



Cite this: *Org. Biomol. Chem.*, 2016,
14, 10018

Received 31st August 2016,
Accepted 29th September 2016
DOI: 10.1039/c6ob01917j
www.rsc.org/obc

Copper-mediated arylsulfanylations and arylselanylations of pyrimidine or 7-deazapurine nucleosides and nucleotides†

Filip Botha,^{‡,a} Michaela Slavíčková,^a Radek Pohl^a and Michal Hocek^{*a,b}

The syntheses of 5-arylsulfanyl- or 5-arylselanylpyrimidine and 7-arylsulfanyl- or 7-arylselanyl-7-deazapurine nucleosides and nucleotides were developed by the Cu-mediated sulfanylations or selanylations of the corresponding 5-iodopyrimidine or 7-iodo-7-deazapurine nucleosides or nucleotides with diaryl disulfides or -diselenides. The reactions were also applicable for direct modifications of 2'-deoxycytidine triphosphate and the resulting 5-arylsulfanyl or 5-arylselanyl-dCTP served as substrates for the polymerase synthesis of modified DNA bearing arylsulfanyl or arylselanyl groups in the major groove.

Introduction

DNA molecules bearing modifications in the major groove have found diverse applications mainly in bioanalysis and chemical biology.¹ 5-Substituted pyrimidine and 7-substituted 7-deazapurine 2'-deoxyribonucleoside 5'-O-triphosphates (dNTPs) are good substrates for DNA polymerases in the enzymatic synthesis of base-modified DNA.^{2,3} Modified dNTPs are mostly synthesized by the triphosphorylation of the corresponding modified nucleosides⁴ but this approach can fail in the case of some reactive modifications not compatible with the triphosphorylation methodology. Therefore, direct methods of functionalization of dNTPs are desirable but are inherently difficult due to the lability of dNTPs which are prone to hydrolysis. So far, the only reported reactions suitable for modification of dNTPs have been the aqueous cross-coupling reactions of halogenated dNTPs,^{3,5} thiol-maleimide addition,⁶ some amide-forming reactions of 5-aminoalkyl-ethynyl-dUTP,⁷ hydrazone-formation,⁸ Diels-Alder⁹ and the CuAAC click reaction.¹⁰ The Suzuki-Miyaura cross-coupling reaction with arylboronic acids¹¹ and the Sonogashira reactions with terminal acetylenes¹² are the most general and useful reactions used in the synthesis of base-modified dNTPs. In addition, several examples of the Heck coupling¹³ with acrylates, as well

as the Stille reaction¹⁴ with aryl- or alkenylstannanes were recently reported. To the best of our knowledge, no method for direct attachment of a heteroatom to dNTPs has been published.

5-Alkylsulfanyl- or arylsulfanyl-pyrimidine nucleosides were reported to inhibit thymidylate kinase¹⁵ and slightly destabilized DNA duplexes,¹⁶ whereas saturated 5-phenylsulfanyl-thymidine analogues were used¹⁷ as radical precursors for photochemical generation of thymine in DNA. Some 7-arylsulfanyl-7-deazaadenosine analogues displayed¹⁸ weak cytostatic effects, while the corresponding 7-S-substituted 7-deazaguanine derivatives have never been reported. 5-Selenylated pyrimidine nucleotides inhibit thymidylate synthase¹⁹ and have been utilized²⁰ for modification of DNA or RNA for X-ray crystallography and 5-(phenylselenylmethyl)uracil was used²¹ as a T radical precursor for DNA crosslinking. Also the related 5-(phenyltelluranyl)uracil nucleoside has been prepared²² and, after incorporation into DNA, it was used for X-ray and STM imaging. However, no selenylated 7-deazapurines have been known so far. Therefore, we report here the synthesis of the arylsulfanyl and arylselanyl derivatives of pyrimidine and 7-deazapurine nucleosides and nucleotides and their potential for polymerase incorporation into DNA.

Results and discussion

Synthesis

Previously, 5-(alkylsulfanyl)pyrimidine bases or nucleosides were prepared by alkylation of 5-mercaptopuracil,²³ reactions of toxic 5-(chloromercuri)pyrimidines with disulfides,²⁴ or more recently by Pd-catalyzed coupling of 5-bromopyrimidine

^aInstitute of Organic Chemistry and Biochemistry, Academy of Science Czech Republic, Gilead Sciences and IOCB Research Center, Flemingovo nám. 2, 16610 Prague 6, Czech Republic. E-mail: hocek@uochb.cas.cz

^bDepartment of Organic Chemistry, Faculty of Science, Charles University in Prague, Hlavova 8, 12843 Prague 2, Czech Republic

† Electronic supplementary information (ESI) available: Experimental part, and copies of spectra. See DOI: 10.1039/c6ob01917j

‡ Passed away on July 11, 2016.



derivatives with thiols,²⁵ whereas 7-arylsulfanyl-7-deazapurines were prepared by Cu-mediated S-H sulfenylation.¹⁸ The 5-selenylated pyrimidines were prepared by Mn-mediated C-H selenylations²⁰ or electrophilic aromatic selenylation.²⁶

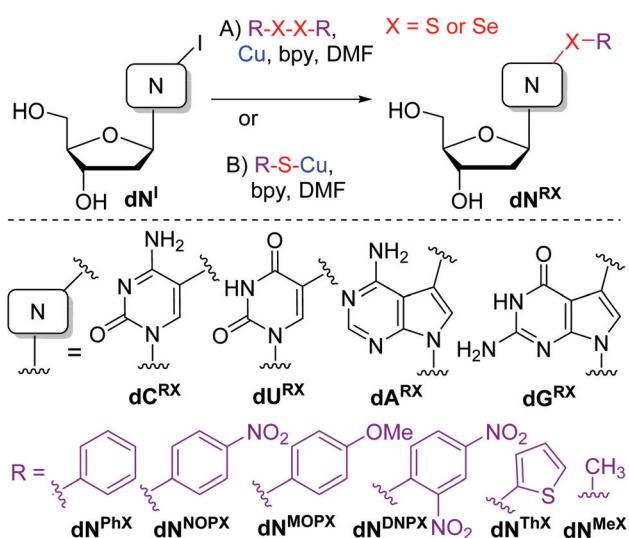
Inspired by the work of Taniguchi²⁷ on the copper-catalyzed reactions of diaryldisulfides or diaryldiselenides with iodoarenes, we started our study by testing the reactions of unprotected halogenated nucleosides.⁵ The reaction conditions were first tested on 5-iodo-2'-deoxycytidine (**dC^I**) in reaction with diphenyldisulfide. The Cu-catalyzed (10 mol% of CuI) reactions in the presence or absence of Mg²⁷ gave complex mixtures of products. Therefore, we used stoichiometric amounts of copper powder in the presence of 2,2'-bipyridine (bpy). The reactions were performed at 80–110 °C in DMF (Scheme 1). Under these conditions (Method A), the desired 5-phenylsulfanyl-2'-deoxycytidine was formed as the major product (in addition to small amounts of dehalogenated 2'-deoxycytidine) and isolated in a good yield of 58%. A similar conversion and yield were achieved when using pre-generated phenylsulfanyl-cuprate (Method B).

The same reaction of nucleoside **dC^I** (Method A) was then performed with a small series of diaryldisulfides to obtain the corresponding 5-(4-nitrophenyl)sulfanyl (**dC^{NOPS}**), 5-(4-meth-

oxyphenyl)sulfanyl (**dC^{MOPS}**), 5-(2,4-dinitrophenyl)sulfanyl (**dC^{DNPS}**) and 5-(2-thienylsulfanyl) (**dC^{ThS}**) 2'-deoxycytidines in moderate yields (21–50%). The reaction (Method A) with diphenyldiselenide gave the 5-(phenylselanyl)cytosine nucleoside **dC^{PhSe}** in good 50% yield, whereas the corresponding 5-(methylselanyl)C nucleoside **dC^{MeSe}** was only obtained in low 18% yield.

Then we tested other iodinated nucleosides (Scheme 1). The reaction of 5-iodo-2'-deoxyuridine (**dU^I**) with PhSCu (Method B) provided the 5-substituted **dU^{PhS}** nucleoside in 47% yield, whereas the reactions with dithienyldisulfide or diselenides (Method A) gave the other corresponding 5-arylsulfanyl- or phenyl- or methylselanyl uracil nucleosides (**dU^{ThS}**, **dU^{PhSe}** and **dU^{MeSe}**) in low yields. The reactions of 7-iodo-7-deazaadenine (**dA^I**) and -7-deazaguanine (**dG^I**) nucleosides with PhSCu (Method B) gave the 7-(phenylsulfanyl)deazapurine nucleosides **dA^{PhS}** and **dG^{PhS}** in acceptable 50 or 39% yields, whereas the reactions with diphenyldiselenide furnished the corresponding phenylselanyl nucleosides **dA^{PhSe}** and **dG^{PhSe}** in moderate yields. Again, the reaction with dimethyldiselenide gave very low conversion and **dA^{MeSe}** was isolated only in 14% yield. Apparently the reactivity of dimethyldiselenide is very low and the methylsulfanylation is of very limited synthetic applicability.

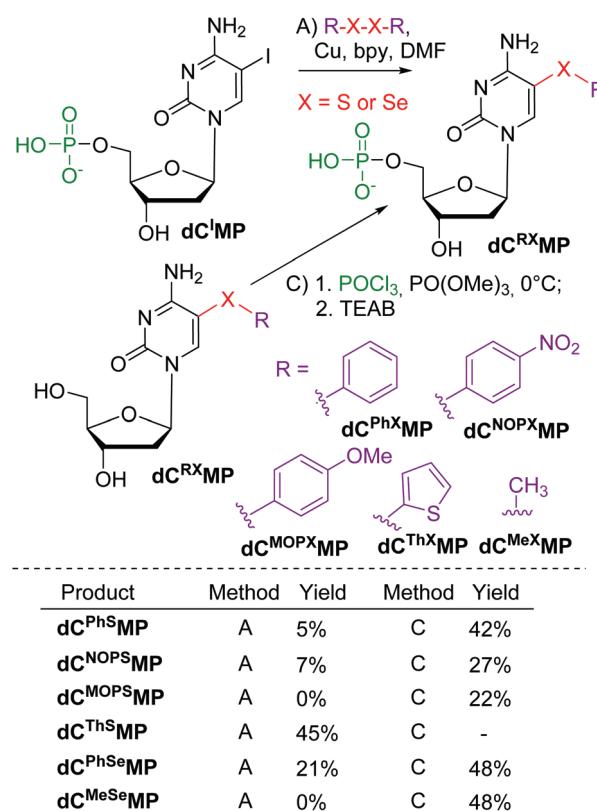
Next, we tested the reactions of nucleotides and started with stable nucleoside 5'-O-monophosphates (dNMPs). The model iodinated **dC^IMP** was tested in reactions with diaryldisulfides or diselenides (Scheme 2, Method A). Most of these



Product	Method	Yield
dC^{PhS}	A	58%
dC^{PhS}	B	56%
dC^{NOPS}	A	50%
dC^{MOPS}	A	21%
dC^{DNPS}	A	28%
dC^{ThS}	A	46%
dC^{PhSe}	A	50%
dC^{MeSe}	A	18%

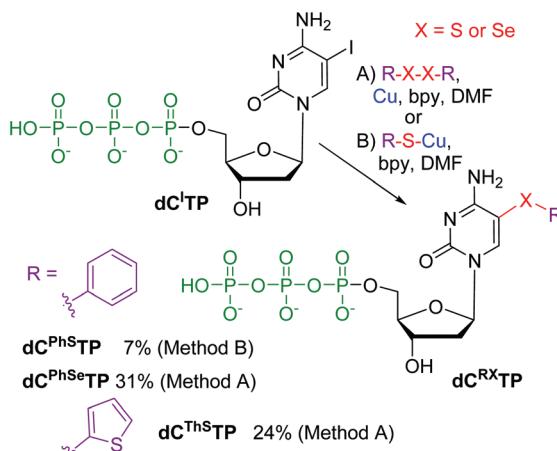
Product	Method	Yield
dU^{PhS}	B	47%
dU^{ThS}	A	26%
dU^{PhSe}	A	24%
dU^{MeSe}	A	11%
dA^{PhS}	B	50%
dA^{PhSe}	A	32%
dA^{MeSe}	A	14%
dG^{PhS}	B	39%
dG^{PhSe}	A	45%

Scheme 1 Sulfanylations and selanylations of nucleosides.



Scheme 2 Sulfanylations and selanylations of **dC^IMP**.





Scheme 3 Sulfanylations and selanylations of dNTPs.

reactions gave very low conversions and only two products, **dC^{Ths}MP** and **dC^{PhSe}MP**, were isolated in acceptable yields. On the other hand, the phosphorylation of the 5-arylsulfanyl- or arylselanyl-cytosine nucleosides gave the desired modified nucleotides in better yields (22–48%).

Finally, we tested the reactions for direct modification of hydrolytically labile dNTPs (Scheme 3). Thus the iodinated triphosphate **dC^ITP** was reacted with PhSCu (Method B) to give the desired 5-(phenylsulfanyl)-dCTP (**dC^{Phs}TP**) in low 7% yield. Better conversions were achieved when using reactions with diaryldisulfides or diselenides (Method A). The desired **dC^{Ths}TP** and **dC^{PhSe}TP** were obtained in good yields of 24 and 31% (which are fully comparable to the typical yields of the cross-coupling reactions of dNTPs^{11–14}).

Polymerase incorporation of modified nucleotides

The three new 5-S- or Se-linked dNTPs (**dC^{Phs}TP**, **dC^{Ths}TP** and **dC^{PhSe}TP**) were then tested as substrates for DNA polymerases. At first we tested them in a primer extension (PEX) reaction with KOD XL, Vent(exo-) or Pwo polymerases, 15-mer primer^{248-sh} and a 19-mer template **temp^{oligo1C}** (for sequences, see Table 1). Fig. 1 shows the PAGE analysis of the PEX reactions. While KOD XL and Vent(exo-) polymerases gave quite clean bands of the 19-mer oligonucleotide (ON) products bearing one modified **dC^{RX}** nucleotide, Pwo gave a mixture of the full-lengths and a truncated product.

Then we tested the same nucleotides (**dC^{Phs}TP**, **dC^{Ths}TP** and **dC^{PhSe}TP**) in a more challenging PEX reaction using a

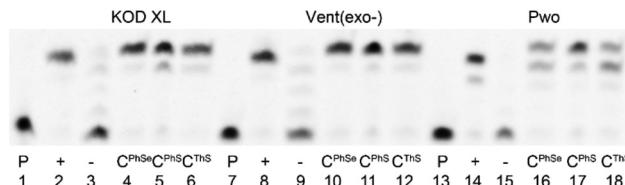


Fig. 1 PEX reactions with **temp^{oligo1C}** using KOD XL, Vent(exo-) or Pwo polymerase. Lanes 1,7,13, P: primer; +: products of PEX with natural dNTPs; -: products of PEX with dTTP, dATP, dGTP; lanes 4–6, 10–12 and 16–18, **C^{RX}**: products of PEX with dTTP, dATP, dGTP and functionalized **dC^{RX}TP**.

31-mer template **temp^{Prb4baseII}** (Fig. 2). This PEX reaction leads to a 31-mer DNA containing four modified **dC^{RX}** nucleotides. KOD XL was found to be the best polymerase which gave clean full-length products in all three cases, whereas the other two enzymes gave less clean products containing minor amounts of truncated products. The PEX products were characterized by MALDI-TOF analysis (Table 2).

Finally, we tested the nucleotides (**dC^{Phs}TP**, **dC^{Ths}TP** and **dC^{PhSe}TP**) in PCR amplification using a 98-mer template (**temp^{FLV-A}**). Fig. 3 shows that all three dNTPs were good substrates of KOD XL polymerase in PCR reaction and gave the corresponding full-length amplified products (double-stranded DNA with modification in both strands). The yield of PCR with **dC^{PhSe}TP** was further improved by the addition of Mg^{2+} or a

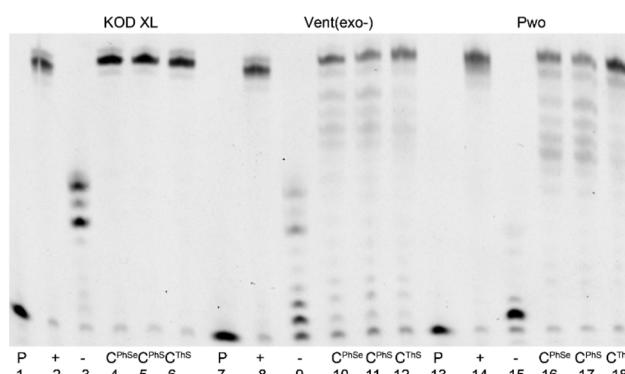


Fig. 2 PEX reactions with **temp^{Prb4baseII}** using KOD XL, Vent(exo-) or Pwo polymerase. Lanes 1,7,13, P: primer; +: products of PEX with natural dNTPs; -: products of PEX with dTTP, dATP, dGTP; lanes 4–6, 10–12 and 16–18, **C^{RX}**: products of PEX with dTTP, dATP, dGTP and functionalized **dC^{RX}TP**.

Table 1 List of ON sequences used in this study

Oligo	Sequence
Primer ^{248-sh}	5'-CATGGCGGGCATGGG-3'
Temp ^{oligo1C}	5'-CCCGCCCATGCCGCCATG-3'
Temp ^{Prb4baseII}	5'-CTAGCATGAGCTCAGTCCCATGCCGCCATG-3'
Primer ^{LT25TH}	5'-CAAGGACAAAATACCTGTATTCCCT-3'
Primer ^{L20}	5'-GACATCATGAGAGACATCGC-3'
Temp ^{FLV-A}	5'-GACATCATGAGAGACATGCCCTGGCTAATAGGACTACTTCTAATCTGTAAGAGCAGATCCCTGGACAGGCAA GGAATACAGGTATTTGTCCTTG-3'



Table 2 MALDI-TOF data of modified oligodeoxyribonucleotides

ssDNA	M (calc.) (Da)	M (found) [M or M + H] ⁺ (Da)
ON ^{4ThS}	10 073.2	10 075.1
ON ^{4PhS}	10 049.3	10 050.8
ON ^{4PhSe}	10 241.1	10 240.2

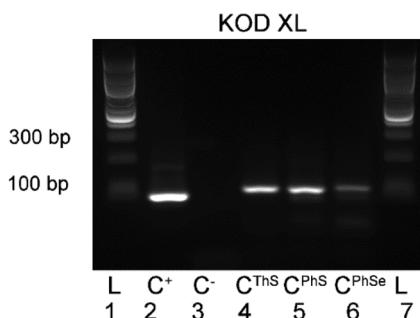


Fig. 3 PCR experiments using KOD XL DNA polymerase. Lanes 1, 7, L: ladder; lane 2, C⁺: products of PEX with natural dNTPs; lane 3, C⁻: products of PEX with dTTP, dATP, dGTP; lanes 4–6, C^{RX}: products of PCR with dTTP, dATP, dGTP and functionalized dC^{RX}TP.

higher concentration of the modified nucleotide (see Fig. S1–S3 in the ESI[†]).

Conclusions

In conclusion, we developed a new method for the direct functionalization of 5-iodopyrimidine and 7-iodo-7-deazapurine nucleosides and nucleotides based on Cu-mediated aryl-sulfanylation or aryl/alkylselenylation. The reactions are even applicable for modification of fragile halogenated dNTPs. The S- or Se-modified dNTPs are good substrates for DNA polymerases and can be used as building blocks for the enzymatic synthesis of modified ONs or DNA.

In this way, an aryl substituent can be attached to the nucleobase (in nucleoside, nucleotides or DNA) through a flexible sp³-hybridized sulfide or selenide linkage, which in principle offers a possibility for further transformations (e.g. oxidations). The arylsulfanyl or arylselenyl group can also serve as a radical precursor and the selenyl substituents can be used for X-ray crystallography of nucleic acids. The aryl group can be functionalized (e.g. NO₂ or MeO groups) so the approach can be potentially used for redox²⁸ or fluorescent²⁹ labelling of nucleic acids. Research along these lines is ongoing.

Experimental

For the full Experimental part, procedures and characterization of all compounds, see the ESI.[†]

Acknowledgements

This work was supported by the Academy of Sciences of the Czech Republic (RVO: 61388963 and Praemium Academiae to M. H.), the Czech Science Foundation (14-04289S to F. B., M. S. and M. H.), and Gilead Sciences, Inc. (Foster City, CA, U. S. A.).

Notes and references

- 1 *Modified Nucleic Acids, Nucleic Acids and Molecular Biology Series*, ed. K. Nakatani and Y. Tor, Springer, 2016, vol. 31, pp. 1–276.
- 2 Reviews: (a) A. Hottin and A. Marx, *Acc. Chem. Res.*, 2016, **49**, 418–427; (b) M. Hollenstein, *Molecules*, 2012, **17**, 13569–13591.
- 3 Reviews: (a) M. Hocek, *J. Org. Chem.*, 2014, **79**, 9914–9921; (b) J. Dadová, H. Cahová and M. Hocek, Polymerase Synthesis of Base-Modified DNA, in *Modified Nucleic Acids*, ed. K. Nakatani and Y. Tor, Springer International Publishing, Cham, 2016, pp. 123–144.
- 4 (a) J. Ludwig, *Acta Biochim. Biophys. Acad. Sci. Hung.*, 1981, **16**, 131–133; (b) T. Kovacs and L. Otvos, *Tetrahedron Lett.*, 1988, **29**, 4525–4528.
- 5 Reviews on the cross-coupling reactions of unprotected nucleosides and nucleotides: (a) K. H. Shaughnessy, *Molecules*, 2015, **20**, 9419–9454; (b) G. Hervé, G. Sartori, G. Enderlin, G. Mackenzie and C. Len, *RSC Adv.*, 2014, **4**, 18558–18594.
- 6 M. Welter, D. Verga and A. Marx, *Angew. Chem., Int. Ed.*, 2016, **55**, 10131–10135.
- 7 (a) A. Baccaro, A. L. Steck and A. Marx, *Angew. Chem., Int. Ed.*, 2012, **51**, 254–257; (b) X. Ren, M. Gerowska, A. H. El-Sagheer and T. Brown, *Bioorg. Med. Chem.*, 2014, **22**, 4384–4390.
- 8 V. Raindlová, R. Pohl, B. Klepetářová, L. Havran, E. Šimková, P. Horáková, H. Pivoňková, M. Fojta and M. Hocek, *ChemPlusChem*, 2012, **77**, 652–662.
- 9 (a) V. Borsenberger, M. Kukwikila and S. Howorka, *Org. Biomol. Chem.*, 2009, **7**, 3826–3835; (b) V. Borsenberger and S. Howorka, *Nucleic Acids Res.*, 2009, **37**, 1477–1485.
- 10 (a) X. Yang, C. Dai, A. D. Molina and B. Wang, *Chem. Commun.*, 2010, **46**, 1073–1075; (b) Y. Cheng, C. Dai, H. Peng, S. Zheng, S. Jin and B. Wang, *Chem. – Asian J.*, 2011, **6**, 2747–2752.
- 11 P. Capek, H. Cahová, R. Pohl, M. Hocek, C. Gloeckner and A. Marx, *Chem. – Eur. J.*, 2007, **13**, 6196–6203.
- 12 L. H. Thoresen, G. S. Jiao, W. C. Haaland, M. L. Metzker and K. Burgess, *Chem. – Eur. J.*, 2003, **9**, 4603–4610.
- 13 J. Dadová, P. Vidláková, R. Pohl, L. Havran, M. Fojta and M. Hocek, *J. Org. Chem.*, 2013, **78**, 9627–9637.
- 14 A. Krause, A. Hertl, F. Muttach and A. Jäschke, *Chem. – Eur. J.*, 2014, **20**, 16613–16619.
- 15 A. Hampton, R. R. Chawla and F. Kappler, *J. Med. Chem.*, 1982, **25**, 644–649.



16 M. Ahmadian, P. Zhang and D. E. Bergstrom, *Nucleic Acids Res.*, 1998, **26**, 3127–3135.

17 (a) J. M. San Pedro and M. M. Greenberg, *ChemBioChem*, 2013, **14**, 1590–1596; (b) M. J. Resendiz, A. Schön, E. Freire and M. M. Greenberg, *J. Am. Chem. Soc.*, 2012, **134**, 12478–12481.

18 M. Klečka, L. P. Slavětínská, E. Tloušťová, P. Džubák, M. Hajdúch and M. Hocek, *MedChemComm*, 2015, **6**, 576–580.

19 (a) R. F. Schinazi, J. Arbiser, J. J. S. Lee, T. I. Kalman and W. H. Prusoff, *J. Med. Chem.*, 1986, **29**, 1293–1295; (b) S. Choi, T. I. Kalman and T. J. Bardos, *J. Med. Chem.*, 1979, **22**, 618–621.

20 (a) A. E. Hassan, J. Sheng, J. Jiang, W. Zhang and Z. Huang, *Org. Lett.*, 2009, **11**, 2503–2506; (b) W. Zhang, J. Sheng, A. E. Hassan and Z. Huang, *Chem. – Asian J.*, 2012, **7**, 476–479; (c) Z. Wen, H. E. Abdalla and H. Zhen, *Sci. China: Chem.*, 2013, **56**, 273–278.

21 (a) I. S. Hong and M. M. Greenberg, *Org. Lett.*, 2004, **6**, 5011–5013; (b) I. S. Hong and M. M. Greenberg, *J. Am. Chem. Soc.*, 2005, **127**, 10510–10511; (c) I. S. Hong, H. Ding and M. M. Greenberg, *J. Am. Chem. Soc.*, 2006, **128**, 2230–2231; (d) X. Peng, I. S. Hong, H. Li, M. M. Seidman and M. M. Greenberg, *J. Am. Chem. Soc.*, 2008, **130**, 10299–10306.

22 J. Sheng, A. E. Hassan, W. Zhang, J. Zhou, B. Xu, A. S. Soares and Z. Huang, *Nucleic Acids Res.*, 2011, **39**, 3962–3971.

23 M. P. Kotick, C. Szantay and T. J. Bardos, *J. Org. Chem.*, 1969, **34**, 3806–3813.

24 D. E. Bergstrom, P. Beal, J. Jenson and X. Lin, *J. Org. Chem.*, 1991, **56**, 5598–5602.

25 D. G. Kananovich, A. Reino, K. Ilmarinen, M. Roomuskos, M. Karelsson and M. Loop, *Org. Biomol. Chem.*, 2014, **12**, 5634–5644.

26 M. Abdo, Y. Zhang, V. L. Schramm and S. Knapp, *Org. Lett.*, 2010, **13**, 2982–2985.

27 (a) N. Taniguchi and T. Onami, *Synlett*, 2003, 829–832; (b) N. Taniguchi and T. Onami, *J. Org. Chem.*, 2004, **69**, 915–920.

28 J. Balintová, M. Plucnara, P. Vidláková, R. Pohl, L. Havran, M. Fojta and M. Hocek, *Chem. – Eur. J.*, 2013, **19**, 12720–12731.

29 D. Dziuba, P. Jurkiewicz, M. Cebecauer, M. Hof and M. Hocek, *Angew. Chem., Int. Ed.*, 2016, **55**, 174–178.