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Tyrosine bioconjugation with hypervalent iodine†

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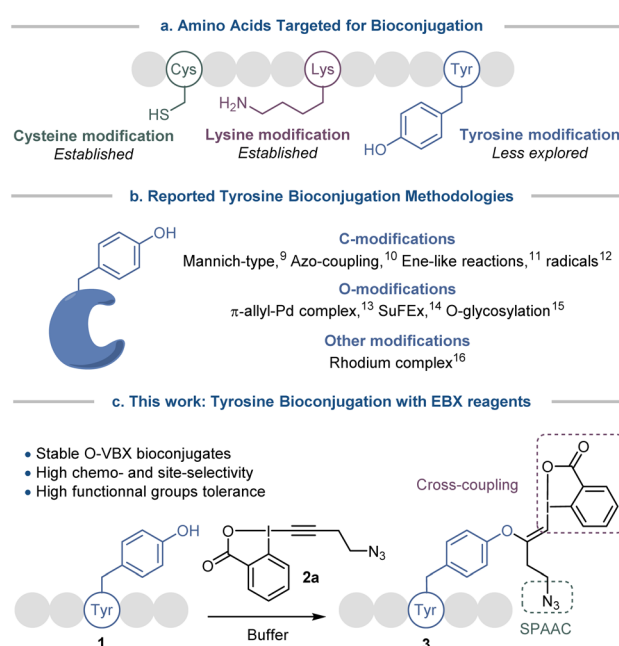
Hypervalent iodine reagents have recently emerged as powerful tools for late-stage peptide and protein functionalization. Herein we report a tyrosine bioconjugation methodology for the introduction of hypervalent iodine onto biomolecules under physiological conditions. Tyrosine residues were engaged in a selective addition onto the alkynyl bond of ethynylbenziodoxolones (EBX), resulting in stable vinylbenziodoxolones (VBX) bioconjugates. The methodology was successfully applied to peptides and proteins and tolerated all other nucleophilic residues, with the exception of cysteine. The generated VBX were further functionalized by palladium-catalyzed cross-coupling and azide-alkyne cycloaddition reactions. The method could be successfully used to modify bioactive natural products and native streptavidin to enable thiol-mediated cellular uptake.

Introduction

Site-specific chemical modification of peptides and proteins is becoming increasingly important in research and industry for monitoring cellular events or designing therapeutics, targeting ligands and molecular probes.¹ However the number of chemical transformations that are suitable for efficient biomolecule functionalization is limited by the stringent conditions required (mild and aqueous conditions, high selectivity, low toxicity) and developing chemo- and site-selective transformations remains a prominent challenge.² Traditional methods for bioconjugation target nucleophilic lysine and cysteine residues (Scheme 1a).² However, functionalization of the abundant lysine tends to lack selectivity. Modification of the rarer cysteine often requires cleavage of disulfide bonds, which play an important role in the folding and stability of proteins,³ or the expression of non-natural proteins with selectively introduced cysteines. To overcome these limitations and expand the

functionalization toolbox, less exploited amino acids such as methionine,⁴ tryptophan,⁵ histidine⁶ and tyrosine⁷ have been investigated.

Tyrosine bioconjugation in particular shows promising results (Scheme 1b).⁷ Among natural amino acids, it is an interesting residue for site-selective modification, as it is relatively rare on protein surfaces,⁸ and is often buried within the



Scheme 1 (a) Amino acids targeted for bioconjugation. (b) Reported tyrosine bioconjugation methodologies. (c) Development of a tyrosine-selective bioconjugation method with hypervalent iodine reagents.

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streptavidin was modified to enable thiol-mediated cellular uptake.

Optimization of the labelling on peptide tetramer 1a

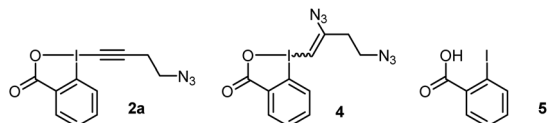
All these strategies have advantages, but also inherent limitations, such as low site- or chemo-selectivity with competitive amino acids, side reactions, the use of expensive or toxic transition metals or the stability of the reagents and the bioconjugates. Therefore the development of alternative methods is still highly desirable. With their low toxicity, high functional group tolerance and stability in biocompatible media, hypervalent iodine reagents have recently emerged as powerful tools for late-stage peptide and protein functionalization.¹⁸ In 2019, our group reported the synthesis of vinylbenziodoxolone reagents (VBX) by stereoselective addition of phenols, sulfonamides and thiols nucleophiles onto ethynylbenziodoxolones (EBX).^{19,20} The VBX were shown to be bench-stable and the enhanced reactivity of the hypervalent bond allowed their use as electrophiles in palladium-catalyzed cross-couplings at room temperature. During this work,¹⁹ an N- and C-protected tyrosine could be used as a nucleophile, but the reaction conditions developed for small organic molecules were not compatible with peptides and proteins.

Table 1 Optimization of the labelling of tetramer **1a** with JW-RF-010 (**2a**)^a



Entry	Buffer (Molarity)	pH	T (°C)	Yield ^b
1	Tris (10 mM)	8.2	37	76%
2	Tris (1 mM)	8.2	37	52%
3	Tris (100 mM)	8.2	37	96%
4	Tris (1 M)	8.2	37	90%
5	PB (100 mM)	8.2	37	86%
6	HEPES (100 mM)	8.2	37	87%
7	10× PBS	8.2	37	86%
8	Tris (100 mM)	7.0	37	24%
9	Tris (100 mM)	9.0	37	>99%
10	Tris (100 mM)	9.0	rt	98%
11	Tris (100 mM)	9.0	50	70%
12	Tris (100 mM)	9.0	90	50%
13 ^c	Tris (100 mM)	9.0	37	58%
14 ^d	Tris (100 mM)	9.0	37	80%

^a Conditions: AFYA-NH₂ **1a** (1.0 μmol), N₃-EBX **2a** (3.0 equiv), Buffer (2% v/v DMSO), 2 mM, 24 h. ^b HPLC-MS yields are given. The yields were approximated as the ratio of Aprod/Atotal where Aprod = area in mAU of the product peak and Atotal = area in mAU of all peptides products (product, starting material, and side products if present). ^c Reaction time: 1 h. ^d Reaction time: 4 h.



Decreasing the buffer molarity to 1 mM slowed down the bioconjugate formation, whereas increasing to 100 mM allowed to reach 96% HPLC-yield (entries 2–3). Under higher molarity, solubility issues of the peptide and higher EBX decomposition were observed (entry 4). The reaction displayed high tolerance towards buffer (entries 5–7), but additional side products were detected in PB, HEPES and PBS buffers.²³ The pH was found to be an important factor for the efficiency of the labelling. At pH close to physiological pH (7.0), only 24% of O-VBX was formed (entry 8), whereas under more basic conditions (pH 9.0), quantitative peptide functionalization could be achieved (entry 9). Performing the reaction at room temperature slightly slowed down the labelling (entry 10). At higher temperature, the labelling remained efficient, but higher EBX decomposition was observed (entries 11–12). The developed methodology required 24 hours to reach full conversion of the peptide to the corresponding labelled product. However, decent conversion could be obtained in shorter time. After 1 hour, almost 60% conversion was achieved (entry 13), and up to 80% yield was obtained in 4 hours (entry 14).

Scope of peptides

In order to investigate the functional group tolerance of the labelling method, tetrapeptides **1** containing various unprotected natural amino acids were then engaged in the reaction (Scheme 2a). Reproducibility of the reaction on larger scale (20 instead of 1 μ mol) was first confirmed by full conversion of AFYA-NH₂ (**1a**) to the corresponding O-VBX **3a**, which was isolated in 64% yield following HPLC purification and characterized by ¹H, ¹³C and 2-dimensional NMR spectroscopy.²⁴ A sterically hindered leucine residue did not affect the reactivity and O-VBX bioconjugate **3b** was obtained in 65% isolated yield. High chemoselectivity was achieved in the presence of tryptophan, however peptide **3c** could only be isolated as a 1:2 mixture with N₃-VBX **4**. No side reactions occurred in the presence of the nucleophilic and basic arginine (**3d**), histidine (**3e**) and lysine (**3f**) residues.

When cysteine-containing tetramer **1g** was submitted to the reaction conditions, fast addition of the cysteine residue was observed,²⁰ followed by reaction of the tyrosine, leading to a doubly labelled S- and O-VBX product **3g** in 40% isolated yield. Due to the inherent higher nucleophilicity of thiols, the functionalization of tyrosine in the presence of free cysteine has usually not been reported,^{9,12c,15,25} except for a few exceptions with selected biomolecules.¹³ Serine (**3h**), methionine (**3i**) and aspartic acid (**3j**) did not affect the reactivity, whereas a slightly lower yield due to incomplete conversion was observed for asparagine (**3k**). Finally, the position of tyrosine in the tetramer was varied (**1l–1n**). All peptides were successfully labelled to give products **3l–n**, including N- and C-terminal tyrosine residues (**3m** and **3n**).

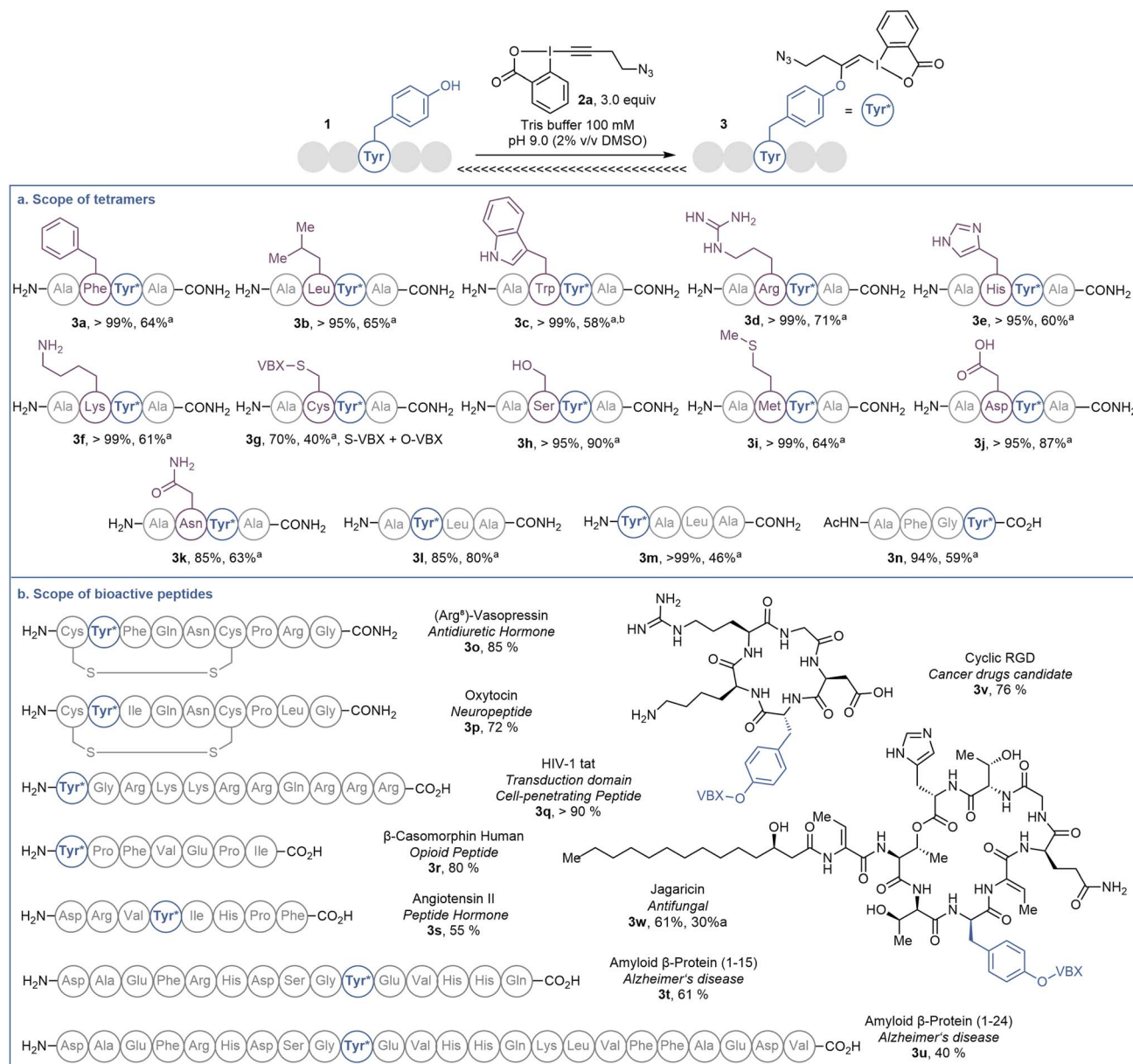
The promising functional group tolerance and high chemoselectivity observed on tetramers drove us to apply the methodology to more complex peptides (Scheme 2b). The chemoselectivity of the peptides labelling was confirmed by MS/MS analysis (see ESI† for details). The neurohypophysial hormones vasopressin (**1o**) and oxytocin (**1p**), both containing a disulfide bond, were successfully functionalized at the tyrosine position (**3o** and **3p**) with high conversion and no damage to the macrocyclic structure. High labelling conversion was also obtained at the N-terminal tyrosine of HIV-1-tat (**1q**) and β -casomorphin human (**1r**) peptides (VBXs **3q** and **3r**). Lower efficiency was observed on angiotensin II (**1s**), as well as on bigger amyloid β -proteins **1t** and **1u**, with however still high chemoselectivity towards the tyrosine residue (VBXs **3s**, **3t** and **3u**). The cyclopentapeptide RGD (**1v**), containing an Arg–Gly–Asp motif and commonly used in targeted therapy for its property to bind specifically to integrin receptor on cell surface,²⁶ was successfully labelled to give VBX **3v** in 76% yield. Jagaricin (**1w**) is a cyclic lipopeptide natural product with promising antifungal properties.²⁷ Despite the diversity of chemical structures present including threonine, histidine, glutamine and sensitive dehydrothreonine units, jagaricin (**1w**) was selectively labelled on the tyrosine residue with EBX **2a** in 61% HPLC-MS yield and could be isolated in 30% yield (**3wa**).²⁸

Preliminary results on proteins

Next, the capacity of EBX **2a** to label tyrosine on proteins was assessed (Scheme 3). When the small regulatory native protein Ubiquitin (8.6 kDa) was submitted to the reaction conditions, nearly no reaction was observed. This confirmed that only accessible tyrosine can be functionalized and no other residues react. However, with denaturing conditions (6.0 M GdmHCl) to gain access to the buried tyrosine together with a higher excess of EBX **2a** (10 equiv) and a longer reaction time (72 hours) (conditions A^a), modified ubiquitin **6** was obtained in 24% yield.

Selective modification of residue Y59 was confirmed by targeted top-down mass spectrometry analysis (see ESI† for details). Higher conversion could be obtained using 50 equiv of EBX **2a**, but without increase in yield of **6** due to side reactions (conditions B^a). The same conditions A^a were then applied to the hemeprotein myoglobin (17 kDa) containing 2 tyrosine residues. Chemo- and site-selectivity was achieved on the more reactive tyrosine Y146 to give **7** in 19% yield. Finally, we studied the functionalization of the tetrameric recombinant protein streptavidin (52 kDa), which contains 6 tyrosine residues per monomer (13 kDa), which are more accessible. Under native conditions (conditions A), 10 equiv of EBX **2a** allowed to mono-label streptavidin on the most accessible tyrosine Y31, Y42, Y48 or Y71 to give **8**. This result reflects the reactivity and accessibility of these amino acids compared to Y10 and Y84, which were not modified. Increasing the amount of EBX **2a** to 50 equiv allowed to doubly modify the protein after 24 hours of incubation (conditions B). Again, only Y31, Y42, Y48 and Y71 were functionalized. Finally, under denaturing conditions, the 4 reactive tyrosine residues could be labelled (conditions B^a).





Scheme 2 (a) Scope of tetramers on 20.0 μmol. (b) Scope of bioactive peptides on 1.0 μmol or 1.0 mg. Tyr* = Tyr modified with EBX. HPLC-MS yields are given, determined as indicated in Scheme 1. ^aIsolated yield. ^bObtained as a 1 : 2 mixture with 4.

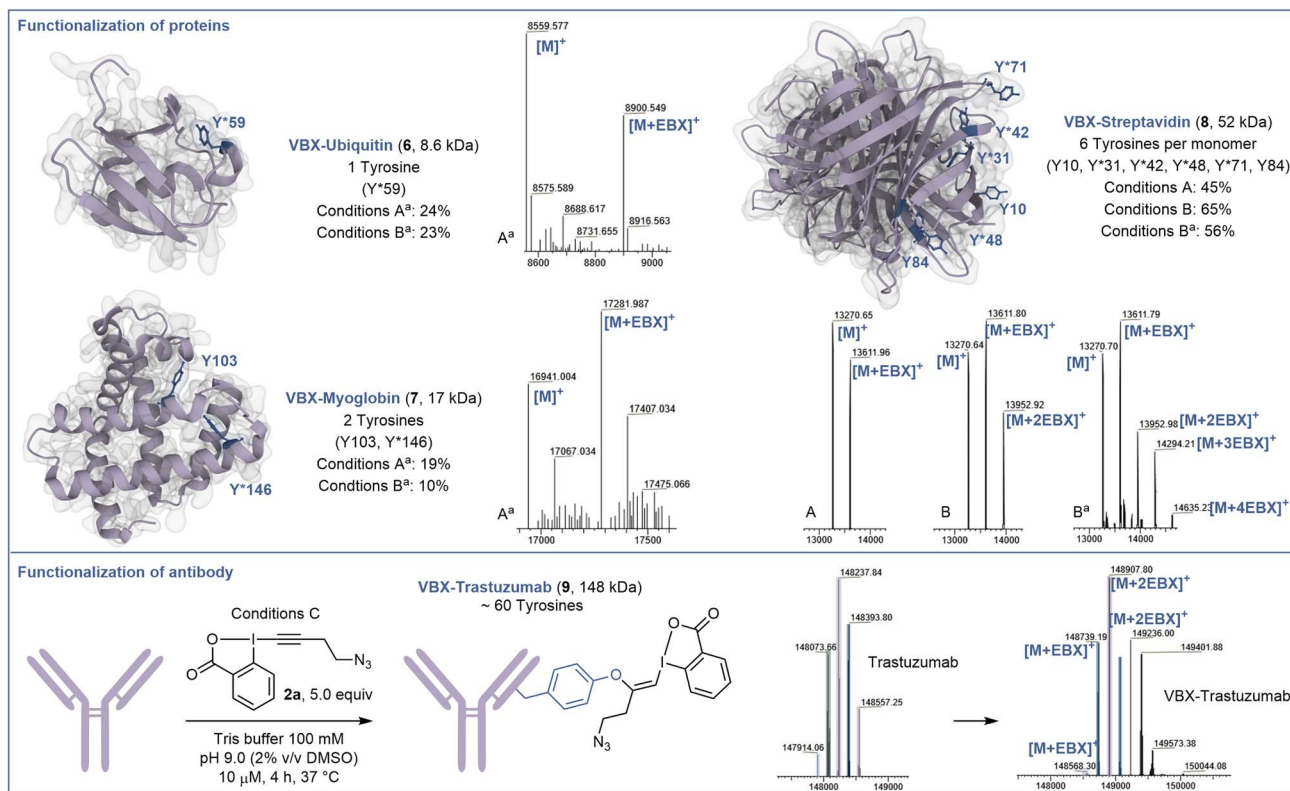
Interestingly, when another mutant streptavidin (66 kDa) was used, a better conversion was observed (see ESI†).

The incomplete conversion observed indicated that the tyrosines of the protein investigated so far were not fully accessible. We therefore decided to investigate the functionalization of trastuzumab (148 kDa), a monoclonal antibody used to treat breast cancer,²⁹ containing a high number of tyrosine residues including some with high accessibility and reactivity.³⁰ Gratefully, and despite the glycans present on the heavy chains, under mild conditions without denaturation, trastuzumab could be efficiently labelled with an average of 2 EBX and complete conversion after 4 hours to give **9**. A longer reaction time and higher excess of EBX allowed to reach a higher degree of bioconjugation (see ESI† for details).

Scope of EBX and further functionalization

Beside azide-bearing **2a**, other hypervalent iodine reagents could be used as labelling reagents under the same reaction conditions (Scheme 4). EBX with alkyne (**2b**), chlorine (**2c**) and alcohol (**2d**) functional groups as well as a rhodamine fluorophore (**2e**), were successfully added to the N-terminal tyrosine of β-casomorphin human peptide (**3r**) to give VBXs **3rb–3re**. In addition, jagaricin **3w**, was labeled with a fluorescent rhodamine **2e** and the isolated O-VBX (**3we**) could be used as a fluorescent stain in *Candida albicans* cells (see ESI† for microscopy images). Interestingly, TMS-EBX (**2f**) led to unsubstituted bioconjugate **3rg**. Such a result was previously observed on cysteine,³¹ and is due to a fast and complete desilylation of TMS-EBX (**2f**) to give the free EBX (**2g**). However, unlike with cysteine,

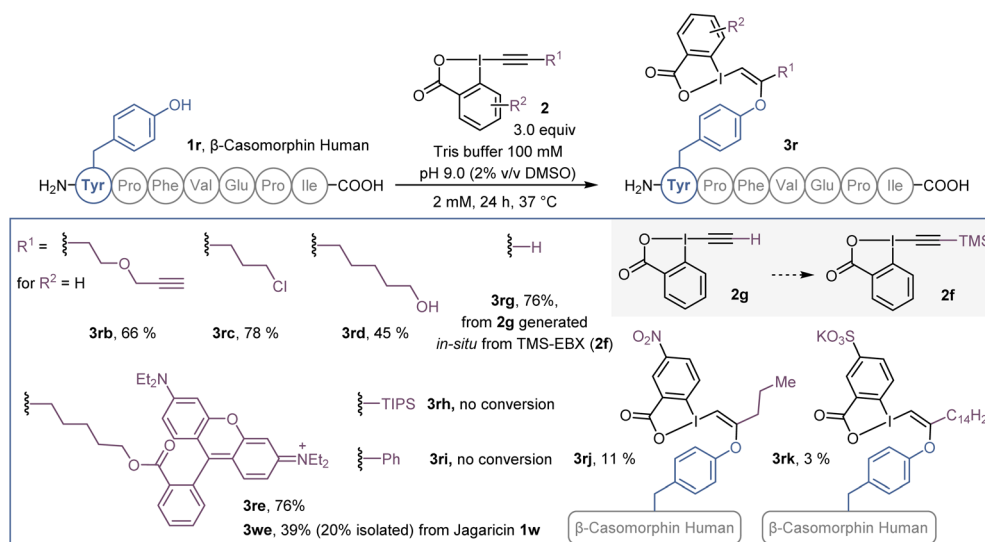




Scheme 3 Functionalization of proteins and antibody. Conditions A: Protein (10.0 nmol), N₃-EBX 2a (10.0 equiv), 100 μM in Tris buffer (100 mM, pH 9.0), 72 h. Conditions B: Protein (10.0 nmol), N₃-EBX 2a (50.0 equiv), 100 μM in Tris buffer (100 mM, pH 9.0), 24 h. Conditions C: Trastuzumab (1.0 nmol), N₃-EBX 2a (5.0 equiv), 10 μM in Tris buffer (100 mM, pH 9.0), 4 h. The ratio indicated corresponds to the signal intensity of all the functionalized products mass over the sum of the intensities of all other products with a threshold of 5% intensity. ^aDenaturing conditions: Tris buffer (100 mM, pH 9.0, 6.0 M GdmHCl).

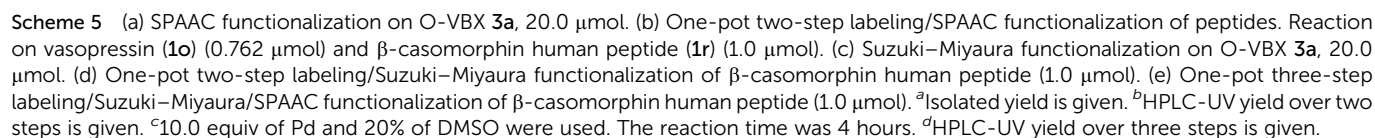
where the generated S-VBX underwent a slow rearrangement into the ethynylated product, the unsubstituted O-VBX **3rg** remained stable over time. During screening of EBX reagents, some limitations were observed. TIPS- and Ph-EBX (**2h** and **2i**)

did not provide the expected labelled product **3rh** and **3ri**. No reaction occurred, which could be due to the low solubility of these reagents in aqueous media. Similarly, low conversion was obtained with *p*-NO₂ substituted EBX **2j** to give product **3rj**.



Scheme 4 Scope of EBX reagents on β-casomorphin human peptide **1r** and jagaricin (**1w**). HPLC-MS yields are given as indicated in Scheme 1.

In addition, the hypervalent iodine handle displayed high reactivity for cross-coupling reactions under mild conditions. Our group previously reported a Suzuki–Miyaura cross-coupling of the hypervalent iodine bond of S-VBX with boronic acids in aqueous media.²⁰ Under similar conditions, labelled AFYA-NH₂ tetramer **3a** was successfully coupled with boronic acid **14a** in 54% isolated yield (Scheme 5b). Coupling of *p*-methoxyphenyl boronic acid (**14a**) was also successful with β-casomorphin



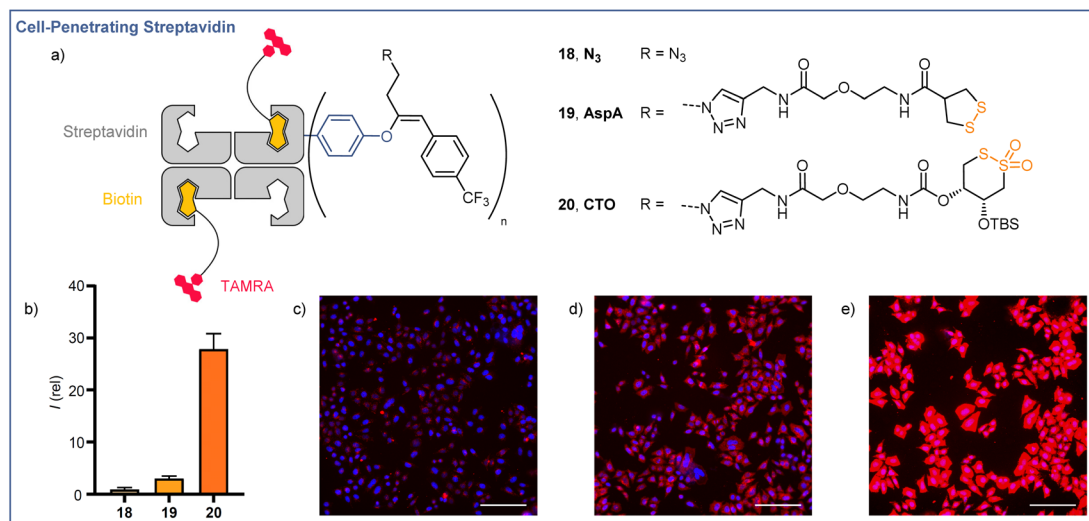


Fig. 1 Cellular uptake of streptavidin using O-VBX. (a) Schematic representations of fluorescent biotin-streptavidin complexes used in uptake studies. (b) Relative fluorescence intensities of live HeLa MZ cells in SDCM images following incubation with 10 μ M N₃, AspA, or CTO for 6 h. Images of HeLa cells incubated with **18** N₃ (c), **19** AspA (d), and **20** CTO (e) at 10 μ M for 6 h (Blue = Hoechst 33342, Red = TAMRA). Scale bars: 150 μ m. Brightness and contrast were adjusted equally in all images.

peptide (**1r**) using a one-pot two-step procedure. A fluorescein-substituted boronic acid **14b** also reacted with the *in situ* generated O-VBX **3r**, but a higher loading of palladium was required, as well as a higher ratio of DMSO to allow solubilization of the coupling partner.

Finally, both reactive handles were successfully employed in a labeling/Suzuki-Miyaura/SPAAC one-pot three-step process to afford doubly-functionalized β -casomorphin peptide **17**. A biotin unit was installed using the palladium catalyzed reaction on the hypervalent iodine moiety, whereas the PEG unit was introduced by the click reaction.

Application to the thiol-mediated cellular uptake of streptavidin

The cellular membrane provides a barrier to the passage of large, hydrophilic molecules, such as proteins, into the cytosol. Thiol-mediated uptake, postulated to function by transporter units engaging in dynamic covalent exchange cascades with cellular thiols and disulfides, has been employed previously for the efficient cytosolic delivery of streptavidin.^{35–39} Using the orthogonal reactivities offered by the EBX modification developed here, we were able to functionalize streptavidin (66 kDa) with both a transporter for thiol-mediated uptake, *via* CuAAC 'click' chemistry with the azide handle, and a lipophilic CF₃ functionalized aromatic unit,⁴⁰ *via* Suzuki coupling with the hypervalent iodine motif. The functionalized proteins were still easily complexed with 2 equiv of a red fluorescent TAMRA-biotin derivative (Fig. 1a), and uptake of the complexes was studied in HeLa MZ cells. Compared with the protein after Suzuki coupling, but prior to click functionalization (**18**, R = N₃), streptavidin functionalized with asparagusic acid (**19**, R = AspA) showed ~3-fold increase in cellular uptake whereas streptavidin functionalized with a cyclic thiosulfonate (**20**, R = CTO), gave ~28-fold increase in cellular uptake *versus* the N₃

control (Fig. 1b). These results were in accordance with the relative reactivities of the two transporter motifs in thiol-disulfide exchange, and previous studies with small molecule fluorophore cargoes.⁴¹

Structure-activity relationships for cyclic thiosulfonate transporters and thiol-mediated uptake inhibitors revealed a strong dependence in either case on the presence of hydrophobic directing groups to target aprotic environments such as the cellular membrane and proteins, in which the proticity-dependent cascade exchange of cyclic thiosulfonates is enhanced.⁴¹ The ~9-fold increase in uptake efficiency observed between AspA and CTO complexes exceeds the ~3-fold difference seen with small molecule fluorophore cargoes, the greater differential perhaps resulting from the additional hydrophobic directing group provided by the CF₃-functionalised aromatic unit, which is known to be more important for CTO transporters.⁴¹

In the case of AspA and CTO, a diffuse pattern of fluorescence was observed in spinning disk confocal microscopy (SDCM) images (Fig. 1d and e). In line with previous reports, this implied delivery to the cytosol rather than entrapment within endosomes following endocytosis, whereas N₃ complex **18** showed a punctate fluorescence indicative of endocytosis (Fig. 1c).^{42,43} These results indicate the potential of readily accessible, broadly stable cyclic thiosulfonates as transporters for the efficient cytosolic delivery of proteins *via* thiol-mediated uptake, and highlight the possibilities offered by the dual, orthogonal functionalizations available following EBX-tyrosine modification.

Conclusions

In summary, we have reported a chemo- and site-selective tyrosine bioconjugation methodology using hypervalent



iodine reagents. Under mild and biocompatible conditions, tyrosine residues reacted with EBX reagents to generate stable O-VBX bioconjugates. The high functional group tolerance of the conjugation method allowed to selectively label a broad range of bioactive peptides, including the natural product jagaricin (**3w**). Preliminary results were obtained with selected proteins and an antibody. The generated O-VBX conjugates could be further functionalized orthogonally by palladium-catalyzed Suzuki–Miyaura cross-coupling and azide–alkyne cycloaddition, providing a wide range of labelled biomolecules. The potential of the doubly-orthogonal functionalization was demonstrated in a cellular uptake experiment, which further establishes that the functionalized streptavidin retains its structural integrity and activity to bind biotin, a crucial feature for applications in chemical biology. This work further highlights the potential of hypervalent iodine reagents in biomolecule labeling. Moreover, the high tyrosine selectivity described compares well with existing methods for O-functionalization of tyrosine residues, in which labelling of other nucleophilic amino acids such as lysine and histidine has often been reported.¹⁴

Data availability

Experimental procedures, compound characterization and microscopy images are provided within the ESI† and raw data is available at zenodo.org: <https://doi.org/10.5281/zenodo.7074420>.

Author contributions

N. D. developed and optimized the bioconjugation methodology, examined the scope of the reaction on peptides and proteins, investigated functionalization of the bioconjugates and prepared the related part of the manuscript and experimental parts. J. R. J. M. performed the cellular uptake experiments and prepared the related part of the manuscript and experimental parts. L. M. and N. G. performed the mass analysis and prepared the related experimental part. S. G. performed structural analysis studies on the jagaricin conjugates **3w** and **3we** and determined the biological activity of **3w**. J. L. S. performed the microscopy experiments with **3we**. P. S. supervised the experiments on the jagaricin conjugates and proofread the manuscript. S. M. supervised the cellular uptake experiments and proofread the manuscript. J. W. supervised the bioconjugation work, proofread the manuscript and experimental part and coordinated the research project.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- (a) K. Fosgerau and T. Hoffmann, *Drug Discovery Today*, 2015, **20**, 122; (b) Q.-Y. Hu, F. Berti and R. Adamo, *Chem. Soc. Rev.*, 2016, **45**, 1691–1719; (c) S. B. Gunnoo and A. Maddar, *Org. Biomol. Chem.*, 2016, **14**, 8002–8013; (d) J. L. Lau and M. K. Dunn, *Bioorg. Med. Chem.*, 2018, **26**, 2700–2707.
- (a) C. D. Spicer and B. G. Davis, *Nat. Commun.*, 2014, **5**, 4740; (b) O. Koniev and A. Wagner, *Chem. Soc. Rev.*, 2015, **44**, 5495–5551; (c) O. Boutureira and G. J. L. Bernardes, *Chem. Rev.*, 2015, **115**, 2174–2195; (d) E. A. Hoyt, P. M. S. D. Cal, B. L. Oliveira and G. J. L. Bernardes, *Nat. Rev. Chem.*, 2019, **3**, 147–171; (e) T. Tamura and I. Hamachi, *J. Am. Chem. Soc.*, 2019, **141**, 2782–2799; (f) A. Boto, C. C. González, D. Hernández, I. Romero-Estudillo and C. J. Saavedra, *Org. Chem. Front.*, 2021, **8**, 6720–6759; (g) S. J. Walsh, J. D. Bargh, F. M. Dannheim, A. R. Hanby, H. Seki, A. J. Counsell, X. Ou, E. Fowler, N. Ashman, Y. Takada, et al., *Chem. Soc. Rev.*, 2021, **50**, 1305–1353; (h) C. Sornay, V. Vaur, A. Wagner and G. Chaubet, *R. Soc. Open Sci.*, 2022, **9**, 211563.
- C. S. Sevier and C. A. Kaiser, *Nat. Rev. Mol. Cell Biol.*, 2002, **3**, 836–847.
- (a) S. Lin, X. Yang, S. Jia, A. M. Weeks, M. Hornsby, P. S. Lee, R. V. Nichiporuk, A. T. Iavarone, J. A. Wells, F. D. Toste, et al., *Science*, 2017, **355**, 597–602; (b) M. T. Taylor, J. E. Nelson, M. G. Suero and M. J. Gaunt, *Nature*, 2018, **562**, 563–568; (c) J. Kim, B. X. Li, R. Y.-C. Huang, J. X. Qiao, W. R. Ewing and D. W. C. MacMillan, *J. Am. Chem. Soc.*, 2020, **142**, 21260–21266.
- (a) J. M. Antos and M. B. Francis, *J. Am. Chem. Soc.*, 2004, **126**, 10256–10257; (b) Y. Seki, T. Ishiyama, D. Sasaki, J. Abe, Y. Sohma, K. Oisaki and M. Kanai, *J. Am. Chem. Soc.*, 2016, **138**, 10798–10801; (c) S. J. Tower, W. J. Hetcher, T. E. Myers, N. J. Kuehl and M. T. Taylor, *J. Am. Chem. Soc.*, 2020, **142**, 9112–9118.
- (a) J. Ohata, M. B. Minus, M. E. Abernathy and Z. T. Ball, *J. Am. Chem. Soc.*, 2016, **138**, 7472–7475; (b) S. Jia, D. He and C. J. Chang, *J. Am. Chem. Soc.*, 2019, **141**, 7294–7301.
- Recent reviews: (a) P. A. Szijj, K. A. Kostadinova, R. J. Spears and V. Chudasama, *Org. Biomol. Chem.*, 2020, **18**, 9018–9028; (b) D. A. Dorta, D. Deniaud, M. Mével and S. G. Gouin, *Chem. - Eur. J.*, 2020, **26**, 14257–14269.
- N. Echols, P. Harrison, S. Balasubramanian, N. M. Luscombe, P. Bertone, Z. Zhang and M. Gerstein, *Nucleic Acids Res.*, 2002, **30**, 2515–2523.
- N. S. Joshi, L. R. Whitaker and M. B. Francis, *J. Am. Chem. Soc.*, 2004, **126**, 15942–15943.



- 10 (a) J. M. Hooker, E. W. Kovacs and M. B. Francis, *J. Am. Chem. Soc.*, 2004, **126**, 3718–3719; (b) F. W. Kimani and J. C. Jewett, *Angew. Chem., Int. Ed.*, 2015, **54**, 4051–4054.
- 11 (a) H. Ban, J. Gavriluk and C. F. Barbas, *J. Am. Chem. Soc.*, 2010, **132**, 1523–1525; (b) H. Ban, M. Nagano, J. Gavriluk, W. Hakamata, T. Inokuma and C. F. Barbas, *Bioconjugate Chem.*, 2013, **24**, 520–532; (c) M. Bauer, I. Ahmed, A. Vigovskaya and L. Fruk, *Bioconjugate Chem.*, 2013, **24**, 1094–1101.
- 12 (a) K. Kim, D. A. Fancy, D. Carney and T. Kodadek, *J. Am. Chem. Soc.*, 1999, **121**, 11896–11897; (b) K. L. Seim, A. C. Obermeyer and M. B. Francis, *J. Am. Chem. Soc.*, 2011, **133**, 16970–16976; (c) K. Maruyama, T. Ishiyama, Y. Seki, K. Sakai, T. Togo, K. Oisaki and M. Kanai, *J. Am. Chem. Soc.*, 2021, **143**, 19844–19855; (d) A. M. Marmelstein, M. J. Lobba, C. S. Mogilevsky, J. C. Maza, D. D. Brauer and M. B. Francis, *J. Am. Chem. Soc.*, 2020, **142**, 5078–5086; (e) B. X. Li, D. K. Kim, S. Bloom, R. Y.-C. Huang, J. X. Qiao, W. R. Ewing, D. G. Oblinsky, G. D. Scholes and D. W. C. MacMillan, *Nat. Chem.*, 2021, 1–7; (f) C. S. Mogilevsky, M. J. Lobba, D. D. Brauer, A. M. Marmelstein, J. C. Maza, J. M. Gleason, J. A. Doudna and M. B. Francis, *J. Am. Chem. Soc.*, 2021, **143**, 13538–13547.
- 13 S. D. Tilley and M. B. Francis, *J. Am. Chem. Soc.*, 2006, **128**, 1080–1081.
- 14 (a) E. C. Hett, H. Xu, K. F. Geoghegan, A. Gopalsamy, R. E. Kyne, C. A. Menard, A. Narayanan, M. D. Parikh, S. Liu, L. Roberts, et al., *ACS Chem. Biol.*, 2015, **10**, 1094–1098; (b) H. S. Hahm, E. K. Toroitich, A. L. Borne, J. W. Brulet, A. H. Libby, K. Yuan, T. B. Ware, R. L. McCloud, A. M. Ciancone and K.-L. Hsu, *Nat. Chem. Biol.*, 2020, **16**, 150–159; (ac) J. W. Brulet, A. L. Borne, K. Yuan, A. H. Libby and K.-L. Hsu, *J. Am. Chem. Soc.*, 2020, **142**, 8270–8280; (ad) T. Huang, S. Hosseini-barkooie, A. L. Borne, M. E. Granade, J. W. Brulet, T. E. Harris, H. A. Ferris and K.-L. Hsu, *Chem. Sci.*, 2021, **12**, 3295–3307.
- 15 T. J. Wadzinski, A. Steinauer, L. Hie, G. Pelletier, A. Schepartz and S. J. Miller, *Nat. Chem.*, 2018, **10**, 644–652.
- 16 (a) P. Wang, Y. Cheng, C. Wu, Y. Zhou, Z. Cheng, H. Li, R. Wang, W. Su and L. Fang, *Org. Lett.*, 2021, **23**, 4137–4141; (b) M. J. Lobba, C. Fellmann, A. M. Marmelstein, J. C. Maza, E. N. Kissman, S. A. Robinson, B. T. Staahl, C. Urnes, R. J. Lew, C. S. Mogilevsky, et al., *ACS Cent. Sci.*, 2020, **6**, 1564–1571.
- 17 J. Ohata, M. K. Miller, C. M. Mountain, F. Vohidov and Z. T. Ball, *Angew. Chem., Int. Ed.*, 2018, **57**, 2827–2830.
- 18 E. M. D. Allouche, E. Grinhagena and J. Waser, *Angew. Chem., Int. Ed.*, 2022, **60**, 2–17.
- 19 P. Caramenti, N. Declas, R. Tessier, M. D. Wodrich and J. Waser, *Chem. Sci.*, 2019, **10**, 3223–3230.
- 20 R. Tessier, J. Ceballos, N. Guidotti, R. Simonet-Davin, B. Fierz and J. Waser, *Chem.*, 2019, **5**, 2243–2263.
- 21 D. Abegg, R. Frei, L. Cerato, D. Prasad Hari, C. Wang, J. Waser and A. Adibekian, *Angew. Chem., Int. Ed.*, 2015, **54**, 10852–10857.
- 22 VBX **4** was probably formed through the nucleophilic addition of an azide to the alkynyl triple bond of EBX.
- A. Yoshimura, C. D. Huss, M. Liebl, G. T. Rohde, S. M. Larson, G. B. Frahm, M. W. Luedtke, T. J. Schumacher, Z. S. Gardner, V. V. Zhdankin, P. S. Postnikov, M. S. Yusubov, T. Kitamura and A. Saito, *Adv. Synth. Catal.*, 2021, **363**, 3365–3371. The azide anion would probably origin from a non-yet identified degradation pathway of EBX **2a**.
- 23 Addition of the phosphate or sulfonate salt of the buffer on the EBX.
- 24 O-VBX **3a** displays a high stability at low and high pH and temperature and in presence of a low and high concentration of GSH (see ESI† for details).
- 25 Additional selected examples: (a) D. W. Romanini and M. B. Francis, *Bioconjugate Chem.*, 2008, **19**, 153–157; (b) J. M. McFarland, N. S. Joshi and M. B. Francis, *J. Am. Chem. Soc.*, 2008, **130**, 7639–7644; (c) H.-M. Guo, M. Minakawa, L. Ueno and F. Tanaka, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 1210–1213; (d) J. Gavriluk, H. Ban, M. Nagano, W. Hakamata and C. F. Barbas, *Bioconjugate Chem.*, 2012, **23**, 2321–2328.
- 26 M. Alipour, M. Baneshi, S. Hosseinkhani, R. Mahmoudi, A. Jabari Arabzadeh, M. Akrami, J. Mehrzad and H. Bardania, *J. Biomed. Mater. Res.*, 2020, **108**, 839–850.
- 27 K. Graupner, K. Scherlach, T. Bretschneider, G. Lackner, M. Roth, H. Gross and C. Hertweck, *Angew. Chem., Int. Ed.*, 2012, **51**, 13173–13177.
- 28 The bioactivity of the isolated lipopeptide **3wa** against the pathogenic yeast *Candida albicans* was tested. Compared to the natural product jagaricin (**3w**), which displayed a minimal inhibition concentration (MIC) of 1.6 $\mu\text{g/mL}$, the derivative exhibited a MIC of 50 $\mu\text{g/mL}$.
- 29 R. Nahta and F. J. Esteva, *Oncogene*, 2007, **26**, 3637–3643.
- 30 S. Sato, M. Matsumura, T. Kadonosono, S. Abe, T. Ueno, H. Ueda and H. Nakamura, *Bioconjug. Chem.*, 2020, **31**, 1417–1424.
- 31 R. Tessier, R. K. Nandi, B. G. Dwyer, D. Abegg, C. Sornay, J. Ceballos, S. Erb, S. Cianféroni, A. Wagner, G. Chaubet, A. Adibekian and J. Waser, *Angew. Chem., Int. Ed.*, 2020, **59**, 10961–10970.
- 32 A. K. Mishra, R. Tessier, D. P. Hari and J. Waser, *Angew. Chem., Int. Ed.*, 2021, **60**, 17963–17968.
- 33 (a) In aqueous media, EBX **2k** bearing a sulfonate on the aromatic ring was reported to preferably undergo alkynylation instead of VBX formation with cysteine nucleophiles (ref. 29). The S-VBX products could be observed as a minor product, which could suggest either that an α -addition mechanism was favored or that 1,2-sulfur shift was accelerated (ref. 30b). On the contrary, neutral alkyl-substituted-EBXs such as **2a** led to S-VBX products exclusively via a β -addition pathway (ref. 20). If an α -addition would occur with tyrosine, an O-alkynylation reaction would be expected. However, to our knowledge, such reactivity was not reported with EBX reagents and phenol nucleophiles, and the corresponding ynol ether would be expected to be unstable. The lower yield observed with EBX **2j** are more difficult to rationalize at this stage.; (b) R. Frei, M. D. Wodrich, D. P. Hari, P.-A. Borin,



- C. Chauvier and J. Waser, *J. Am. Chem. Soc.*, 2014, **136**, 16563–16573.
- 34 J. C. Jewett and C. R. Bertozzi, *Chem. Soc. Rev.*, 2010, **39**, 1272–1279.
- 35 G. Gasparini and S. Matile, *Chem. Commun.*, 2015, **51**, 17160–17162.
- 36 J. López-Andarias, J. Saabach, D. Moreau, Y. Cheng, E. Derivery, Q. Laurent, M. González-Gaitán, N. Winssinger, N. Sakai and S. Matile, *J. Am. Chem. Soc.*, 2020, **142**, 4784–4792.
- 37 Y. Okamoto, R. Kojima, F. Schwizer, E. Bartolami, T. Heinisch, S. Matile, M. Fussenegger and T. R. Ward, *Nat. Commun.*, 2018, **9**, 1943.
- 38 J. Fu, C. Yu, L. Li and S. Q. Yao, *J. Am. Chem. Soc.*, 2015, **137**, 12153–12160.
- 39 B. Lim, Y. Cheng, T. Kato, A.-T. Pham, E. Le Du, A. K. Mishra, E. Grinhagena, D. Moreau, N. Sakai, J. Waser and S. Matile, *Helv. Chim. Acta*, 2021, **104**, e2100085.
- 40 A. D. de Araujo, H. N. Hoang, J. Lim, J. Mak and D. P. Fairlie, *Angew. Chem., Int. Ed.*, 2022, anie.202203995.
- 41 T. Kato, B. Lim, Y. Cheng, A.-T. Pham, J. Maynard, D. Moreau, A. I. Poblador-Bahamonde, N. Sakai and S. Matile, *JACS Au*, 2022, **2**, 839–852.
- 42 D. C. Luther, T. Jeon, R. Goswami, H. Nagaraj, D. Kim, Y.-W. Lee and V. M. Rotello, *Bioconjug. Chem.*, 2021, **32**, 891–896.
- 43 S. Du, S. S. Liew, L. Li and S. Q. Yao, *J. Am. Chem. Soc.*, 2018, **140**, 15986–15996.

