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The Positional Influence of the Helical Geometry of the Heteroduplex Substrate on Human RNase H1 Catalysis

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ABSTRACT

In a companion study published in this issue (p. 83), we showed that chimeric substrates containing 2′-methoxyethyl (MOE) nucleotides inhibited human RNase H1 activity. In this study, we prepared chimeric substrates containing a central DNA region with flanking northern-biased MOE nucleotides hybridized to complementary RNA. Conformationally biased and flexible modified nucleotides were positioned at the junctions between the DNA and MOE residues of the chimeric substrates to modulate the effects of the MOE residues on human RNase H1 activity. The strong northern-biased locked-nucleic acid modification exacerbated the negative effects of the MOE modifications resulting in slower human RNase H1 cleavage rates. Enhanced cleavage rates were observed for the eastern-biased 2′-ara-fluorothymidine and bulge inducing *N*-methylthymidine modifications positioned at the 5′-DNA/3′-MOE junction as well as the southern-biased 2′-methylthiothymidine and conformationally flexible tetrafluoroindole (TFI) modifications positioned at the 5′-MOE/3′-DNA junction. The heterocycle of the ribonucleotide opposing the TFI deoxyribonucleotide had no effect on the human RNase H1 activity, whereas nucleotide substitutions adjacent the TFI significantly affected the cleavage rate. Mismatch base pair(s) exhibited similar effects on human RNase H1 activity as the TFI modifications. The effects of the TFI modification and mismatch base pair(s) on human RNase H1 activity were influenced by the position of the modification relative to the nucleotides interacting with the catalytic site of the enzyme rather than the juxtaposition of the modification to the MOE residues. Finally, these results provide a method for enhancing the human RNase H1 activity of chimeric antisense oligonucleotides (ASO) as well as the design of more potent ASO drugs.

Human RNase H1 has been shown to play a dominant role in the activity of DNA-like antisense oligonucleotides (Wu et al., 2004). In several cell lines, the human RNase H1 protein was both overexpressed and reduced using DNA-like antisense oligonucleotides (ASOs) and small interfering RNAs targeting the mRNA of the enzyme. The effects of these manipulations on the potencies of a number of DNA-like ASOs to several different target RNAs showed that increasing the level and activity of human RNase H1 increased the potency of the ASOs and reducing the level of the enzyme resulted in a commensurate reduction in the potency of the ASOs (Wu et al., 2004). Moreover, overexpression of human RNase H1 in mouse liver increased the potency of a DNA-like ASO targeting Fas after intravenous administration.

We have demonstrated that human RNase H1 is composed of an RNA-binding domain, a spacer region, and a catalytic domain (Wu et al., 2001). Once bound to the heteroduplex substrate, the RNA binding and the catalytic domains are separated by approximately one helical turn; the RNA binding domain is positioned 3′ on the RNA relative to the catalytic domain (Lima et al., 2003). The RNA-binding domain is responsible for the strong positional preference for cleavage exhibited by the enzyme and modified nucleotides affecting the interaction between the RNA-binding domain and the substrate produced a shift in the cleavage pattern (i.e., ablation of the 5′-most cleavage site) (Lima et al., 2003). The catalytic domain, on the other hand, is highly sensitive to modifications that alter the geometry of the minor groove surrounding the cleavage site (Lima et al., 2004). To be cleaved by human RNase H1, a substrate must display a minor groove of appropriate dimensions unobstructed by 2′-modifications of the deoxyribose. Furthermore, the intra- and interphosphate distances of the heteroduplex substrate are crucial, as is the flexibility of the backbone (Lima et al., 2004).

Several factors influence the therapeutic utility of ASOs, including, but not limited to, the affinity for the target RNA,

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ABBREVIATIONS: ASO, antisense oligonucleotide; MOE, 2′-methoxyethyl; HPLC, high-performance liquid chromatography; LNA, locked nucleic acids; 2′-S-Me-T, 2′-methylthiothymidine; 2′-ara-F-T, 2′-ara-fluorothymidine; N-Me-T, 2′-methoxyethyl-*N*-methylthymidine; TFI, tetrafluoroindole.

the terminating mechanism (e.g., RNase H), pharmacokinetics, and toxicological properties (for review, see Crooke, 2001). Chimeric ASO configurations designed to take into account these factors have resulted in ASOs with improved potency (for review, see Crooke, 2001). These chimeric ASOs consist of a deoxyribonucleotide region to support RNase H activity flanked by modified nucleotides [e.g., 2′-methoxyethyl (MOE) nucleotides] for enhanced hybridization affinity, increased nuclease resistance, and reduced pro-inflammatory effects. MOE nucleotides exhibit a RNA-like C_3-*endo* sugar conformation and an A-form helical conformation when hybridized to RNA. In addition, the proximity of the 2′-methoxyethyl to the phosphate backbone results in further stabilization of the duplex via an extensive hydration network between the 2′-methoxyethyl oxygens and the bridging and nonbridging phosphate oxygens (Teplova et al., 1999). The conformation induced by the (MOE) nucleotides results in a 0.9° to 1.5° modification increase in the melting temperature of the ASO/RNA duplex, enhanced nuclease resistance (presumably caused by steric hindrance of the nuclease by the 2′-methoxyethyl), and elimination half-lives ranging from 14 to 30 days in all species including man (Freier et al., 1997; Crooke, 2001). Nevertheless, heteroduplexes containing chimeric ASOs exhibit slower human RNase H1 cleavage rates compared with unmodified substrates (Lima et al., 2007). Furthermore, any modification of the antisense DNA can have a profound influence on the overall catalytic rate, the site of cleavage, and the cleavage rates of specific sites. To better understand the mechanisms of the observed reduction in catalytic efficiency of chimeric substrates containing 2′-modified nucleotides and to begin to identify means to mitigate these effects, we introduced modified nucleotides at the MOE/DNA junction of the chimeric ASO to modulate the transmission of conformation of the MOE substitutions into the area of the duplex in which cleavage occurs (Fig. 1). In addition, mismatched base pairs were introduced at various positions in the chimeric substrate and the initial cleavage rates (V_0) for the modified heteroduplexes were compared with the wild-type DNA/RNA heteroduplex.

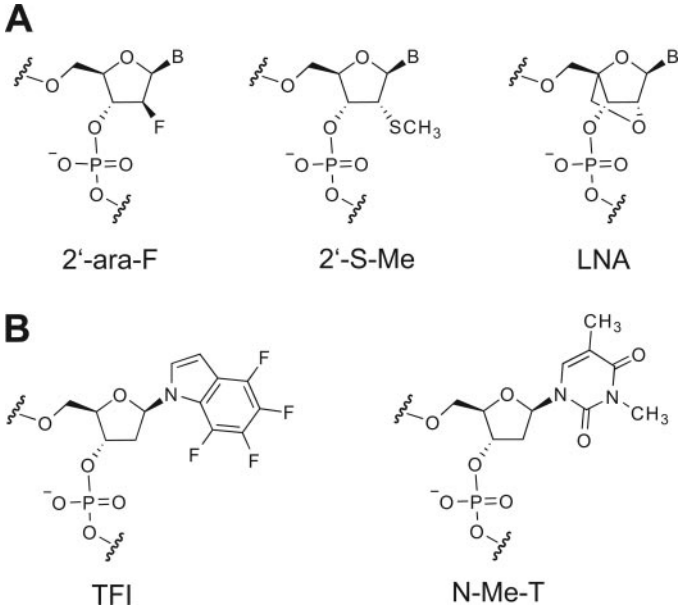


Fig. 1. Structure of the nucleotide modifications. A, modified nucleotides containing conformationally biased sugars include the southern-biased 2′-S-Me-T, the northern-biased LNA, and the eastern-biased 2′-ara-F-T. B, structures of the modifications designed to introduce conformational flexibility into the heteroduplex. These modifications include N-Me-T and TFI.

Materials and Methods

Synthesis of Oligonucleotides. The oligoribonucleotides were synthesized using 5′-*O*-silyl-2′-*O*-bis(2-acetoxyethoxy)methyl ribonucleoside phosphoramidites and procedures described elsewhere (Scaringe et al., 1998). The 5′-*O*-(4,4′-dimethoxytrityl)-2′-deoxy-2′-fluoro-arabino-thymidine-3′-[(2-cyanoethyl)-*N*,*N*-diisopropyl]phosphoramidite and 5′-*O*-(4,4′-dimethoxy-trityl)-*N*-methyl-5-methyluridine-3′-[(2-cyanoethyl)-*N*,*N*-diisopropyl]phosphoramidite was purchased from RI Chemicals (Orange, CA) or other commercial sources. 5′-*O*-(4,4′-Dimethoxy-trityl)-tetra-fluoro-indole-3′-[(2-cyanoethyl)-*N*,*N*-diisopropyl]-phosphoramidite and 5′-*O*-(4,4′-dimethoxytrityl)-2′-*S*-methyl-2′-thio-5-methyluridine-3′-[(2-cyanoethyl)-*N*,-*N*-diisopropyl]phosphoramidite were synthesized as described previously (Fraser et al., 1993; Lai and Kool, 2004). Standard 2′-deoxynucleoside phosphoramidites and solid supports were obtained from Glen Research (Sterling, VA) and used for incorporation of A, T, G, and C residues as 0.1 M solutions in anhydrous acetonitrile. All oligonucleotides were synthesized on functionalized controlled-pore glass on an automated solid-phase DNA synthesizer with the final dimethoxytrityl group retained at the 5′ end. For incorporation of modified amidites [locked nucleic acids (LNA), 2′-methylthiothymidine (2′-S-Me-T), 2′-ara-fluorothymidine (2′-ara-F-T), and 2′-methoxyethyl-*N*-methylthymidine (N-Me-T)], their 0.2 M solutions in acetonitrile (6 equivalents/coupling) of phosphoramidite solutions were delivered in two portions, each followed by a 6-min coupling wait time. All other steps in the protocol supplied by the manufacturer were used without modification. Oxidation of the internucleotide phosphite to the phosphate was carried out using a 0.1 M solution of iodine in 20:1 (v/v) pyridine/water with a 10-min oxidation wait time. The average coupling efficiencies were >97%. To deprotect oligonucleotides containing 2′-deoxy-2′-fluorothymidine and 2′-deoxy-2′-fluoroarabinofuranosylthymine, the solid supports bearing the oligonucleotides were suspended in aqueous ammonia (28–30 mg/100 ml)/ethanol (3:1; 3 ml for 2-μmol scale synthesis) and heated at 55°C for 6 h. For all other modified oligonucleotides after completion of the synthesis, the solid supports bearing the oligonucleotides were suspended in aqueous ammonium hydroxide (28–30 mg/100 ml) and kept at room temperature for 2 h. The solid support was filtered, and the filtrate was heated at 55°C for 6 h to complete the removal of all protecting groups. Crude oligonucleotides were purified on a Waters HPLC C_4 7.8 × 300-mm column (buffer A = 100 mM ammonium acetate, pH 6.5–7; buffer B = acetonitrile; 5–60% of buffer B in 55 min) at a flow rate of 2.5 ml/min ($\lambda_{260\ nm}$). Detritylation was achieved by adjusting the pH of the solution to 3.8 with acetic acid and by keeping at room temperature until complete removal of the trityl group, as monitored by HPLC analysis. The oligonucleotides were then desalted by HPLC to yield modified oligonucleotides in 30 to 40% isolated yield calculated based on the loading of the 3′-base onto the solid support. The oligonucleotides were characterized by electrospray mass spectroscopy, and their purity was assessed by HPLC and capillary gel electrophoresis. The purity of the oligonucleotides was >95%.

Preparation of the Heteroduplex Substrates. Human RNase H1 containing an N-terminal His-tag was expressed and purified as described previously (Lima et al., 2001). The RNA substrate was 5′-end-labeled and purified as described previously (Sambrook et al., 1989; Lima et al., 2001). The specific activity of the labeled oligonucleotide is approximately 3000 to 8000 cpm/fmol. The heteroduplex substrate was prepared in 100 μl containing unlabeled oligoribonucleotide ranging from 100 to 1000 nM, 10^5 cpm of ^{32}P-labeled oligo-

ribonucleotide, 2-fold excess complementary oligodeoxyribonucleotide and hybridization buffer (20 mM Tris, pH 7.5, and 20 mM KCl). Reactions were heated at 90°C for 5 min, cooled to 37°C, and 60 units of Prime RNase Inhibitor (Eppendorf North America, Westbury, NY) and $MgCl_2$ at a final concentration of 1 mM were added. Hybridization reactions were incubated 2 to 16 h at 37°C and 1 mM tris(2-carboxyethyl)phosphine hydrochloride was added.

Multiple-Turnover Kinetics. The human RNase H1 proteins were incubated with dilution buffer (50 mM Tris, 50 mM NaCl, and 100 μM tris(2-carboxyethyl)phosphate, pH 7.5) for 1 h at 24°C. The heteroduplex substrate was prepared in triplicate and each preparation was digested with 0.4 ng of enzyme at 37°C. A 10-μl aliquot of the cleavage reaction was removed at time points ranging from 2 to 120 min and quenched by adding 5 μl of stop solution (8 M urea and 120 mM EDTA). The aliquots were heated at 90°C for 2 min and resolved in a 12% denaturing polyacrylamide gel; the substrate and product bands were quantitated on a PhosphorImager (GE Healthcare, Little Chalfont, Buckinghamshire, UK). The concentration of the converted product was plotted as a function of time. The initial cleavage rate (V_0) was obtained from the slope (moles of RNA cleaved per minute) of the best-fit line for the linear portion of the plot, which comprises, in general <10% of the total reaction and data from at least five time points.

Results

Modified nucleotides were introduced at the MOE-DNA junctions of chimeric oligonucleotides to modulate the conformational transmission of the flanking MOE/RNA regions into the central DNA/RNA region (Fig. 2). The conformationally biased modified nucleotides included the RNA-like northern $C_{3'}$-*endo* locked nucleic acids (LNA), the DNA-like southern $C_{2'}$-*endo* 2′-methylthiothymidine (2′-S-Me-T), and

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC 20 15 10 5 1	1.00
(4-11-5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC	0.96
(5-11-4)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC	1.07
(10)	5′-UCAAAUCCAGAGGCUAGCAG 3′- TAGGTCTCCGA	3.13
α-LNA(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**T**CGTC	0.65
2′-S-Me-T(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**T**CGTC	1.38
2′-ara-F-T(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**T**CGTC	0.97
N-Me-T(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**T**CGTC	0.95
TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**I**CGTC	2.11
α-LNA(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**T**AGGTCTCCGATCGTC	0.80
2′-S-Me-T(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**T**AGGTCTCCGATCGTC	0.95
2′-ara-F-T(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**T**AGGTCTCCGATCGTC	1.41
N-Me-T(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**T**AGGTCTCCGATCGTC	1.45
TFI(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**I**AGGTCTCCGATCGTC	0.97

Fig. 2. Relative human RNase H1 initial cleavage rates and cleavage sites for chimeric heteroduplexes containing the various modified nucleotides at the DNA/MOE junctions. Heteroduplex sequences are shown with the oligoribonucleotide oriented 5′ to 3′ (top sequence) and chimeric ASO 3′ to 5′ (bottom sequence). The modified nucleotides are shown in bold, and the positions within the chimeric heteroduplexes in parentheses from the 5′-termini of the ASO. The underlined sequences represent the positions of the MOE nucleotides. Lines indicate the position of the human RNase H1 cleavages on the heteroduplex substrate. The length of the lines indicates the intensity of the human RNase H1 cleavage band on the polyacrylamide gel for each respective site. Ratio V_0 represents the initial cleavage rates for the heteroduplex containing modified nucleotides at the MOE/DNA junction divided by the 5-10-5 chimeric substrate. The V_0 values are an average of three measurements with estimated errors of CV <5%.

eastern $O_{4'}$-*endo* 2′-ara-fluorothymidine (2′-ara-F-T) (Fig. 1A). The modified nucleotides predicted to introduce comformational flexibility at the MOE-DNA junctions included the 2′-methoxyethyl-*N*-methylthymidine (N-Me-T) and tetrafluoroindole (TFI) (Fig, 1B). The conformationally flexible modifications contain hydrophobic heterocycle bases predicted to Π-stack with adjacent nucleotides but not form hydrogen bonds with the opposing RNA. The modified ASOs were annealed to complementary RNA, and the heteroduplexes were digested with human RNase H1 under multiple-turnover conditions as described under *Materials and Methods*.

The MOE residues negatively affected human RNase H1 activity. For example, the cleavage rates for the chimeric heteroduplexes containing flanking MOE residues (5-10-5, 4-11-5, and 5-11-4) were approximately 3-fold slower than the cleavage rate observed for the heteroduplex without MOE residues (0-10-0) (Fig. 2). Replacing a single MOE residue with a deoxyribonucleotide at the junctions (positions 5 and 16) had no effect because the 4-11-5 and 5-11-4 substrates exhibited cleavage rates similar to that of the 5-10-5 substrate (Fig. 2).

The human RNase H1 cleavage rates for the heteroduplexes containing the junction modifications at the 5′-MOE/3′-DNA junction (position 5) are shown in Fig. 2. The northern-biased LNA at position 5 resulted in a 35% slower cleavage rate compared with the parent 5-10-5 substrate. In contrast, the southern-biased 2′-S-Me-T modification enhanced the cleavage rate. The eastern-biased 2′-ara-F-T modification had no effect on the human RNase H1 activity when substituted at position 5; i.e., comparable cleavage rates were observed for the 2′-ara-F-T heteroduplex and the 5-10-5 substrate. The N-Me-T modification, which does not form hydrogen bonds with the opposing ribonucleotide and is predicted to create a bulge in the heteroduplex, also had no effect on human RNase H1 activity compared with the 5-10-5 substrate. The TFI deoxyribonucleotide, on the other hand, enhanced the human RNase H1 cleavage rate when substituted at position 5 (Fig. 2). This modification also does not form a hydrogen bond with the opposing ribonucleotide but is predicted to Π-stack between the adjacent nucleotides.

Very different results were observed for the same nucleotide modifications positioned at the 5′-DNA/3′-MOE junction (position 16). Again, the northern-biased LNA substitution resulted in slower cleavage rates (Fig. 2). However, the bulge inducing N-Me-T modification as well as the eastern-biased 2′-ara-F-T at position 16 increased the cleavage rate compared with the 5-10-5 substrate, yet both the TFI and 2′-S-Me-T modifications, which resulted in faster cleavage rates when substituted at position 5, had no effect on the cleavage rate at position 16 (Fig. 2). Finally, the overall cleavage rates, as well as the cleavage sites for the 5-10-5, 4-11-5, and 5-11-4 heteroduplexes, were equivalent, demonstrating that simply increasing the length of the DNA portion of the heteroduplex with a modified deoxyribonucleotide substitution at the junction cannot account for the effects induced by the junction modifications (Fig. 2).

The junction modifications affected the cleavage patterns as well as the cleavage rates for the sites nearest the junction modification (Figs. 2 and 3). For example, both the 0-10-0 and 5-10-5 heteroduplexes exhibited two cleavage sites 10 and 12 ribonucleotides from the 5′ terminus of the oligoribonucleotide, although the cleavage rates for these sites were signif-

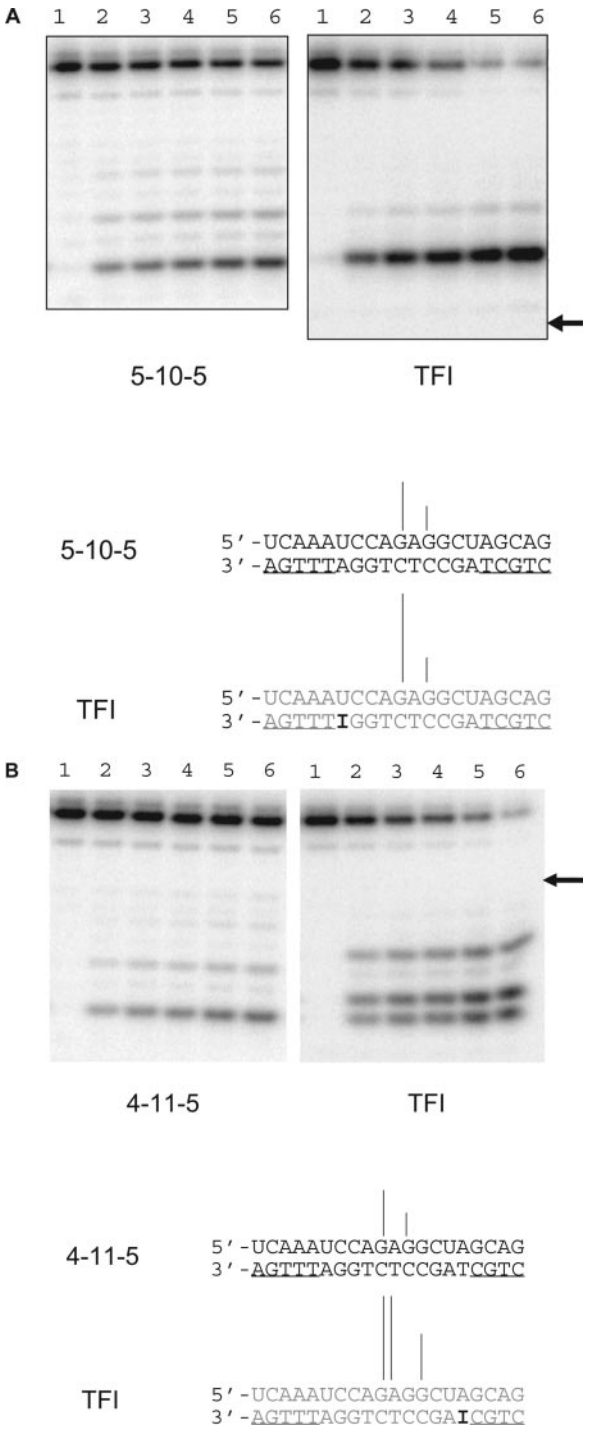


Fig. 3. Human RNase H1 cleavage patterns for chimeric heteroduplex sequences containing TFI deoxyribonucleotides at the MOE/ DNA junctions. A, polyacrylamide gel analysis of the 5-10-5 heteroduplex substrate and 5-10-5 heteroduplex containing and the TFI deoxyribonucleotide at position 15. B, the 4-11-5 heteroduplex substrate and 4-11-5 heteroduplex containing the TFI deoxyribonucleotide at position 5. The substrates were incubated in the absence (lanes 1) and presence of human RNase H1 for 5 (lane 2), 10 (lane 3), 15 (lane 4), 30 (lane 5), and 60 min (lane 6). The arrows indicate the position of the ribonucleotide opposing the TFI modification on the polyacrylamide gel. Heteroduplex sequences are shown with the oligoribonucleotide oriented 5′ to 3′ (top sequence) and chimeric ASO 3′ to 5′ (bottom sequence). The underlined sequences indicate the position of the MOE substitutions and **I** represent the position of the TFI deoxyribonucleotides. Lines indicate the position of the human RNase H1 cleavages on the heteroduplex substrate. The length of the lines indicates the intensity of the human RNase H1 cleavage band on the polyacrylamide gel for each respective site.

icantly slower for the 5-10-5 substrate (Figs. 2 and 3A). Similar cleavage sites were observed for the 4-11-5 and 5-11-4 substrates; again, however, the cleavage rates at these sites were significantly slower compared with the 0-10-0 substrate (Figs. 2 and 3). The slower cleavage rates observed for the LNA substitutions were reflected in the cleavage patterns. In particular, the LNA substitution at position 5 ablated the cleavage activity nearest the modification (ribonucleotide 12) and slowed the cleavage rate at ribonucleotide 10, resulting in a 35% slower overall cleavage rate. The LNA substitution at position 16 reduced the rates of cleavage at both sites but did not ablate cleavage at ribonucleotide 10 (Fig. 2). Conversely, the 2′-S-Me-T substitution at position 5 enhanced the cleavage activity of the nearest cleavage site at ribonucleotide 12. Enhanced cleavage rates were also observed at ribonucleotide 10 for the 2′-ara-F-T and N-Me-T at position 16 (Fig. 2). Finally, the greatest enhancement in RNase H1 activity was observed for TFI modification at position 5, and this substitution produced two new human RNase H1 cleavage sites at ribonucleotides 11 and 13 (Figs. 2 and 3B).

Given that the TFI deoxyribonucleotide showed the greatest improvement in activity compared with the 5-10-5 substrate, the structure induced by this modification was evaluated in more detail. The TFI modification is isosteric with purine deoxyribonucleotides. Therefore, the adenosine ribonucleotide opposing the TFI at position 5 creates a purine-purine base pair, whereas the uridine ribonucleotide opposing the TFI at position 15 creates a pyrimidine-purine base pair. The adenosine ribonucleotide opposing the TFI deoxyribonucleotide at position 5 was substituted with uridine, and the uridine ribonucleotide opposing the TFI deoxyribonucleotide at position 15 was substituted with adenosine (Fig. 4). Neither the uridine substitution opposing the TFI at position 5 [U/TFI (5)] nor the adenosine substitution opposing the TFI at position at position 15 with [A/TFI (15)] had an effect on the cleavage activity (Fig. 4). It is noteworthy that shifting the TFI deoxyribonucleotide from an opposing adenosine ribonucleotide (position 5) to an opposing uridine (position 6) resulted in an approximately 2-fold slower cleavage rate (Fig. 5). In contrast, shifting the TFI deoxyribonucleotide from an opposing adenosine ribonucleotide (position 16) to an opposing uridine (position 15) resulted in an approximately 2-fold faster cleavage rate (Fig. 5). Together, these data suggest that the effects of the TFI deoxyribonucleotide on the human RNase H1 activity seem to depend on the position of the modification within the heteroduplex and not on the heterocycle base of the opposing ribonucleotide.

To better understand how the position of the TFI deoxyribonucleotide within the chimeric heteroduplex influences the affects of the modification on human RNase H1 activity, we substituted the TFI deoxyribonucleotide at various positions within the ASO. In particular, the TFI deoxyribonucleotide was positioned one to five base pairs downstream of the nearest cleavage site at ribonucleotide 12 and two to six base pairs upstream of the nearest cleavage site at ribonucleotide 10 (Fig. 5). The TFI substitutions positioned between the MOE residues and furthest from the human RNase H1 cleavage sites (e.g., TFI at positions 4 and 17) seemed to have no effect on the enzyme activity compared with the 5-10-5 substrate (Fig. 5). These TFI substitutions were positioned five to six base pairs from the nearest human RNase H1 cleavage sites. Furthermore, no effect on enzyme activity was observed for the TFI substitutions at positions 6 and 16, which were positioned at the MOE-DNA junctions and, respectively, 4 and 5 base pairs from the nearest cleavage sites. Conversely, the TFI substitutions at positions 5 and 15, which were also positioned at the MOE-DNA junction and, in this case, three base pairs from the nearest cleavage sites, resulted in an approximate 2-fold improvement in human RNase H1 activity (Fig. 5). A similar improvement in cleavage activity was observed for the TFI substitution at position 14, which was situated two base pairs upstream of the nearest cleavage site and one base pair removed from the MOE-DNA junction. Slower cleavage rates were observed for TFI substitutions at positions 7 and 8, which were two and one base pairs downstream from the nearest cleavage site, respectively, and one and two base pairs away from the MOE-DNA junction, respectively. Finally, the TFI substitution positioned two base pairs downstream of the nearest cleavage site (position 13) had no effect on human RNase H1 activity (Fig. 5). The proximity of the modification to the human RNase H1 cleavage sites clearly had a greater influence on enzyme activity than the juxtaposition of the TFI modification to the MOE residues.

The TFI deoxyribonucleotides are predicted to form stable Π-stacking interactions with the heterocycle bases of the adjacent nucleotides. To evaluate the contribution of the adjacent nucleotides on the effects induced by the TFI deoxyribonucleotides, mismatch base pairs were introduced adjacent to the TFI deoxyribonucleotides (Fig. 6). Mismatch base pairs adjacent to the TFI deoxyribonucleotides seemed to

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC 20 15 10 5 1	1.00
TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**I**CGTC	2.11
U/TFI(5)	5′-UCAAAUCCAGAGGCU**U**GCAG 3′-AGTTTAGGTCTCCGA**I**CGTC	1.88
TFI(15)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTT**I**GGTCTCCGATCGTC	1.93
A/TFI(15)	5′-UCAAA**A**CCAGAGGCUAGCAG 3′-AGTTT**I**GGTCTCCGATCGTC	1.74

Fig. 4. Relative human RNase H1 initial cleavage rates for chimeric heteroduplexes containing point mutations at the ribonucleotides opposing the TFI deoxyribonucleotides. Point mutations and TFI substitutions are shown in bold, and the positions within the heteroduplex in parentheses from the 5′-termini of the ASO. Underlined sequences and ratio V_0 are described in Fig. 2.

negate the influence of the TFI deoxyribonucleotides on human RNase H1 activity. For example, the TFI substitutions at positions 5, 14, and 15 enhanced the cleavage rate approximately 2-fold compared with the 5-10-5 substrate. The introduction of mismatch base pairs adjacent to these substitutions reduced the cleavage rate approximately 2-fold, resulting in cleavage rates comparable with the 5-10-5 substrate heteroduplex without the TFI substitution (Fig. 6). Conversely, the slower cleavage rate observed for the TFI substitution at position 7 was negated with the mismatch base pair at position 6, resulting in a cleavage rate comparable with the 5-10-5 substrate. Finally, although the TFI substitution at position 8 had no effect on the cleavage rate, the introduction of either a C/C or C/A mismatch at position 7 caused a reduction in the cleavage rate (Fig. 6).

To determine whether mismatched base pairs exhibited effects on human RNase H1 similar to those observed for the TFI deoxyribonucleotides, mismatches were introduced at the positions of the TFI substitutions (Fig. 7). Again, the effects of the mismatch base pairs on human RNase H1 activity seemed to be influenced by the position of the mismatch relative to the cleavage sites; in most cases, similar effects on cleavage activity were observed for both the TFI and mismatched base pair substitutions. For example, similar to the TFI substitution at position 4, a G/A or G/G mismatch at this position had no effect on the cleavage activity (Fig. 7A). Similar cleavage activities were also observed for the U/G mismatch and the TFI substitution at position 6 as well as the C/A mismatch and TFI substitution at position 7 (Fig. 7A). Both the C/C and C/T mismatches at position 14 produced a similar 2-fold increase in the cleavage rate as the TFI deoxyribonucleotide at this position (Fig. 7B). It is noteworthy that the A/A mismatches at positions 5, 15, and 16 resulted in slower cleavage rates compared with the TFI substitutions at these positions (Fig. 7).

Discussion

The heteroduplexes containing flanking northern-biased MOE residues (5-10-5, 4-11-5, and 5-11-4) were cleaved significantly more slowly than the heteroduplexes without the MOE substitutions (0-10-0) (Fig. 2). In addition, slower cleavage rates were observed for the cleavage sites closest to the MOE substitutions. Given that A-form duplexes do not support human RNase H1 activity, the solution structures of chimeric heteroduplexes containing RNA-like 2′-modified nucleotides are consistent with these observations (Lima et al., 2004). The solution structures showed that the northern C3-*endo*-biased 2′-modified residues of the chimeric heteroduplexes as well as the adjacent deoxyribonucleotides produced an A-form helical geometry when hybridized to the complementary RNA (Nishizaki et al., 1997). Only the central deoxyribonucleotides exhibited an O4-*endo* sugar pucker, and the characteristic H-form helical geometry of RNA/DNA heteroduplexes (Nishizaki et al., 1997). The effect of the northern-biased modifications on human RNase H1 activity was further supported by the LNAs, which are locked in the northern C3-*endo* pucker and resulted in slower cleavage rates when positioned at the DNA/MOE junctions (Figs. 2 and 8B) (Bondensgaard et al., 2000).

The positional effects of the junction modifications (e.g., position 5 versus 16) are probably due to the binding directionality of the enzyme on the substrate (Fig. 2). In particular, human RNase H1 is predicted to bind the heteroduplex substrate with the RNA-binding domain of the enzyme positioned adjacent to the 5′-DNA/3′-MOE junction (position 16)

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC	1.00
TFI(4)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGAT**I**GTC	1.06
TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**I**CGTC	2.11
TFI(6)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCG**I**TCGTC	1.10
TFI(7)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCC**I**ATCGTC	0.66
TFI(8)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTC**I**GATCGTC	0.78
TFI(17)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGT**I**TAGGTCTCCGATCGTC	1.03
TFI(16)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTT**I**AGGTCTCCGATCGTC	0.97
TFI(15)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTT**I**GGTCTCCGATCGTC	1.93
TFI(14)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTA**I**GTCTCCGATCGTC	2.02
TFI(13)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAG**I**TCTCCGATCGTC	1.09

Fig. 5. Chimeric heteroduplexes containing TFI deoxyribonucleotides at various positions in the chimeric ASO. TFI substitutions are shown in bold, and the positions within the heteroduplex in parentheses from the 5′-termini of the ASO. Underlined sequences and ratio V_0 are described in Fig. 2.

and the catalytic domain positioned adjacent to the 5′-MOE/3′-DNA junction (position 5) (Fig. 8C) (Lima et al., 2003). The RNA-binding domain of human RNase H1 is responsible for proper positioning of the enzyme on the substrate and modifications that disrupt this interaction have been shown to produce a shift in the cleavage pattern (Lima et al., 2003). Given that no shift in the cleavage pattern was observed for the heteroduplexes containing junction modifications closest to the RNA-binding domain (position 16), these results suggest that the junction modifications are affecting changes in the positioning of the enzyme on the substrate (Fig. 2). Instead, the positional effects of the junction modifications are consistent with previous observations in which modified nucleotide substitutions were shown to affect the interactions between the substrate and the catalytic domain of the enzyme (Lima et al., 2004).

The catalytic domain of human RNase H1 shares strong sequence homology with *Bacillus halodurans* RNase H (Wu et al., 1998). The structure of *B. halodurans* RNase H bound to the RNA/DNA heteroduplex indicates that the catalytic domain of the enzyme interacts differently with the nucleotides upstream of the scissile phosphate compared with the nucleotides downstream of the scissile phosphate (Fig. 8C) (Nowotany et al., 2005). For example, downstream of the scissile phosphate, the enzyme interacts exclusively with the RNA strand contacting the phosphates and 2′-hydroxyls, whereas, upstream of the scissile phosphate, the enzyme interacts with both the RNA strand and, via the phosphate-binding pocket, the phosphates and furanose rings of the DNA strand (Fig. 8C). In addition, the enzyme was shown to induce a bend in the DNA strand of the heteroduplex at the phosphate-binding pocket (Nowotany et al., 2005).

Our results are consistent with the observed enzyme induced bend in the heteroduplex (Nowotany et al., 2005). Both the conformationally flexible N-Me-T and TFI modifications positioned adjacent to the phosphate binding pocket (positions 14–16) enhanced RNase H1 activity, although the influence of the N-Me-T modification was observed at a greater distance from the phosphate binding pocket than the TFI modification (Figs. 2, 5 and 8B). This is true probably because N-Me-T induces a greater perturbation in the structure of the substrate. In particular, the TFI modification is predicted to Π-stack with the adjacent nucleotide to form a stable base pair, whereas the methyl group at the N_3 of the N-Me-T modification is predicted to sterically interfere with the heterocycle of the opposing ribonucleotide, prohibiting proper

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGATCGTC	1.00
TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**I**CGTC	2.11
G/A(4), TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**IA**GTC	1.10
G/G(4), TFI(5)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCCGA**IG**GTC	0.94
TFI(7)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCC**I**ATCGTC	0.66
U/G(6), TFI(7)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTCC**IG**TCGTC	1.09
TFI(8)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTC**I**GATCGTC	1.08
C/A(7), TFI(8)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTC**IA**ATCGTC	0.74
C/C(7), TFI(8)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTAGGTCTC**IC**ATCGTC	0.60
TFI(15)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTT**I**GGTCTCCGATCGTC	1.93
C/T(14), TFI(15)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTT**IT**GTCTCCGATCGTC	1.11
C/C(14), TFI(15)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTT**IC**GTCTCCGATCGTC	1.10
TFI(14)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTA**I**GTCTCCGATCGTC	2.02
C/T(13), TFI(14)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTA**IT**TCTCCGATCGTC	1.08
C/C(13), TFI(14)	5′-UCAAAUCCAGAGGCUAGCAG 3′-AGTTTA**IC**TCTCCGATCGTC	0.88

Fig. 6. Relative human RNase H1 initial cleavage rates for chimeric heteroduplexes containing mismatch base pairs adjacent to the TFI deoxyribonucleotides. Point mutations and TFI substitutions are shown in bold and in parentheses within the heteroduplex from the 5′-termini of the ASO. Underlined sequences and ratio V_0 are as described in Fig. 2.

stacking with the adjacent residues (Saenger, 1984; Kool, 2002). The predicted Π-stacking properties of the TFI modification also seem to play an important role in this structure in that mismatched base pairs adjacent to the TFI modification, which presumably disrupt the Π-stacking interaction, resulted in slower cleavage rates (Fig. 6). Introducing conformational flexibility into the substrate seems to be most effective when the modifications are positioned adjacent the phosphate-binding pocket rather than at nucleotides interacting directly with the phosphate-binding pocket (Figs. 5 and 8D). Stable hydrogen bonds also seem to be required downstream of the scissile phosphate because slower cleavage rates were observed for the TFI substitutions at positions 7 and 8 (Figs. 5 and 8D).

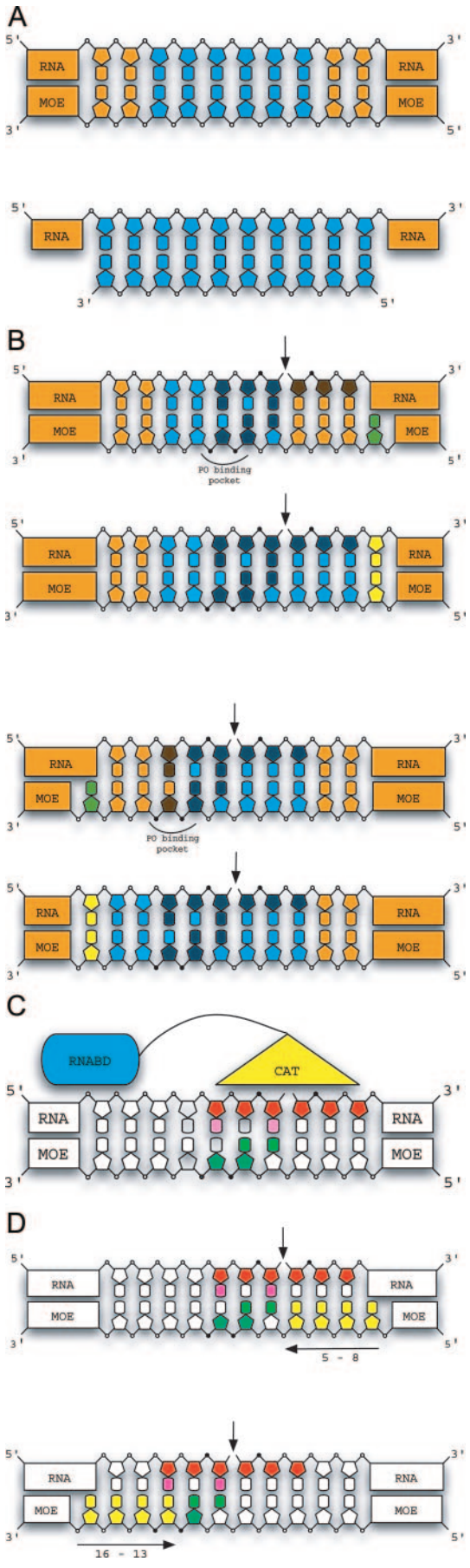
A

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGATCGTC	1.00
TFI(4)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGAT**I**GTC	1.06
G/A(4)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGAT**A**GTC	1.13
G/G(4)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGAT**G**GTC	1.08
TFI(5)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGA**I**CGTC	2.11
A/A(5)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGA**A**CGTC	0.72
U/A(5)	UCAAAUCCAGAGGCU**U**GCAG AGTTTAGGTCTCCGA**A**CGTC	1.05
TFI(6)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCG**I**TCGTC	1.10
U/G(6)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCG**G**TCGTC	0.94
TFI(7)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCC**I**ATCGTC	0.66
C/A(7)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCC**A**ATCGTC	0.70

B

Modification	Heteroduplex	Ratio V_0 (modified/5-10-5)
(5-10-5)	UCAAAUCCAGAGGCUAGCAG AGTTTAGGTCTCCGATCGTC	1.00
TFI(16)	UCAAAUCCAGAGGCUAGCAG AGTT**I**AGGTCTCCGATCGTC	0.97
A/A(16)	UCAAAUCCAGAGGCUAGCAG AGTT**A**AGGTCTCCGATCGTC	0.66
TFI(15)	UCAAAUCCAGAGGCUAGCAG AGTTT**I**GGTCTCCGATCGTC	1.93
A/A(15)	UCAAA**A**CCAGAGGCUAGCAG AGTTT**A**GGTCTCCGATCGTC	1.49
A/U(15)	UCAAA**A**CCAGAGGCUAGCAG AGTTT**U**GGTCTCCGATCGTC	0.91
TFI(14)	UCAAAUCCAGAGGCUAGCAG AGTTTA**I**GTCTCCGATCGTC	2.02
C/T(14)	UCAAAUCCAGAGGCUAGCAG AGTTTA**T**GTCTCCGATCGTC	2.15
C/C(14)	UCAAAUCCAGAGGCUAGCAG AGTTTA**C**GTCTCCGATCGTC	1.90

Fig. 7. Relative human RNase H1 initial cleavage rates for chimeric heteroduplexes containing mismatched base pairs. A, mismatched base pairs positioned at or near the 5′-MOE/3′-DNA jkkunction (positions 4–7). B, mismatched base pairs positioned at or near the 5′-DNA/3′-MOE junction (positions 13–16). Point mutations are shown in bold and in parentheses within the heteroduplex from the 5′-termini of the ASO. Underlined sequences and ratio V_0 are as described in Fig. 2.



Mismatched base pairs seemed to induce a structure similar to the TFI modification. With the exception of the A/A mismatches, similar positional effects on the human RNase H1 activity were observed for both the mismatched base pairs and TFI substitutions (Fig. 7). We were surprised to find that the purine-purine A/A mismatch is isosteric with the TFI/A base pair and was therefore predicted to have a similar effect on human RNase H1 activity (Fig. 1B). Unlike the TFI modification, mismatched base pairs are capable of forming noncanonical hydrogen bonds with the opposing nucleotide (Leontis et al., 2002). These noncanonical hydrogen bonds have been shown to alter the local helical geometry of the duplex, which may account for the difference in cleavage activity between the A/A mismatch and the TFI modifications.

The human RNase H1 activities observed for the junction modifications seemed to be influenced by the MOE residues, because these modifications exhibited significantly different effects on human RNase H1 activity when substituted into substrates containing unmodified DNA (Lima et al., 2004). For example, the southern-biased 2′-S-Me-T modification had previously been shown not to support human RNase H1 activity as a single 2′-S-Me-T substitution in the oligodeoxyribonucleotide of the heteroduplex substrate significantly reduced the human RNase H1 cleavage rate (Lima et al., 2004). In contrast, the 2′-S-Me-T positioned adjacent the MOE modification either enhanced (position 5) or had no effect (position 16) on human RNase H1 activity (Fig. 2). We posited that the reduction in human RNase H1 activity was due to the conformational transmission of the southern-biased 2′-S-Me-T into the adjacent deoxyribonucleotides (Lima et al., 2004). In the case of the chimeric ASO, the northern-biased MOE seems to counteract the conformational transmission of the southern-biased 2′-S-Me-T. When positioned away from the MOE residues, however, the modified nucleotides exhibited effects on human RNase H1 activity similar to those observed for a single modified nucleotide substitution in substrates containing unmodified DNA. For example, the reduction in human RNase H1 activity observed for the

Fig. 8. Model for the interaction of RNase H1 with the chimeric heteroduplex substrate. A, conformational transmission of the MOE residues to the adjacent deoxyribonucleotides. The upper and lower heteroduplexes represent, respectively, the 5-10-5/RNA and 0-10-0/RNA substrates. Heteroduplexes are shown with the RNA strand oriented 5′ to 3′ and chimeric ASO 3′ to 5′. The orange structures represent the C2-*endo* sugar conformation resulting in the A-form helical geometry; the blue structures represent the preferred H-form geometry. B, the putative enzyme/nucleotide interactions for cleavage at ribonucleotides 12 (two upper heteroduplexes) and 10 (two lower heteroduplexes) of chimeric substrates containing cleavage rate enhancing (yellow) and reducing (green) junction modifications. The arrow indicates the positions of the scissile phosphates. The orange and blue structures are as described in A. The brown and dark blue structures indicate the positions of the enzyme interactions with the substrate. C, schematic illustrating the positions of the RNA-binding (RNABD) and catalytic (CAT) domains of human RNase H1 on the chimeric heteroduplex. The red and pink structures indicate the interactions between the enzyme and, respectively, the 2′-hydroxyls and heterocycle bases of the RNA strand. The dark green and light green structures indicate the interactions between the enzyme and, respectively, the deoxyribonucleotide sugars and heterocycle bases of the ASO. The black-filled circles represent the enzyme/phosphate interactions. D, shifting the downstream TFI substitutions (5–8) toward the cleavage site at ribonucleotide 12 (upper heteroduplex) and the upstream TFI substitutions (16–13) toward the cleavage site at ribonucleotide 10 (lower heteroduplex). The arrows and the red, pink, yellow, and green structures are as described in C.

TFI modification positioned one and two nucleotides downstream of the scissile phosphate (positions 7 and 8) was also observed for a single 4-methylbenzimidazole substitution in an unmodified oligodeoxyribonucleotide (Lima et al., 2004). The 4-methylbenzimidazole deoxyribonucleotide is isosteric with TFI and does not form a hydrogen bond with the opposing ribonucleotide (Lima et al., 2004).

Chimeric ASOs containing 2′-alkoxy-modified deoxyribonucleotides offer certain advantages including enhanced hybridization affinity and increased nuclease resistance, leading to longer elimination half-lives in all species and reduced pro-inflammatory effects (for review, see Crooke, 2001). Despite these advantages, chimeric ASO exhibit significantly slower human RNase H1 cleavage rates compared with oligodeoxyribonucleotides (Fig. 2). The results presented here demonstrate that the conformational transmission effects of the northern-biased 2′-alkoxy nucleotides can be modulated with appropriately positioned modified nucleotides and suggest that the incorporation of these modifications into chimeric ASOs should improve the potency of the ASOs. For example, modifications that disrupt base stacking interactions or exhibit an Eastern sugar conformation (e.g., N-Me-T and 2′-ara-F-T) are preferred at the DNA/MOE junction adjacent to the phosphate binding pocket (positions 14–16). On the other hand, modifications exhibiting conformational flexibility or the opposing southern sugar conformation (e.g., TFI and 2′-S-Me-T) are preferred at the DNA/MOE junction adjacent to the ribonucleotides downstream of the scissile phosphate (position 5). The TFI modification can be used to modulate the negative effects of the 2′-alkoxy residues both upstream and downstream of the scissile phosphate, irrespective of the heterocycle of the opposing nucleotide. However, the TFI modification should be positioned adjacent to stable base pairs and not at sites that interact directly with the enzyme (Figs. 6 and 8D). Mismatched base pairs can also be used to enhance the human RNase H1 activity of the chimeric ASOs, although predicting favorable noncanonical base-pair substitutions may prove more difficult than TFI substitutions (Fig. 7). Finally, given that the elimination half-lives and proinflammatory effects of chimeric ASO drugs are determined by the MOE residues, substitution of one or two MOE modifications at the junction should have only modest effects on the properties of these drugs.

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