the above ratio (1.8) for estimation of contribution of Ru²⁺ complex to the absorbance area for a given oligo at 235–335 nm. Starting from 1 μmol of thymidine or complex 8 residues linked to controlled pore glass the following amounts measured in A₂₆₀ units (OD) were obtained after purification: 12 of 10; 67.7 of 11; 1.2 of 12a; 6.9 of 12b; 15.4 of 12c.

Enzymatic Digestion of Middle-Modified ODN. ODN (1–1 nM) and SVP (~1 nM) or spleen phosphodiesterase (1 mg/mL) was incubated in H₂O without the addition of salts and buffer at room temperature for 5 min. The sample was then added to matrix solution for MALDI-TOF-MS.

Thermal Denaturation Experiments. UV melting profiles were obtained by scanning A₂₆₀ absorbance versus time at a heating rate of 1.0 °C/min from 10 to 70 °C. The melting temperature, Tm (±0.5 °C), was determined as the maximum of the first derivative of melting curves. The duplex melting experiments were performed in 1.3 mL of buffer I (20 mM Na₂HPO₄/NaH₂PO₄, 0.1 M NaCl at pH 7.3) at hybrid concentration of ~1 μM. The approximate extinction coefficients for natural ODNs were calculated as previously described.46,51 In cases of the Ru²⁺-tethered ODNs, the extinction coefficients were corrected for the absorbance contribution of the [Ru(phen)₂dppz]²⁺ moiety at 260 nm by subtraction. After preparation, the solutions consisting of two components (for forming of duplexes) were heated to 70 °C for 5 min, and then allowed to cool to 20 °C for 30 min under shaking. During the melting measurements at temperatures below ~15 °C, nitrogen gas was continuously passed through the sample compartment to prevent moisture condensation.

Circular Dichroism Spectra. CD spectrums of Ru²⁺-labeled ODNs and their duplexes were recorded from 550 to 220 nm, and CD spectrums of natural 9mer and its duplex were recorded from 320 to 220 nm. All CD experiments were performed in 0.2 cm path length cuvettes using 8 μM strand concentration in 650 μL of buffer II (20 mM Na₂HPO₄/NaH₂PO₄, 1 M NaCl at pH 7). For CD spectra of duplexes the temperature was maintained at 5 °C by circulating thermostated water through the cuvette holder, while for single-stranded ODNs it was maintained at 5 and 55 °C. The samples were equilibrated at the required temperature for 10 min before recording the spectra. Each spectrum was an average of two scans with the buffer blank subtracted, which was recorded at the same sensitivity (0.2, 0.5, or 2 m°/cm) and scan speed (10 or 20 nm/min). The time constant used were 16 s. Each point in the spectra was manually fed into the SigmaPlot 2000 software in a PC.

DNase I Footprinting. A 10 μL solution containing buffer (100 mM Tris, 10 mM MgCl₂ at pH 7.5), 10 μM of duplex, and 20 000 cpm of 5'-³²P-labeled 11mer 13 was heated to 70 °C for 5 min, and then allowed to cool to 20 °C for 45 min. Cleavage was initiated by the addition of 1 μL of 1.33 units/μL DNase I, 150 mM NaCl, 1 mM MgCl₂ and allowed to react at room temperature before addition of a formamide loading buffer. The mixture was then loaded onto 20% polyacrylamide/7M urea gel and electrophoresed at 700 V for 2 h. DNA fragments were visualized by Molecular Dynamics phosphorimager.

Acknowledgment. We thank the Swedish Natural Science Research Council (NFR) and Swedish Engineering Research Council (TFR) for generous funding. We also thank Dr. P. Lincoln and Professor B. Nordén for providing us with the experimental protocol for ruthenium complex.

JA00398ST