



Cite this: *Org. Biomol. Chem.*, 2015, **13**, 1571

Consecutive three-component synthesis of (hetero)arylated propargyl amides by chemoenzymatic aminolysis–Sonogashira coupling sequence†

Sidra Hassan, Anja Ullrich and Thomas J. J. Müller*

Received 12th November 2014,
Accepted 27th November 2014

DOI: 10.1039/c4ob02386b

www.rsc.org/obc

A novel chemoenzymatic three-component synthesis of (hetero)arylated propargyl amides in good yields based upon Novozyme® 435 (*Candida antarctica* lipase B (CAL-B)) catalyzed aminolysis of methyl carbonylates followed by Sonogashira coupling with (hetero)aryliodides in a consecutive one-pot fashion has been presented. This efficient methodology can be readily concatenated with a CuAAC (Cu catalyzed alkyne azide cycloaddition) as a third consecutive step to furnish 1,4-disubstituted 1,2,3-triazole ligated arylated propargyl amides. This one-pot process can be regarded as a transition metal catalyzed sequence that takes advantage of the copper source still present from the cross-coupling step.

Introduction

Propargyl amides are particularly interesting as biologically active functionalities and as synthetic building blocks. Protein derived propargyl amides have been studied to irreversibly inhibit cysteine proteases¹ while systems containing rigid propargylated aryl cores have been demonstrated to be active as structurally modified homodimeric gonadotropin releasing hormone receptor (GnRHR) antagonist dimers with rigid functionalities such as bistriazole with a hydrophilic polyethylene glycol (PEG) spacer² or a propargylated aryl system as a spacer.³ Synthetically these compounds were prepared by coupling propargylated amino acid derivatives with the aryl iodides.³ Likewise, deoxynucleoside derivatives of *N*-trifluoroacetyl propargyl amides were synthesized.⁴

As synthetic building blocks, propargyl amides have been employed as monomers for the synthesis of chromophore labeled poly(*N*-propargyl amides) as stimulus responsive conjugated polymers.⁵ Optically active *N*-propargyl amides bearing hydroxyl groups have been synthesized and polymerized for studying their secondary structure and chiral-recognition.⁶ Furthermore, propargyl amides are excellent substrates in

coupling–cycloisomerization sequences⁷ that can be expanded to three-component syntheses of blue-luminescent 5-(3-indolyl)oxazoles⁸ and PtCl₂ induced intramolecular cyclizations of *N*-propargyl indole-2-carboxamides to give azepino-[3,4-*b*]indol-1-ones.⁹

The combination of chemical and enzymatic transformations offers numerous opportunities for designing new syntheses. Therefore, these chemoenzymatic transformations have recently received considerable attention and many applications have been found on chiral resolution of racemic or *meso* substrates to furnish enantiomerically enriched chiral building blocks for organic syntheses in a catalytic fashion.¹⁰ In contrast to chemoenzymatic continuous flow processes,¹¹ the concatenation of enzymatic and chemical catalyzed steps in a one-pot fashion thus furnishing novel types of chemoenzymatic sequences remains a major challenge. While the one-pot combination of enzymes and transition metal catalysis is dominated by dynamic kinetic resolution as an important tool in asymmetric synthesis,¹² chemoenzymatic one-pot sequences involving Pd-catalyzed coupling¹³ or Cu-catalyzed alkyne–azide cycloaddition (CuAAC)^{14,15} are still in their infancy. Recently, we have disclosed a consecutive three-component sequence consisting of CAL-B (*Candida antarctica* lipase B) catalyzed aminolysis of methyl esters with propargyl amine furnishing propargyl amides and CuAAC to give amide ligated 1,4-disubstituted 1,2,3-triazoles in good to excellent yields. Here we communicate the first consecutive three-component syntheses of (hetero)arylated propargyl amides by chemoenzymatic aminolysis–Sonogashira coupling sequence.

Lehrstuhl für Organische Chemie, Institut für Organische Chemie und Makromolekulare Chemie, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany. E-mail: ThomasJ.J.Mueller@uni-duesseldorf.de;

Fax: +49 (0)211 8114324; Tel: +49 (0)211 8112298

†Electronic supplementary information (ESI) available: Experimental procedures, characterization, and ¹H and ¹³C NMR spectra of compounds 5 and 7. See DOI: 10.1039/c4ob02386b



Results and discussion

We have previously reported on the efficient CAL-B catalyzed aminolysis for the synthesis of propargyl amides as a milder alternative to the base catalyzed process that occurs with a remarkable chemoselectivity with α -heteroatom substituted methyl carboxylates.¹⁵ Encouraged by the excellent compatibility of CAL-B catalyzed aminolysis with copper catalysis in a single reaction vessel we set out to concatenate this aminolysis step with Sonogashira coupling to access (hetero)arylated propargyl amides in a diversity-oriented one-pot sequence.

First the Sonogashira coupling of propargyl amide **3a**, formed by CAL-B aminolysis of methyl ester **1a** with propargylamine (**2**),¹⁵ and iodo benzene (**4a**) to furnish 3-phenylpropargyl amide **5a** was optimized as a model reaction with respect to a suitable catalyst system, base, solvent and temperature (Scheme 1, Table 1).

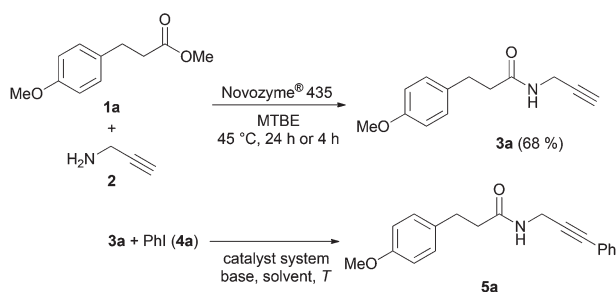
In comparison with standard Sonogashira conditions, propargyl amides are apparently peculiar since all Pd(II) catalyst precursors have failed to give reasonable yields (Table 1, entries 1–4). Even novel carbene ligands that have been

efficiently established for Sonogashira coupling^{16,17} were not successful in the model reaction (Table 1, entries 7 and 8). However, Pd(PPh₃)₄ as the Pd(0) catalyst precursor was proven to be superior (Table 1, entries 5, 9–15).

The choice of the base was equally important. It turned out that 1,1,3,3-tetramethyl guanidine (TMG), successfully employed in Pd-catalyzed coupling-cyclization syntheses of indoles from *ortho*-iodo anilines^{18,19} and in domino sequences involving *N*-propargyl sulfoximines,²⁰ was the most favorable amidine base that not only gave good yields of propargyl amide **5a** but also drastically reduced the reaction times at 45 °C (Table 1, entry 15). Moreover, it is sufficient to employ an equimolar amount of TMG to achieve full conversion. Therefore, with these conditions for the coupling step in hand, the stage was set to combine the CAL-B catalyzed aminolysis with the Sonogashira coupling in a consecutive one-pot fashion.

Upon the Novozyme® 435 catalyzed aminolysis of methyl carboxylates **1** with propargyl amine (**2**) in MTBE (methyl *tert*-butylether) at 45 °C, the formed propargyl amide **3** was subsequently reacted with (hetero)aryl iodides **4** in the presence of DMF as a cosolvent, TMG as a base and catalytic amounts of Pd(PPh₃)₄ and CuI at 45 °C to give 3-(hetero)arylpropargyl amides **5** in a three-component one-pot fashion in moderate to excellent yields (Scheme 2, Table 2).

Taking into account the already established substrate scope of the Novozyme® 435 catalyzed aminolysis¹⁵ the general substitution pattern is equally well accepted in this chemo-enzymatic sequence. Moreover, also a free phenol moiety in substrate **1i** is well tolerated furnishing the propargyl amide **5j** in remarkably high yield (Table 2, entry 10). The same holds true for methyl chloroacetate (**1m**), which is transformed to give the corresponding propargyl amide **5o** in excellent yield (Table 2, entry 15). Most importantly, the chemoselectivity of the aminolysis of the more electrophilic methyl carboxylate in substrate **1p** underlines the superiority of applying CAL-B as a



Scheme 1 Formation of propargyl amide **3a** by CAL-B catalyzed aminolysis of methyl ester **1a** and the optimization of the Sonogashira coupling of propargyl amide **3a** and iodo benzene (**4a**).

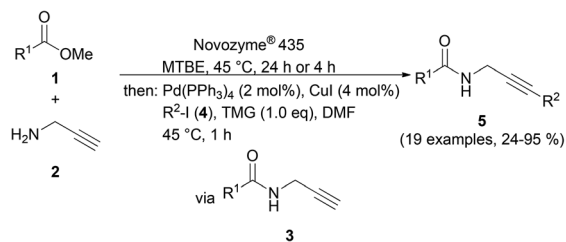
Table 1 Optimization of the Sonogashira reaction of propargyl amide **3a** and iodo benzene (**4a**) giving rise to 3-phenylpropargyl amide **5a**

Entry	Catalyst system	Solvent	Base/additive	T, t	Yield of 5a ^a (%)
1	2 mol% PdCl ₂ (PPh ₃) ₂ , 4 mol% CuI	THF	NEt ₃ (1.0 equiv.)	rt to 50 °C, 24 h	— ^b
2	2 mol% PdCl ₂ (PPh ₃) ₂ , 4 mol% CuI	1,4-Dioxane	NEt ₃ (1.0 equiv.)	rt to 70 °C, 24 h	13
3	2 mol% PdCl ₂ (PPh ₃) ₂ , 4 mol% CuI	1,4-Dioxane	Pyrrolidine (1.0 equiv.)	rt to 70 °C, 24 h	25
4	2 mol% PdCl ₂ (PPh ₃) ₂ , 4 mol% CuI	1,4-Dioxane	Pyrrolidine (1.5 equiv.)	rt to 70 °C, 24 h	33
5	5 mol% Pd(PPh ₃) ₄ , 1 mol% CuI	DMF	Pyrrolidine/DMF (1 : 4 v/v)	45 °C, 6 h	75
6	2.5 mol% Pd ₂ (dba) ₃ ·CHCl ₃ , 10 mol% P(2-furyl) ₃	MeCN	NaOt-Bu (2.0 equiv.)	45 °C, 24 h	— ^b
7	2.5 mol% Pd ₂ (dba) ₃ ·CHCl ₃ , 10 mol% IPr-HCl ^c	MeCN	NaOt-Bu (2.0 equiv.)	45 °C, 24 h	— ^b
8	5 mol% Pd(OAc) ₂ , 10 mol% IPr-HCl ^c	MeCN	K ₂ CO ₃ (2.0 equiv.), TBAC (2.0 equiv.)	45 °C, 24 h	— ^b
9	2 mol% Pd(PPh ₃) ₄ , CuI	DMF	NEt ₃ (1.0 equiv.)	rt, 24 h	53
10	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	DIPEA ^d (1.5 equiv.)	45 °C, 6 h	67
11	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	Pyrrolidine (1.0 equiv.)	45 °C, 8 h	56
12	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	Pyrrolidine (1.5 equiv.)	45 °C, 4 h	85
13	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	DABCO ^e (1.0 equiv.)	45 °C, 8 h	57
14	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	DBU ^f (1.0 equiv.)	45 °C, 8 h	69
15	2 mol% Pd(PPh ₃) ₄ , 4 mol% CuI	DMF	TMG ^g (1.0 equiv.)	45 °C, 1 h	83

^a Isolated yield after chromatography on silica gel. ^b No product formation. ^c IPr-HCl: 1,3-bis(2,6-diisopropylphenyl)imidazolium chloride.

^d DIPEA: diisopropylethylamine. ^e DABCO: 1,4-diazabicyclo[2.2.2]octane. ^f DBU: 1,8-diazabicyclo[5.4.0]undec-7-ene. ^g TMG: 1,1,3,3-tetramethyl guanidine.





Scheme 2 Consecutive three-component synthesis of 3-(hetero)aryl-propargyl amides **5** by CAL-B catalyzed aminolysis–Sonogashira coupling sequence.

catalyst in the sequence. However, it should be noted that 2-iodopyridine and 1,3-diiodobenzene failed to undergo the Sonogashira step under the optimized conditions.

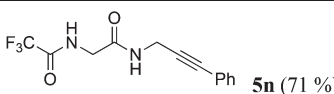
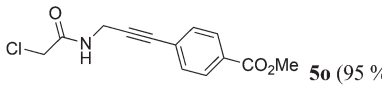
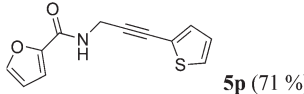
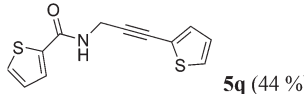
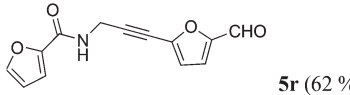
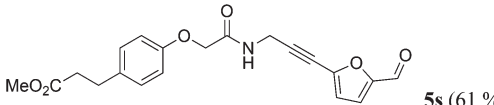
Finally, we have combined the chemoenzymatic aminolysis–Sonogashira coupling with a terminal CuAAC step furnishing propargyl amide functionalized 1-aryl 4-benzyl 1,2,3-triazoles **7** in good yields (Scheme 3). Commencing with the CAL-B catalyzed aminolysis, the propargyl amides **3** are reacted with *p*-iodo[(trimethylsilyl)ethynyl]benzene (**4i**) to give the TMS-protected 3(*p*-ethynyl)phenyl propargyl amides **8**, which

Table 2 Chemoenzymatic three-component synthesis of 3-(hetero)arylpropargyl amides **5**

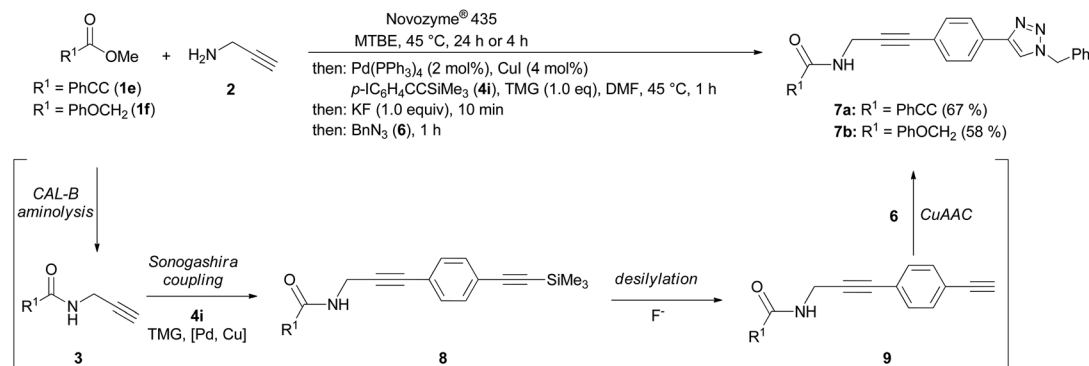
Entry	Methyl ester 1	(Hetero)aryl iodide 4	3-(Hetero)aryl propargyl amide 5
1 ^a	R ¹ = <i>p</i> -MeOC ₆ H ₄ CH ₂ CH ₂ (1a)	R ² = Ph (4a)	5a (58 %)
2 ^a	R ¹ = C ₆ H ₅ CH ₂ (1b)	4a	5b (53 %)
3 ^a	1b	R ² = <i>p</i> -MeO ₂ CC ₆ H ₄ (4b)	5c (74 %)
4 ^a	R ¹ = C ₆ H ₅ CH ₂ CH ₂ (1c)	4a	5d (54 %)
5 ^a	R ¹ = <i>E</i> -C ₆ H ₅ CH=CH (1d)	R ² = <i>p</i> -MeOC ₆ H ₄ (4c)	5e (26 %)
6 ^a	R ¹ = C ₆ H ₅ C≡C (1e)	4a	5f (51 %)
7 ^b	R ¹ = C ₆ H ₅ OCH ₂ (1f)	4a	5g (24 %)
8 ^b	R ¹ = C ₆ H ₅ NHCH ₂ (1g)	4a	5h (77 %)
9 ^b	R ¹ = C ₆ H ₅ SCH ₂ (1h)	4a	5i (77 %)
10 ^a	R ¹ = <i>p</i> -HOC ₆ H ₄ CH ₂ CH ₂ (1i)	4b	5j (85 %)
11 ^a	1h	4c	5k (62 %)
12 ^b	R ¹ = (CH ₂) ₅ NCH ₂ (1j)	R ² = <i>p</i> -H ₃ CCOC ₆ H ₄ (4d)	5l (64 %)
13 ^a	R ¹ = Me(CH ₂) ₅ CH ₂ (1k)	4c	5m (59 %)



Table 2 (Contd.)

Entry	Methyl ester 1	(Hetero)aryl iodide 4	3-(Hetero)aryl propargyl amide 5
14 ^a	R ¹ = F ₃ CCONHCH ₂ (1l)	4a	 5n (71 %)
15 ^b	R ¹ = ClCH ₂ (1m)	4b	 5o (95 %)
16 ^a	R ¹ = 2-furyl (1n)	R ² = 2-thienyl (4e)	 5p (71 %)
17 ^a	R ¹ = 2-thienyl (1o)	4e	 5q (44 %)
18 ^a	1n	R ² = 5-OHC-2-furyl (4f)	 5r (62 %)
19 ^b	R ¹ = <i>p</i> -(MeO ₂ CCH ₂ CH ₂)C ₆ H ₄ OCH ₂ (1p)	4f	 5s (61 %)

^a 24 h time for CAL-B catalyzed aminolysis. ^b 4 h time for CAL-B catalyzed aminolysis.



Scheme 3 Consecutive four-component synthesis of 3-(4-1,2,3-triazolyl)phenyl propargyl amides **7** by CAL-B catalyzed aminolysis–Sonogashira coupling–CuAAC sequence.

are rapidly desilylated by potassium fluoride to furnish the ethynyl derivatives **9**. The presence of the Sonogashira cocatalyst CuI and benzyl azide (**6**) terminates the sequence by a CuAAC giving rise to the formation of functionalized 1,2,3-triazoles **7** in the sense of a transition metal catalyzed one-pot sequence.²¹

Conclusions

In conclusion, we have disclosed a novel chemoenzymatic one-pot synthesis of 3-(hetero)arylpropargyl amides **5** by CAL-B catalyzed aminolysis–Sonogashira coupling sequence. This combination of enzyme-metal catalyzed methodology is well suited for application to more sophisticated peptides and aryl halides as a bioorganic tool for the efficient generation of

peptidomimetics in a one-pot fashion. Furthermore, the potential to concatenate CuAAC as a third step opens up new avenues for the rapid alignment of various functionalities in the sense of diversity-oriented synthesis of complex chromophores.²² Studies directed to further expand and develop this chemoenzymatic sequence are currently underway.

Experimental

Chemoenzymatic three-component synthesis of methyl 4-(3-(4-hydroxyphenyl)propanamido)prop-1-yn-1-yl benzoate (**5j**) (typical procedure)

To a solution of propargylamine (**2**) (55 mg, 1.00 mmol) in dry MTBE (2.0 mL) in a screw-cap Schlenk vessel, methyl *p*-hydroxy



dihydrocinnamate (**1i**) (216 mg, 1.20 mmol) and Novozyme® 435 (108 mg, 50% w/w of substrate **1i**) were successively added and the reaction was allowed to shake in an incubating shaker at 45 °C for 24 h. After the complete conversion (monitored by TLC), DMF (2.0 mL) was added to the reaction mixture which was then flushed with argon for 15 min. Then methyl *p*-iodobenzoate (**4b**) (262 mg, 1.00 mmol), TMG (115 mg, 1.00 mmol), Pd(PPh₃)₄ (23 mg, 0.02 mmol), and CuI (8 mg, 0.04 mmol) were successively added to the reaction mixture under argon and the reaction was allowed to shake at 45 °C for 1 h. The reaction mixture was filtered to remove the enzyme beads. Then, brine (5.0 mL) was added to the filtrate, followed by extraction with ethyl acetate (3 × 10.0 mL). The combined organic layers were dried with anhydrous Na₂SO₄ and after column chromatography on silica gel (*n*-hexane/ethyl acetate), 288 mg (85%) of analytically pure compound **5j** was obtained as a colorless solid, Mp 151 °C.

¹H NMR (300 MHz, DMSO-*d*₆): δ = 2.35 (t, ³J = 7.9 Hz, 2 H), 2.72 (t, ³J = 7.9 Hz, 2 H), 3.85 (s, 3 H), 4.13 (d, ³J = 5.5 Hz, 2 H), 6.64 (d, ³J = 8.4 Hz, 2 H), 6.99 (d, ³J_{4,3} = 8.4 Hz, 2 H), 7.54 (d, ³J = 8.5 Hz, 2 H), 7.94 (d, ³J = 8.5 Hz, 2 H), 8.38 (t, ³J = 5.5 Hz, 1 H), 9.14 (s, 1 H). ¹³C NMR (75 MHz, DMSO-*d*₆): δ = 28.5 (CH₂), 30.1 (CH₂), 37.2 (CH₂), 52.3 (CH₃), 80.7 (C_{quat}), 90.6 (C_{quat}), 115.0 (CH), 127.1 (C_{quat}), 129.0 (CH), 129.1 (C_{quat}), 129.3 (CH), 131.2 (C_{quat}), 131.6 (CH), 155.4 (C_{quat}), 165.6 (C_{quat}), 171.3 (C_{quat}). EI-MS (*m/z* (%)): 337 (M⁺, 13), 336 ([M – H]⁺, 22), 230 (C₁₃H₁₂NO₃⁺, 100), 188 (C₁₁H₁₀NO₂⁺, 19), 120 (C₈H₈O⁺, 20), 107 (C₇H₇O⁺, 52). IR (ATR) $\tilde{\nu}$ [cm^{–1}] = 3385 (m), 3291 (m), 2966 (m), 2951 (w), 2924 (w), 2845 (w), 1705 (s), 1632 (s), 1601 (w), 1533 (m), 1516 (s), 1435 (m), 1362 (w), 1344 (m), 1288 (m), 1279 (s), 1259 (m), 1225 (s), 1198 (m), 1175 (m), 1103 (m), 1011 (w), 966 (w), 862 (m), 831 (w), 816 (m), 766 (s), 684 (m), 640 (w). Anal. calcd for C₂₀H₁₉NO₄ (337.4): C 71.20, H 5.68, N 4.15; Found: C 70.96, H 5.38, N 4.07.

Chemoenzymatic four-component synthesis of *N*-(3-(4-(1-benzyl-1*H*-1,2,3-triazol-4-yl)phenyl)prop-2-yn-1-yl)-2-phenoxyacetamide (**7b**) (typical procedure)

To a solution of propargylamine (**2**) (55 mg, 1.00 mmol) in dry MTBE (2.0 mL) in a screw-cap Schlenk vessel, methyl 2-phenoxyacetate (**1f**) (199 mg, 1.20 mmol) and Novozyme® 435 (100 mg, 50% w/w of substrate **1f**) were successively added and the reaction was allowed to shake in an incubating shaker at 45 °C for 4 h. After the complete conversion (monitored by TLC), DMF (2.0 mL) was added to the reaction mixture, which was then flushed with argon for 15 min. Then (4-iodophenyl)-ethynyl trimethylsilane (**4i**) (300 mg, 1.00 mmol), TMG (115 mg, 1.00 mmol), Pd(PPh₃)₄ (23 mg, 0.02 mmol), and CuI (8 mg, 0.04 mmol) were successively added to the reaction mixture under argon and the reaction was allowed to shake at 45 °C for 1 h. Then potassium fluoride (58 mg, 1.00 mmol) was added to the reaction mixture and after 10 min benzyl azide (**6**) (133 mg, 1.00 mmol) was added. After 1 h of shaking in the incubating shaker the reaction mixture was filtered to remove the enzyme beads. Then, brine (5.0 mL) was added to the filtrate followed by extraction with ethyl acetate (3 ×

10.0 mL). The combined organic layers were dried with anhydrous Na₂SO₄ and after column chromatography on silica gel (*n*-hexane/ethyl acetate) 245 mg (58%) of analytically pure compound **7b** was obtained as a yellow solid, Mp 147 °C.

Yellow solid. Mp 147 °C. ¹H NMR (300 MHz, *d*₆-DMSO): δ = 4.21 (d, ³J = 5.6 Hz, 2 H), 4.54 (s, 2 H), 5.65 (s, 2 H), 6.97–7.00 (m, 3 H), 7.28–7.39 (br m, 7 H), 7.45 (d, ³J = 8.4 Hz, 2 H), 7.59–7.62 (m, 1 H), 7.86 (d, ³J = 8.4 Hz, 2 H), 8.69 (s, 1 H). ¹³C NMR (75 MHz, *d*₆-DMSO): δ = 28.5 (CH₂), 53.1 (CH₂), 66.8 (CH₂), 81.3 (C_{quat}), 87.7 (C_{quat}), 114.7 (CH), 121.2 (CH), 121.5 (C_{quat}), 122.1 (CH), 125.3 (CH), 127.9 (CH), 128.2 (CH), 129.5 (CH), 130.7 (C_{quat}), 132.0 (CH), 135.9 (C_{quat}), 145.9 (C_{quat}), 157.6 (C_{quat}), 167.7 (C_{quat}). MALDI-MS: *m/z* = 423 ([M + H]⁺). IR (ATR) $\tilde{\nu}$ [cm^{–1}] = 3034 (w), 2922 (w), 2910 (w), 2856 (w), 1662 (s), 1598 (w), 1587 (w), 1519 (m), 1489 (s), 1456 (w), 1435 (w), 1409 (w), 1350 (w), 1286 (w), 1242 (s), 1226 (s), 1170 (w), 1080 (w), 1060 (w), 1047 (w), 1028 (w), 1018 (w), 1001 (w), 835 (m), 798 (m), 756 (s), 721 (s), 657 (w), 603 (w). Anal. calcd for C₂₆H₂₂N₄O₂ (422.5): C 73.92, H 5.25, N 13.26; Found: C 74.06, N 5.32, H 13.47.

Acknowledgements

The authors cordially thank CLIB Graduate Cluster for the financial support (scholarship of S.H.) and the Fonds der Chemischen Industrie.

Notes and references

- 1 C. Arkona and J. Rademann, *Angew. Chem., Int. Ed.*, 2013, **52**, 2.
- 2 K. M. Bongers, R. J. B. H. N. van der Berg, L. H. Heitman, A. P. IJzerman, J. Oosterom, C. M. Timmers, H. O. Overkleeft and G. A. van der Marel, *Bioorg. Med. Chem.*, 2007, **15**, 4841.
- 3 K. M. Bongers, R. J. B. H. N. van den Berg, A. D. Knijnenburg, L. H. Heitman, A. P. IJzerman, J. Oosterom, C. M. Timmers, H. S. Overkleeft and G. A. van der Marel, *Bioorg. Med. Chem.*, 2008, **16**, 3744.
- 4 N. K. Garg, C. C. Woodroffe, C. J. Lacenere, S. R. Quake and B. M. Stoltz, *Chem. Commun.*, 2005, 4551.
- 5 R. Nomura, K. Yamada and T. Masuda, *Chem. Commun.*, 2002, 478.
- 6 F. Sanda, T. Fujii, J. Tabei, M. Shiotsuki and T. Masuda, *Macromol. Chem. Phys.*, 2008, **209**, 112.
- 7 (a) E. Merkul and T. J. J. Müller, *Chem. Commun.*, 2006, 4817; (b) E. Merkul, O. Grotkopp and T. J. J. Müller, *Synthesis*, 2009, 502; (c) E. Merkul, C. Boersch, W. Frank and T. J. J. Müller, *Org. Lett.*, 2009, **11**, 2269.
- 8 O. Grotkopp, A. Ahmad, W. Frank and T. J. J. Müller, *Org. Biomol. Chem.*, 2011, **9**, 8130.
- 9 M. Gruit, A. P. Davtyan and M. Beller, *Org. Biomol. Chem.*, 2011, **9**, 1148–1159.



- 10 For a recent monograph, see *e.g.* *Enzyme Catalysis in Organic Synthesis*, ed. K. Drauz, H. Gröger and O. May, Wiley-VCH, 3rd edn, 2012.
- 11 For coupled chemo(enzymatic) reactions in continuous flow, see *e.g.* R. Yuryev, S. Strompen and A. Liese, *Beilstein J. Org. Chem.*, 2011, **7**, 1449.
- 12 For reviews, see *e.g.* (a) O. Pàmies and J.-E. Bäckvall, *Chem. Rev.*, 2003, **103**, 3247; (b) J. H. Lee, K. Han, M.-J. Kim and J. Park, *Eur. J. Org. Chem.*, 2010, 999; (c) P. Hoyos, V. Pace and A. R. Alcántara, *Adv. Synth. Catal.*, 2012, **354**, 2585.
- 13 E. Burda, W. Hummel and H. Gröger, *Angew. Chem., Int. Ed.*, 2008, **47**, 9551.
- 14 A. Cuertos, F. R. Bisogno, I. Lavandera and V. Gotor, *Chem. Commun.*, 2013, **49**, 2625.
- 15 S. Hassan, R. Tschersich and T. J. J. Müller, *Tetrahedron Lett.*, 2013, **54**, 4641.
- 16 A. Saito, K. Iimura and Y. Hanzawa, *Tetrahedron Lett.*, 2010, **51**, 1471.
- 17 Y.-M. Pan, F.-J. Zheng, H.-X. Lin and Z.-P. Zhan, *J. Org. Chem.*, 2009, **74**, 3148.
- 18 M. C. Fagnola, I. Candiani, G. Visentin, W. Cabri, F. Zarini, N. Mongelli and A. Bedeschi, *Tetrahedron Lett.*, 1997, **38**, 2307.
- 19 A. L. Smith, G. I. Stevenson, C. J. Swain and J. L. Castro, *Tetrahedron Lett.*, 1998, **39**, 8317.
- 20 R. F. Schumacher, A. Honraedt and C. Bolm, *Eur. J. Org. Chem.*, 2012, 3737.
- 21 T. J. J. Müller, *Top. Organomet. Chem.*, 2006, **19**, 149.
- 22 T. J. J. Müller and D. M. D'Souza, *Pure Appl. Chem.*, 2008, **80**, 609.

