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Expanding Biohybrid-mediated Asymmetric Catalysis into the Realm of RNA

Nicolas Duchemin,^a Erica Benedetti,^a Lucas Bethge,^b Stefan Vonhoff,^b Sven Klussmann,^b Jean-Jacques Vasseur,^c Janine Cossy,^a Michael Smietana^{*,c} and Stellios Arseniyadis^{*,a,d}

The recent development of biohybrid catalytic systems has allowed synthetic chemists to reach high levels of selectivity on a wide variety of valuable synthetic transformations. In this context, DNA-based catalysts have emerged as particularly appealing tools. Interestingly, while long RNA sequences (ribozymes) are known to catalyze specific biochemical reactions with remarkable efficiencies, RNA-based catalysts in-volving a catalytically active metal complex interacting in a non-covalent fashion with short sequences have never been evaluated to date. We report here our results, which have led to the first example involving a short RNA-based catalyst.

Ten years ago, Roelfes and Feringa published the first article pertaining to the use of double-stranded DNA (dsDNA) as a stereochemical control element in a Diels-Alder reaction.¹ Distinct from artificial DNAzyme approaches obtained through the systematic evolution of ligands by exponential enrichment processes (SELEX),² this landmark was received with a lot of enthusiasm from scientists working in the field of asymmetric artificial biohybrid-mediated catalysis who, along with the initial authors, extended the concept to several other reactions including asymmetric Michael additions, Friedel–Crafts alkylations as well as fluorinations and cyclopropanations.³ In the past few years, many studies have aimed at deciphering structural rationalizations and understanding the main parameters that control the stereochemical outcome of a given DNA-based asymmetric transformation.⁴ Our group recently joined this journey by showing that dsDNA made from L nucleotides instead of the natural occurring D nucleotides could be used to control the selectivity outcome of a reaction and thus allow a trivial and reliable access to both enantiomers.⁵ Following this study, we also reported the first generation of a DNA-based catalyst bound to a cellulose matrix capable of achieving high levels of selectivity on various Cu(II)-catalyzed asymmetric transformations under continuous-flow conditions,^{6a} as well as new anchoring strategy based on the use of minor groove binders.^{6b} These results prompted many interrogations regarding the use of ribonucleic acid (RNA) in asymmetric metal-catalyzed reactions. Indeed, compared to dsDNAs, dsRNAs exhibit certain structural differences such as a wide and shallow minor groove associated with a deep and narrow major groove with 11 base pairs per turn versus 10 in the case of dsDNA (Figure 1). In addition, dsRNAs bear an additional 2'-OH group which increases their thermal stability by locking the duplex into a compact A-form helix.⁷

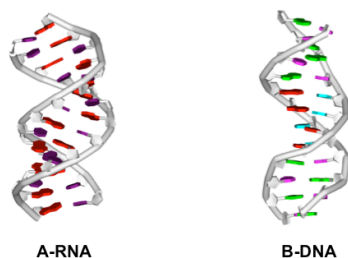


Figure 1. Structural features of right-handed A-RNA and B-DNA.

While it is well known that naturally occurring ribozymes, which are large folded RNA platforms, catalyze cleavage and juncture of internucleosidic linkages through metal-ion interactions,⁸ artificial ribozymes have also been shown to catalyze various synthetic transformations including Diels-Alders,⁹ Michael additions¹⁰ aldol condensations,¹¹ aminoacylations¹² and peptide bond-forming reactions.¹³ The oxidation of tyramine to the corresponding tyramine dimer using a cyclic dinucleotide riboswitch fused with a G-quadruplex motif has also been recently reported.¹⁴ Interestingly however, except for a few examples,^{9f,15} most of these *in vitro*-evolved ribozymes require at least one of the reactant to be covalently attached to RNA. Moreover, while the importance of specific cations, such as Mg²⁺ ions in the case of Diels-Alderase ribozymes, has been demonstrated,¹⁶ Cu²⁺ ions were shown to be ineffective.^{9c} Finally, catalytically active mirror-image ribozymes (Spiegelzymes), which are resistant to nuclease degradation,¹⁷ have also been described by Jäschke¹⁸ and Erdmann.¹⁹

Considering these points and following our previous work pertaining to the use of L-dsDNA in the context of metal-based asymmetric catalysis, we became interested in the potential use of short and defined synthetic L-oligoribonucleotides (L-dsRNA) that lack a catalytically active binding pocket.²⁰ Indeed, in contrast with the ribozyme approach, the chiral induction would here result from a non-covalent anchorage of the catalytically active metal complex into the chiral microenvironment provided by the RNA helix. We report here the results of our endeavor, which have led to the first example of an asymmetric Friedel-Crafts alkylation using an RNA-based hybrid catalyst.

Table 3. Friedel–Crafts alkylations with dsRNA

Entry	Product	Conversion ^a (%)	ee ^a (%)
1		>99	(–) 54
2		>99	(–) 40
3		>99	(–) 30
4		>99	(–) 38
5		93	(–) 10
6		70	(–) 14

Conditions: 2 mM base pair solution of RNA in a 20 mM MOPS solution (400 μ L; pH 6.5), 0.3 mM of $\text{Cu}(\text{dmbpy})(\text{NO}_3)_2$ in a 20 mM MOPS solution (200 mL), 0.5 M solution of enone in CH_3CN (1.2 μ L), 2.5 M solution of indole in CH_3CN (1.2 μ L), 1 d, 5 $^\circ\text{C}$. ^a Determined by chiral SFC analysis.

With this set of conditions in hand,²⁴ we next undertook to explore the substrate scope of the reaction. The results are depicted in Table 3. Hence, in sharp contrast with previously reported data obtained with dsDNA sequences, enones containing an aliphatic substituent were found to be better tolerated than the ones bearing an aromatic group.⁵ As π - π interactions between the substrates and RNA bases may induce some distortion, this might explain this observation though more studies need to be undertaken in order to fully understand and tame this new type of bio-hybrid catalytic system.

In summary, this study represents the first example of an asymmetric Friedel–Crafts alkylation using an RNA-based bio-hybrid catalyst. Though modest, the enantioselectivities observed are a manifest proof of concept that small RNA sequences can be used to control the enantioselective outcome of a given reaction. These results show tremendous promise and underline the many different requirements regarding RNA sequences and folding compared to their ribozymes analogues. A precise understanding of the governing factors is now needed to rationalize and tune the RNA chiral environment into a competitive chiral scaffold.

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Notes and references

^a Laboratoire de Chimie Organique, Institute of Chemistry, Biology and Innovation (CBI) - ESPCI ParisTech/CNRS (UMR8231)/PSL* Research University, 10 rue Vauquelin, 75231 Paris Cedex 05, France

^b NOXXON Pharma AG. Max-Dohrn-Strasse 8–10, 10589 Berlin, Germany.

^c Institut des Biomolécules Max Mousseron, UMR 5247 CNRS, Université de Montpellier, ENSCM Place Eugène Bataillon, 34095 Montpellier, France. E-mail: michael.smietana@umontpellier.fr

^d School of Biological and Chemical Sciences, Queen Mary University of London, Joseph Priestley Building, Mile End Road, London E1 4NS, United Kingdom. E-mail: s.arseniyadis@qmul.ac.uk

† Electronic Supplementary Information (ESI) available: Details of experimental procedures, ¹H NMR and ¹³C NMR spectra as well as SFC chromatograms. See DOI: 10.1039/c000000x/

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- 24 **General procedure for the RNA-catalysed Friedel-Crafts alkylation.** To a 3 mM base pair solution of the desired RNA sequence in a 20 mM MOPS buffer (400 μ L) was added a 0.9 mM solution of [Cu(dmbpy)(NO₃)₂] in a 20 mM MOPS buffer (200 μ L). The resulting solution (2 mM base pair, 600 μ L) was cooled to 5 °C. To the cold mixture was added a 0.5 M solution of enone in MeCN (1.2 μ L), followed by a 2.5 M solution of substituted indole in MeCN (1.2 μ L). The reaction was mixed by inversion at 5 °C in a cold room. After 1 d, the mixture was warmed to rt and extracted with Et₂O (3 x 2 mL). The combined organic layers were washed with brine (2 mL), dried over Na₂SO₄, filtered through a plug of silica gel and concentrated under reduced pressure, to give the crude product which was subjected to SFC analysis without further purification.