ChemComm



COMMUNICATION

View Article Online View Journal | View Issue

Check for updates

Cite this: Chem. Commun., 2024, 60, 5824

Received 14th March 2024, Accepted 8th May 2024

DOI: 10.1039/d4cc01177e

rsc.li/chemcomm

Iterative click reactions using trivalent platforms for sequential molecular assembly †‡

Gaku Orimoto and Suguru Yoshida 🕩 *

A facile synthesis of multi(triazole)s by iterative click reactions is disclosed. Good functional group tolerance of sequential click assembly by sulfur-fluoride exchange (SuFEx), copper-catalyzed azide-alkyne cycloaddition (CuAAC), and thia-Michael reaction realizes the iterative click reactions. Diverse multi(triazole)-type mid-molecules can be synthesized easily from readily available modules through good chemoselective reactions without functional group transformation steps.

Iterative ligation methods have played significant roles in synthesizing diverse functional molecules including peptides and nucleic acids from simple modules in broad disciplines such as materials chemistry, pharmaceutical sciences, and chemical biology. For example, peptide synthesis is realized by iterative methods through the conjugation of protected amino acids and deprotection (Fig. 1A), which are fundamental ways to prepare bioactive mid-molecules.¹ Herein, we disclose an efficient method to synthesize mid-molecules from simple modules by iterative click reactions onto trivalent platform molecules without deprotection steps.

Click reactions are gaining attention from a wide range of researchers for reliable molecular conjugation.² We have developed a variety of trivalent platforms for efficient molecular assembly by sequential click reactions.^{3–5} In particular, we recently succeeded in the synthesis of trivalent platform **1a** that served in the sequential click conjugation by the SuFEx reaction,⁶ copper-catalyzed azide–alkyne cycloaddition (CuAAC),⁷ and thia-Michael reaction,⁸ where the triazole formation remarkably enhanced the Michael reactivity of acrylamides (Fig. 1B).^{4c,4e} It is worth noting that we succeeded in the one-pot assembly of

modules onto trivalent platform **1a**.^{4e} With the orthogonality of the click reactions in mind, we conceived an idea that iterative click reactions can be accomplished by the SuFEx reaction, CuAAC, and thia-Michael reaction using linkers having two clickable groups such as an alkyne and a silyl ether moiety. The robust reliability of click reactions will allow us to synthesize diverse multi(triazole)s from simple starting materials. In this study, we synthesized various trivalent platforms bearing azide, alkene, and fluorosulfonyl groups, and divergent triazoles with a variety of functionalities (Fig. 1C, upper). On the basis of good functional group tolerance in sequential conjugations, we then developed an iterative click reaction which enabled us to synthesize tris(triazole)s from simple modules (Fig. 1C, lower).



Fig. 1 (A) Peptide synthesis. (B) Our previous studies. (C) Overview of this work.

Department of Biological Science and Technology, Faculty of Advanced Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan. E-mail: s-yoshida@rs.tus.ac.jp

[†] Dedicated to Professor Koichi Narasaka with gratitude on the occasion of his 80th birthday (Sanju).

[‡] Electronic Supplementary Information (ESI) available: Experimental procedures, characterization for new compounds including NMR spectra. See DOI: https://doi.org/10.1039/d4cc01177e



Fig. 2 Syntheses of trivalent platforms **1**. Yields for 1st, 2nd, and 3rd step were shown. See the ESI‡ for details. ^a Condensation was conducted with chloro-N, N, N', N'-tetramethylformamidinium hexafluorophosphate and *N*-methylimidazole in MeCN at rt. PyBOP = ((1*H*-Benzo[*d*][1,2,3]triazol-1-yl)oxy)tri(pyrrolidin-1-yl)phosphonium hexafluorophosphate.

We first synthesized a range of acrylamides **1b–1e** bearing fluorosulfonyl groups from 2-azidoacrylic acid (Fig. 2). Condensation of 2-azidoacrylic acid (**6**) with amines 7 having an *N*-Boc amide group followed by deprotection of the Boc group and subsequent addition to ethenesulfonyl fluoride (**8**) took place smoothly to afford trivalent platforms **1b–1e** leaving azide, alkene, fluorosulfonyl, secondary or tertiary amide, and iodo moieties untouched. Of note, a broad range of amines such as not only primary and secondary alkyl amines but also aromatic amines participated in the acrylamide synthesis without damaging electrophilic alkene moieties by the undesired Michael addition.

A wide variety of highly functionalized modules 2–4 were conjugated using trivalent platform 1a by sequential click assembly (Fig. 3). In the SuFEx reaction of 1a as the first step, various aromatic alcohols reacted selectively at the fluorosulfonyl group to afford sulfonyl esters **9b–9j** in high yields keeping



Fig. 3 Sequential click assembly using platform **1a**. See the ESI‡ for details. (A) General scheme. (B) SuFEx reaction of **1a**. (C) Triazole formation of **9a**. (D) Michael addition to **10a**. ^a DMF was used as a solvent instead of CH_2Cl_2 . ^b The reaction of **9a** with **11** was performed in CH_2Cl_2 at rt. ^c The reaction of **10a** with **11** was performed in CH_2Cl_2 at rt. ^c The reaction of **10a** with **11** was performed in CH_2Cl_2 at rt. ^c The reaction of **10a** with **11** was performed in CH_2Cl_2 at rt. ^c The reaction of **10a** with diethyl malonate and t-BuOK in THF was performed at rt. TBTA = tris(benzyltriazolylmethyl)amine.



Fig. 4 (A) Synthesis of various triazoles 13. (B) Synthesis of triazole 14. (C) Synthesis of bis(triazole) 15. Reaction conditions; M: NEt₃, CH₂Cl₂, rt; S: DBU, CH₂Cl₂, rt; C: cat. (MeCN)₄CuBF₄, cat. TBTA, CH₂Cl₂, rt; see the ESI: for details.

reactive functionalities (Fig. 3A and B). It is worth noting that the SuFEx reaction proceeded with excellent chemoselectivities at the aromatic hydroxy group in the presence of other nucleophilic groups such as aliphatic alcohol, amide, or amine moieties, in which undesired Michael addition to the remaining acrylamide moiety was not observed. We succeeded in the synthesis of heteroaromatic sulfonyl esters **9i** and **9j** from 5-quinolinol or 2-pyridone keeping 2-azidoacrylamide moiety intact. In addition, perfluoroal-cohol was efficiently conjugated to trivalent platform **1a**, which will serve as a perfluoroalkyl tag moiety.⁹ The synthesis of alkyl sulfonate **9k** also suggests great potential for applications involving ligand-directed labeling,¹⁰ activity-based proteome analyses,¹¹ and covalent drug discovery¹² based on the scission of sulfonate groups.

The second step by the CuAAC reaction using diverse alkynes allowed us to prepare triazoles **10b–10j** bearing various functionalities in good yields, in which we chose **9a** as a model substrate to simplify the analysis of products (Fig. 3A and C). In particular, 2-(triazolyl)acrylamide moieties were not damaged in the presence of reactive functionalities such as hydroxy, pyridyl, iodo, triflyloxy, formyl, chloro, and amide groups in the products under the Lewis-acidic conditions. It is worthy to note that a wide variety of biochemically significant moieties such as uridine, HaloTag ligand, biotin, and fluorescent sulforhodamine were efficiently introduced by the CuAAC reaction leaving the alkenyl group intact. Strain-promoted azide–alkyne cycloaddition of **9a** with cycloalkyne **11** took place smoothly to provide triazole **10k** in high yield.¹³

A range of nucleophiles 4 were successfully applied to the Michael additions of the resulting 2-(triazolyl)acrylamides 10a, which was selected as a model substrate to simplify the characterization of products (Fig. 3A and D). For example, aromatic and aliphatic thiols efficiently reacted at the remaining alkene moiety to provide sulfides 5b-5d by the thia-Michael reaction without damaging amide, ester, and fluorescent dansyl moieties. Not only the primary amino group of lysine methyl ester but also the endocyclic nitrogen atoms of adenine or cytosine served in the efficient Michael addition furnishing amines 5e-5g in good yields.¹⁴ Additionally, *n*-butanol and dimethyl malonate were also applicable in the Michael reaction under basic conditions, in which 2-(triazolyl)amide and alkoxysulfonyl groups remained unreacted. These results obviously demonstrate that a broad range of triazoles can be synthesized by assembling various starting materials having diverse reactive functional groups onto trivalent platform 1 in a modular synthetic manner.

The good functional group tolerance of the sequential click assembly realized an iterative conjugation using linkers 12 bearing ethynyl and *tert*-butyl(dimethyl)silyloxy groups by repeating CuAAC and SuFEx reactions (Fig. 4A). Indeed, we accomplished the selective synthesis of triazole 13a from azide 9a leaving the remaining acrylamide and silyloxy group untouched. Also, the CuAAC reaction allowed us to synthesize triazoles 13b and 13c selectively using linkers 12b and 12c with ethynyl and aromatic hydroxy groups. Since the silyloxy group survived in thia-Michael reaction of thiol 4a to triazole 13a, we succeeded in the facile preparation of triazole 14 in excellent yield by further SuFEx conjugation with trivalent platform 1a (Fig. 4B).

We found that the order of the sequential conjugation using trivalent platform **1a** was switchable (Fig. 4C). For instance, after the CuAAC and thia-Michael addition of **1a** with alkyne **3a** and thiol **4a**, respectively, keeping the fluorosulfonyl group unreacted, the SuFEx reaction with linker **12a** took place



Fig. 5 Synthesis of tris(triazole) 16. Reaction conditions; M: NEt₃, CH₂Cl₂, rt; S: DBU, CH₂Cl₂, rt; C: cat. (MeCN)₄CuBF₄, cat. TBTA, CH₂Cl₂, rt; see the ESI‡ for details.

Communication

smoothly without damaging the ethynyl group. The resulting alkyne reacted efficiently with trivalent platform **1a** to afford bis(triazole) **15** in high yields leaving the exomethylene and fluorosulfonyl group untouched. Due to the great potential of sulfonyl fluorides in the proximity-promoted conjugation, mid-molecules having fluorosulfonyl groups will gain attention from researchers in pharmaceutical sciences.¹⁵

The synthesis of tris(triazole) 16 was achieved by the iterative click reactions resulting in the elongation of the main chain and assembly of modules 4k and 4l (Fig. 5). Indeed, the triazole formation using azide 14 with linker 12a followed by the thia-Michael reaction of thiol 4k and the SuFEx reaction with trivalent platform 1a was realized without side reactions such as undesired elimination by the retro-Michael reaction or decomposition of sulfonic acid ester moieties. Then, CuAAC with linker 12a and Michael addition of amine 4l proceeded smoothly to provide tris(triazole) 16 in high yields. Thus, we succeeded in the synthesis of tris(triazole) 16 by the iterative click reactions using thiols 4a and 4k, amine 4l, linker 12a, and trivalent platform 1a in a modular synthetic manner. This efficient chain elongation, as well as significant functional group tolerance of click reactions clarified in Fig. 3, obviously demonstrates that the iterative click reaction enables us to synthesize diverse multi(triazole)s, which are of great importance as functionalized peptide bioisosteres.¹⁶

In conclusion, we demonstrated the excellent functional group tolerance of the sequential click assembly by SuFEx, CuAAC, and thia-Michael reaction. Based on the chemoselective molecular conjugation methods, facile synthesis of multi(triazole)s has been developed by iterative click reactions without functional group transformation steps. Due to the wide scope of click reactions and good accessibility of modules, a huge chemical library of multi(triazole)-type mid-molecules will be constructed in a modular synthetic manner. Further studies such as one-pot click assembly of functional molecules onto trivalent platforms and applications to bioassay using diverse mid-molecules are ongoing in our laboratory.

This work was supported by JSPS KAKENHI Grant Number JP23K179200 (S.Y.) and Asahi Glass Foundation (S.Y.).

Conflicts of interest

There are no conflicts to declare.

Notes and references

1 For reviews of peptide synthesis, see: J. M. Palomo, *RSC Adv.*, 2014, 4, 32658.

- 2 J. Lahann, *Click Chemistry for Biotechnology and Materials Science*, John Wiley & Sons, West Sussex, 2009.
- For reviews of sequential click reactions, see: (a) A.-C. Knall and C. Slugovc, *Chem. Soc. Rev.*, 2013, 42, 5131; (b) Z.-J. Zheng, D. Wang, Z. Xu and L.-W. Xu, *Beilstein J. Org. Chem.*, 2015, 11, 2557; (c) S. Yoshida, *Org. Biomol. Chem.*, 2020, 18, 1550; (d) D. Sato, Z. Wu, H. Fujita and J. S. Lindsey, *Organics*, 2021, 2, 161; (e) M. S. Yadav, S. Rajkhowa, S. K. Singh, M. K. Jaiswal and V. K. Tiwari, *ChemistrySelect*, 2024, 9, e202400776.
- 4 For recent our studies on sequential click reactions using tri- or tetravalent platforms, see: (a) T. Meguro, Y. Sakata, T. Morita, T. Hosoya and S. Yoshida, *Chem. Commun.*, 2020, 56, 4720; (b) N. Terashima, Y. Sakata, T. Meguro, T. Hosoya and S. Yoshida, *Chem. Commun.*, 2020, 56, 14003; (c) H. Takemura, S. Goto, T. Hosoya and S. Yoshida, *Chem. Commun.*, 2020, 56, 15541; (d) S. Yoshida, Y. Sakata, Y. Misawa, T. Morita, T. Kuribara, H. Ito, Y. Koike, I. Kii and T. Hosoya, *Chem. Commun.*, 2021, 57, 899; (e) H. Takemura, G. Orimoto, A. Kobayashi, T. Hosoya and S. Yoshida, *Org. Biomol. Chem.*, 2022, 20, 6007.
- 5 For recent examples of sequential click reactions using trivalent platforms, see: (a) V. Vaněk, J. Pícha, B. Fabre, M. Buděšínský, M. Lepšík and J. Jiráček, *Eur. J. Org. Chem.*, 2015, 3689; (b) B. Fabre, J. Pícha, V. Vaněk, M. Buděšínský and J. Jiráček, *Molecules*, 2015, 20, 19310; (c) B. Fabre, J. Pícha, V. Vaněk, I. Selicharová, M. Chluinová, M. Collinsová, L. Žáková, M. Buděšínský and J. Jiráček, *ACS Comb. Sci.*, 2016, 18, 710; (d) A.-C. Knall, M. Hollauf, R. Saf and C. Slugove, *Org. Biomol. Chem.*, 2016, 14, 10576; (e) T. Yokoi, H. Tanimoto, T. Ueda, T. Morimoto and K. Kakiuchi, *J. Org. Chem.*, 2018, 83, 12103; (f) T. Yokoi, T. Ueda, H. Tanimoto, T. Morimoto and K. Kakiuchi, *J. Org. Chem.*, 2021, 8, 5793; (h) S. Sun, J. A. Homer, C. J. Smedley, Q.-Q. Cheng, K. B. Sharpless and J. E. Moses, *Chem.*, 2023, 9, 2128.
- 6 For reviews of the SuFEx chemistry, see: (a) J. Dong, L. Krasnova, M. G. Finn and K. B. Sharpless, Angew. Chem., Int. Ed., 2014, 53, 9430; (b) A. S. Barrow, C. J. Smedley, Q. Zheng, S. Li, J. Dongd and J. E. Moses, Chem. Soc. Rev., 2019, 48, 4731; (c) Y.-P. Meng, S.-M. Wang, W.-Y. Fang, Z.-Z. Xie, J. Leng, H. Alsulami and H.-L. Qin, Synthesis, 2020, 673.
- 7 (a) C. W. Tornøe, C. Christensen and M. Meldal, J. Org. Chem., 2002,
 67, 3057; (b) V. V. Rostovtsev, L. G. Green, V. V. Fokin and K. B. Sharpless, Angew. Chem., Int. Ed., 2002, 41, 2596; (c) T. R. Chan, R. Hilgraf, K. B.
 Sharpless and V. V. Fokin, Org. Lett., 2004, 6, 2853; (d) A. K. Agrahari,
 P. Bose, M. K. Jaiswal, S. Rajkhowa, A. S. Singh, S. Hotha, N. Mishra and
 V. K. Tiwari, Chem. Rev., 2021, 121, 7638.
- 8 A. B. Lowe, Polym. Chem., 2014, 5, 4820.
- 9 G. Park, K.-S. Ko, A. Zakharova and N. L. Pohl, *J. Fluorine Chem.*, 2008, **129**, 978.
- 10 T. Tamura, S. Tsukiji and I. Hamachi, J. Am. Chem. Soc., 2012, 134, 2216.
- 11 G. C. Adam, B. F. Cravatt and E. J. Sorensen, *Cell Chem. Biol.*, 2001, 8, 81.
- 12 S. Ray and A. S. Murkin, Biochemistry, 2019, 58, 5234.
- 13 J. Dommerholt, F. P. J. T. Rutjes and F. L. van Delft, *Top. Curr. Chem.*, 2016, 374, 16.
- 14 Aza-Michael addition has also gained attention in click chemistry. See: J. C. Worch, C. J. Stubbs, M. J. Price and A. P. Dove, *Chem. Rev.*, 2021, **121**, 6744.
- 15 B. Yang, H. Wu, P. D. Schnier, Y. Liu, J. Liu, N. Wang, W. F. DeGrado and L. Wan, *Proc. Natl. Acad. Sci. U. S. A.*, 2018, **115**, 11162.
- 16 (a) N. Agouram, E. M. El Hadrami and A. Bentama, *Molecules*, 2021, 26, 2937; (b) A. Staśkiewicz, P. Ledwoń, P. Rovero, A. M. Papini and R. Latajka, *Front. Chem.*, 2021, 9, 674705.