C5-Amino acid functionalized LNA: positively poised for antisense applications†

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Incorporation of positively charged C5-amino acid functionalized LNA uridines into oligodeoxyribonucleotides (ONs) results in extraordinary RNA affinity, binding specificity and stability towards 3′-exonucleases.

Modulation of gene expression by antisense-based approaches continues to stimulate the development of novel chemically modified nucleotides in search of oligonucleotides with improved RNA affinity, binding specificity, and pharmacokinetic profiles. Of the many modifications studied for antisense applications, conformationally restricted nucleotides, and locked nucleic acid (LNA) in particular, have emerged as particularly promising chemistries toward this end. Over the past 15 years, major efforts have been devoted to increase the chemical diversity of LNA nucleotides through additional modification of the sugar ring, with the aim of improving properties for antisense applications. Modification of the nucleobase of LNA, on the other hand, is an underexplored strategy for optimization of pharmacodynamic and pharmacokinetic properties.

Modification of the C5-position of pyrimidines is particularly interesting due to synthetic feasibility and functional group tolerance, as attached moieties are directed into the major groove with minimal perturbation of the duplex structure. We have previously shown that attachment of small hydrophilic moieties to the C5-position of LNA uridine (U) such as 3-aminopropyn-1-yl promotes even greater target affinity than canonical LNA, while attachment of large hydrophobic substituents such as cholesterol confers complete stability against exonucleases, albeit at the expense of decreased target affinity. At the onset of the present study, we hypothesized that hydrophilic moieties of intermediate size would contribute to both additionally improved affinity and nuclease stability. Furthermore, positively charged moieties often improve cellular uptake through electrostatic interactions. Amino acids are a class of molecules that fit the size, hydrophilicity and charge criteria. Driven by the desire to exploit the properties of both LNA and basic amino acid residues, we report the synthesis of three C5-amino acid functionalized LNA-U phosphoramidites and the biophysical characterization of ONs modified with these units.

Synthesis of phosphoramidites 4x/y/z initiates from known nucleoside 1 (Scheme 1). Deprotection of the trifluoroacetamide (TFA) group using saturated methanolic ammonia reveals the aminopropynyl group at the C5-position of 2 in 97% yield. TSTU-mediated coupling of TFA-protected glycine, leucine or lysine gives 3x/y/z in moderate yields (48–58%). Subsequent O3′-phosphitylation affords phosphoramidites 4x/y/z, which were used for incorporation of monomers X/Y/Z into ONs by automated DNA solid-phase synthesis (15 min, 4,5-dicyanoimidazole as activator, average coupling yield > 90%). The composition and

Scheme 1: Reagents and conditions: (i) sat. NH4OH/MeOH (97%); (ii) TFA-protected amino acid, N,N′,N″,N‴-tetramethyl-O--(N-succinimidyl)uronium tetrifuoroborate (TSTU), N,N-diisopropylethylamine (DIPEA), DMF (48–58%); (iii) 2-cyanoethyl N,N-diisopropylchlorophosphoramidite, DIPEA, CH2Cl2 (37–64%); (iv) DNA synthesis. DMTr = 4,4′-dimethoxytrityl.
purifi...y of all modified ONs was ascertained by MALDI-MS analysis (Table S1, ESIF) and ion-pair reversed-phase HPLC, respectively.

ONs modified with C5-amino acid functionalized LNA-U monomers X/Y/Z display higher affinity toward complementary RNA than ONs modified with canonical LNA thymidine (monomer L) (Table 1). Incorporation of glycine-conjugated monomer X consistently increases the thermal denaturation temperatures ($T_m$’s) of 9-mer mixed-sequence model duplexes by 10–11 °C, while leucine-conjugated monomer Y results in slightly less thermostable duplexes ($\Delta T_m = +7.0$ to $+10.5$ °C). ONs containing lysine-conjugated monomer Z display the highest RNA affinity in this series ($\Delta T_m = +11.0$ to $+14.0$ ℃). In fact, Z is as affinity-enhancing as C5-aminopropyl LNA-U (monomer N). Similar trends are observed towards DNA targets, although slightly less pronounced stabilization is observed (Table S2, ESIF).

Thermodynamic parameters for duplex formation were determined from denaturation curves through curve fitting (Table S3, ESIF). Changes in free energy ($\Delta G$) follow similar trends as $T_m$’s. Thus, ONs containing monomers X/Y/Z show greater affinity toward RNA than DNA targets (RNA: $\Delta G_{0}^{298}$ = −8 to −23 kJ mol$^{-1}$; DNA: $\Delta G_{0}^{298}$ = −5 to −17 kJ mol$^{-1}$), and greater target affinity than ONs modified with LNA-T. The additional stabilization provided by the C5-amino acid functionalized LNA monomers is a result of more favorable enthalpy. This is likely due to extended π-conjugation of the nucleobase and improved stacking within the duplex, as well as electrostatic screening of the negatively charged duplex by protonated amino acid residues. The latter is a reasonable assumption considering that the $pK_a$ for z-amino groups of free amino acids and the ε-amino group of lysine is $>9.16$ and $10.67$, respectively.

To study in greater detail just protonation of the amino acid residues of monomers X/Y/Z contributes to duplex stabilization, thermal denaturation profiles were recorded in buffers of decreasing ionic strength (110, 40, and 10 mM sodium phosphate buffer). As expected, lower absolute $T_m$’s are observed at low ionic strengths due to decreased electrostatic shielding of the two negatively charged duplex strands (Tables S4 and S5, ESIF). Interestingly, ONs modified with monomers X/Y/Z show greater relative affinity increases toward RNA and DNA targets at lower ionic strengths as evidenced by the trend in $\Delta T_m$’s (Fig. 1 and Fig. S2, ESIF). For example, the $\Delta T_m$ for the duplex between lysine-modified Z and complementary RNA is 12.5 °C and 18.0 °C at [Na+] = 110 mM and 10 mM, respectively (Table S4, ESIF). These effects are much weaker for LNA-modified ONs (L1–L4), which strongly suggests that the C5-amino acid moieties of monomers X/Y/Z indeed are protonated and contribute to duplex stability.

The specificity of ONs modified with C5-amino acid-functionalized LNA-U monomers X/Y/Z was evaluated by measuring the $T_m$’s of duplexes between modified ONs and RNA or DNA containing a mismatched nucleotide either directly across from the central modification (B1-series) or 2′-deoxyadenosine (B2-series). Just like LNA-T/1 (L1) or C5-aminopropyl modified (N1), X1/Y1/Z1 show comparable or improved discrimination of mismatched RNA and DNA relative to D1 (Table 2 and Table S6, ESIF). Discrimination of the challenging T/U-G mismatch is particularly effective. Doubly modified X4/Y4/Z4 also discriminate mismatched RNA targets well, whereas discrimination of mismatched DNA targets is far less efficient (Table S7, ESIF). The latter may be a result of stabilizing non-specific electrostatic interactions occurring in DNA duplexes.

ONs with C5-amino acid functionalized LNA-U monomers positioned close to the 3′-terminus (X2/Y2/Z2) were evaluated for nuclease stability using snake venom phosphodiesterase (SVLPDE), a 3′-exonuclease (Fig. 2). As expected, unmodified DNA (D2) is completely cleaved within 40 min. Incorporation of a single LNA-T (L2) still results in complete digestion, although at a significantly slower rate. Satisfyingly, X2/Y2/Z2 were completely stable to SVLPDE once degradation of the 2–3 terminal 2′-deoxyribonucleotides.

Table 1: $T_m$’s of duplexes between B1–B4-series and complementary RNA

| ON Sequence | $\Delta T_m$/mod |
|-------------|-----------------|
| B1 | L | B | N | X | Y | Z |
| 5′-GTG ABA TGC | +8.5 | +13.0 | +10.5 | +9.5 | +12.5 |
| 3′-CAG CAT ACG | +5.5 | +10.0 | +10.5 | +11.0 |
| 3′-CAG TAB ACG | +8.5 | +12.5 | +10.0 | +7.0 | +14.0 |
| 3′-CAG BAB ACG | +7.5 | +11.0 | +10.8 | +9.3 | +13.0 |

$\Delta T_m$/mod = change in $T_m$ per modification relative to unmodified reference duplex (R1: R2 or D1: D2 both $T_m = 28.0$ °C; R1: 5′-GUG AUA UGC; R2: 3′-CAG UAU ACG; $T_m$’s determined as the maximum of the first derivative of the melting curve ($A_{260}$ vs. $T$) recorded in medium salt phosphate buffer ([Na+] = 110 mM, [Cl−] = 100 mM, pH 7.0 (NaH₂PO₄/Na₂HPO₄)), using 1.0 μM of each strand. Monomer L = LNA-T. Monomer N = C5-(3-aminopropyl-1-yl)-LNA-U. Previously reported.7

Table 2: Thermal discrimination of mismatched RNA targets by B1-series

| ON Sequence | RNA: 3′-CAC UMU ACG |
|-------------|---------------------|
| M = A | $T_m$ (°C) | $\Delta T_m$ (°C) |
| D1 | 5′-GTG ATA TGC | 28.0 | −18.0 | −5.5 | <−18.0 |
| L1 | 5′-GTG ALA TGC | 36.5 | −20.0 | −9.0 | <−19.5 |
| N1 | 5′-GTG ANA TGC | 41.0 | −18.5 | −11.5 | −22.5 |
| X1 | 5′-GTG AXA TGC | 38.5 | −17.0 | −11.5 | <−19.0 |
| Y1 | 5′-GTG AYA TGC | 37.5 | −16.0 | −9.0 | <−19.0 |
| Z1 | 5′-GTG AZA TGC | 40.5 | −17.0 | −11.5 | <−19.0 |

$\Delta T_m$ = change in $T_m$ relative to fully matched B1:R2 duplex (M = A) shown in bold. Previously reported.7
had ceased, as evidenced by the plateau in their degradation profiles.

Encouraged by these results, we designed a fully phosphorothioated 3'-exonuclease (SVPDE) performed in magnesium buffer (50 mM Tris- HCl, 10 mM MgCl2, pH 9.0) by using 3.3 μM ONs and 0.52 μg (0.03 U) of SVPDE at 37 °C. Degree of ON cleavage calculated as the change in absorbance at 260 nm with respect to unmodified DNA [(A260(B2) – A260,initial(B2))/A260,final(D2) – A260,initial(D2)].

In summary, C5-amino acid functionalized LNA uridine phosphorodiamidites represent a novel approach to chemical diversification of LNA. ONs containing monomers X/Y/Z display significantly higher affinity toward complementary RNA than canonical LNA ONs due to extended conjugation of the nucleobase, as well as stabilizing electrostatic interactions. The excellent specificity of LNA modified ONs towards singly mismatched C5-LNA-U monomers.

The promising biological properties and cationic character render C5-amino acid functionalized LNA positively poised for antisense applications.

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Notes and references
‡ For an alternative synthesis of compound 2, see ESI.†
§ Coupling between 5′-protected amino acids and 2 was unsuccessful.

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