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Cysteine protecting groups: applications in peptide and protein science

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Protecting group chemistry for the cysteine thiol group has enabled a vast array of peptide and protein chemistry over the last several decades. Increasingly sophisticated strategies for the protection, and subsequent deprotection, of cysteine have been developed, facilitating synthesis of complex disulfide-rich peptides, semisynthesis of proteins, and peptide/protein labelling *in vitro* and *in vivo*. In this review, we analyse and discuss the 60+ individual protecting groups reported for cysteine, highlighting their applications in peptide synthesis and protein science.

1. Introduction

The concept of protecting, and subsequently deprotecting, functional groups is of paramount importance in synthetic chemistry.^{1–3} Protecting group strategies in particular feature extensively in the synthesis of peptides, whereby amino acid building blocks are coupled to one another *via* amide bonds. This is unsurprising, given the array of functional groups that are found within the 20 proteinogenic amino acids, including: amines, alcohols, thioethers, imidazole rings, and carboxylic acids.⁴ Of the proteinogenic amino acids, cysteine (Cys) has garnered enormous interest within the field of peptide (and protein) chemistry and biology, owing to the unique properties

of its thiol side chain. For example, disulfide bonds, which can be formed *via* the covalent linkage of two Cys thiol side chains, are of utmost importance in defining certain peptides and proteins conformational, proteolytic, chemical, and biophysical properties.^{5,6} Disulfide-containing peptides have also gained huge interest as therapeutic agents.^{7–9} In 1953 Vigneaud, Ressler, Swan, Roberts, Katsoyannis, and Gordon, demonstrated the chemical synthesis of the hormone oxytocin, a disulfide containing peptide that is the focus of a great deal of therapeutic research (Fig. 1a).^{10,11} Vigneaud was later awarded the Nobel prize in Chemistry in 1955. The hormone insulin, which is produced in the pancreas and contains one intrachain and two interchain disulfide bonds, has been a critical component of treating Type I diabetes over the last 100 years (Fig. 1b).¹² Disulfide-containing peptides also feature in a number of Food and Drug Administration (FDA) approved therapeutics, such as Ziconotide (Prialt™, a disulfide-rich peptide

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novel methodology for use in peptide chemistry and protein bioconjugation.

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for treating severe chronic pain, Fig. 1c),¹³ Linaclotide (Linzess™, a disulfide-rich peptide for treating severe irritable bowel syndrome),¹⁴ and ⁶⁸Ga-DOTATOC (Fig. 1d, an octreotide-based tumour imaging agent).¹⁵ In biology, Cys often finds itself of critical importance in redox processes,¹⁶ and in the active sites of enzymes such as cysteine proteases.¹⁷ Cys is also often the site of choice when it comes to the site-specific modification of proteins, also known as bioconjugation, owing to its favourable properties (nucleophilic profile of the thiol at neutral/near-neutral pH, low natural abundance, general ease of incorporation into proteins *via* site-directed mutagenesis).¹⁸ This growing field in chemical biology has led to the development of a range of therapeutically relevant bioconjugates, most notable of which include antibody–drug conjugates (ADCs);¹⁹ these include FDA approved Adcetris™ (Fig. 1e, brentuximab vedotin, used to treat lymphoma), Polivy™ (polatuzumab vedotin, used to treat lymphoma), and Padcev™ (enfortumab vedotin, used to treat urothelial cancer), all of which have their therapeutic payload covalently attached to the antibody *via* Cys conjugation.²⁰

The reactivity profile of Cys enables a plethora of applications in chemistry and biology related to peptides and proteins. However, this reactivity also leads to significant challenges when employing the residue for peptide chemistry in particular. The reactive nature of the thiol side chain makes it prone to side reactions such as alkylation and oxidation.²¹ Particularly for disulfide-rich peptides, ensuring the regioselective formation/correct connectivity of disulfides presents a significant challenge in peptide synthesis.^{5,6} Ensuring racemisation of Cys at the α -carbon stereocenter does not occur during peptide synthesis also presents a notable challenge; this is especially true for synthesising peptides containing a C-terminal Cys.²² Other side reactions related to Fmoc SPPS include formation of 3-(1-piperidinyl)alanine by-products at the C-terminal Cys position formed by an elimination–addition reaction involving piperidine.^{23,24} Unsurprisingly, this has led to significant research into strategies to

protect (and subsequently deprotect) the thiol side chain to overcome these challenges, and to further expand upon the synthesis of biomolecules. Indeed, protection of Cys during standard peptide synthesis is therefore often critical to avoid undesired alkylation/oxidation, allowing for synthesis of the desired peptide. In the case of disulfide-containing peptide synthesis, the development of “orthogonal” Cys protecting groups (which can be selectively deprotected in the presence of one another) has proved paramount to ensuring regioselective disulfide formation.⁶

Herein we review the different thiol protecting groups reported for Cys throughout the last 70+ years. We analyse and discuss each of the individual 60+ protecting groups that have been reported for Cys protection (and deprotection). For each group (and where applicable), this review will focus on (a) the conditions used for its deprotection, (b) use in Boc and Fmoc peptide synthesis, (c) its comparison to other related Cys protecting groups, and (d) notable applications of the Cys protecting group in peptide and protein chemistry.

2. Organisation of review

This review begins with a brief introduction to key concepts relevant to the content covered within the review and Cys protecting group chemistry as a whole. This is then followed by a table (Table 1) and a series of discussions about each individual protecting group. Taking inspiration from previously reported literature,^{4–6} the protecting groups within this review have been divided into separate categories based on the conditions that have primarily been used for their deprotection. We note that, in cases where multiple methods of deprotection are available, certain protecting groups do not sit rigidly within these categories. The categories are as follows: Acid labile, oxidatively labile, base labile, enzymelabile, hydrazine-labile, palladium-labile, and reductively labile. The “benzyl” protecting group, protecting groups specific to N-terminal Cys, and the “safety catch” protecting group, have also been assigned to their own separate categories. Additionally, in order to give historical context, the groups in each category are broadly arranged in chronological order. For additional reading, we direct the reader to extensive reviews on general amino acid protecting groups by Isidro-Llobet, Álveraz, and Albericio,⁴ along with reviews that focus on regioselective disulfide formation by Postma, and Albericio,⁶ and more recently by He, Pan, Mayer, and Li.⁵ We also wish to highlight a recent review by Laps, Satish, and Brik discussing recent advances in transition metal chemistry relating to peptide/protein synthesis.²⁵

3. Key concepts in cysteine protecting group chemistry

3.1 Solid phase peptide synthesis

Briefly, chemical peptide synthesis dates back well over 100 years ago, when Curtius synthesised benzoylglycylglycine, an N-protected dipeptide, in 1882 using benzoyl chloride and the silver salt of glycine.¹⁷ In the early 1900s, Fischer and Fourneau reported the



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promoted to Reader (2017) and then Professor (2019) at the same institution. Vijay's research has been highlighted by Forbes, Scientific American, CNN News, Nature Chemistry and the Royal Society of Chemistry.



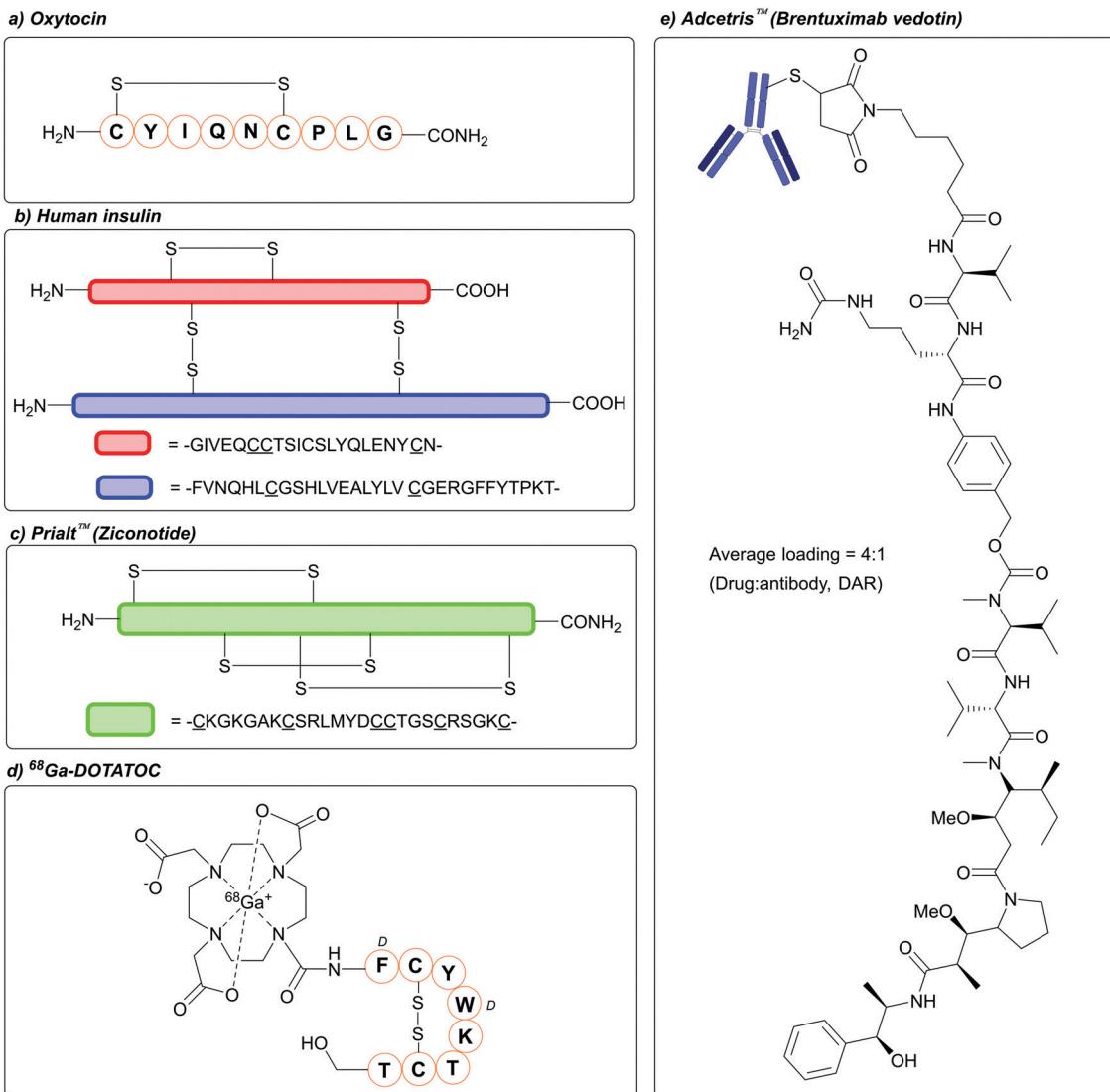


Fig. 1 Examples of Cys-containing biomolecules of therapeutic interest. (a) Oxytocin, (b) Human insulin, (c) Prialt™/Ziconotide, (d) ^{68}Ga -DOTATOC, (e) Adcetris™/Brentuximab vedotin.

synthesis of the unprotected dipeptide *via* hydrolysis of glycine ester to give the diketopiperazine, which subsequently hydrolysed to give glycylglycine.²⁶ Later, in 1932, the concept of using protecting groups to temporarily mask functional groups in the context of peptide synthesis was established when Bergmann and Zervas introduced the carbobenzoxy group (Cbz or Z) for the protection of amines.²⁶ Another key concept was then introduced in 1955 by Sheehan and Hess, where *N,N*-dicyclohexylcarbodiimide (DCC) was established as an amide coupling reagent for peptide synthesis.²⁷ This would later be followed by the introduction of the acid-labile *tert*-butyloxycarbonyl (Boc) protecting group in 1957 by Carpino,²⁸ McKay, and Albertson.²⁹ Peptide synthesis would later be revolutionised by the advent of solid phase peptide synthesis (SPPS) reported in 1963 by Merrifield.³⁰ Here, peptides are synthesised through sequential coupling of protected amino acids on a solid support (typically a polystyrene resin); impurities and excess reagents can then be removed by simple wash and filtration of

the solid support (Fig. 2). Specific cocktails of reagents can then be used to cleave and isolate the peptide from the resin; different resins have since been reported over the last few decades, which yield peptides with different functional groups at the *C*-terminus once cleaved *e.g.* acid, amide, thioester.³¹ Carpino, along with Han, would then introduce the base-labile 9-fluorenylmethoxycarbonyl (Fmoc) protecting group in 1970.³² The combination of these concepts has led to development of two solid phase strategies for peptide synthesis: the Boc/Benzyl (Bn) strategy, and the Fmoc/*tert*-butyl (tBu) strategy. The Fmoc/tBu strategy is now the more routinely used, as it avoids both the repeated acidic treatments of the peptide, and the use of hydrogen fluoride (HF) (which requires specialist equipment and is extremely toxic) that is required in Boc/Bn peptide synthesis.³³ For a more extensive breakdown of the history of peptide chemistry and related key concepts, we direct the reader's attention to discussions in recently published reviews.^{33,34}



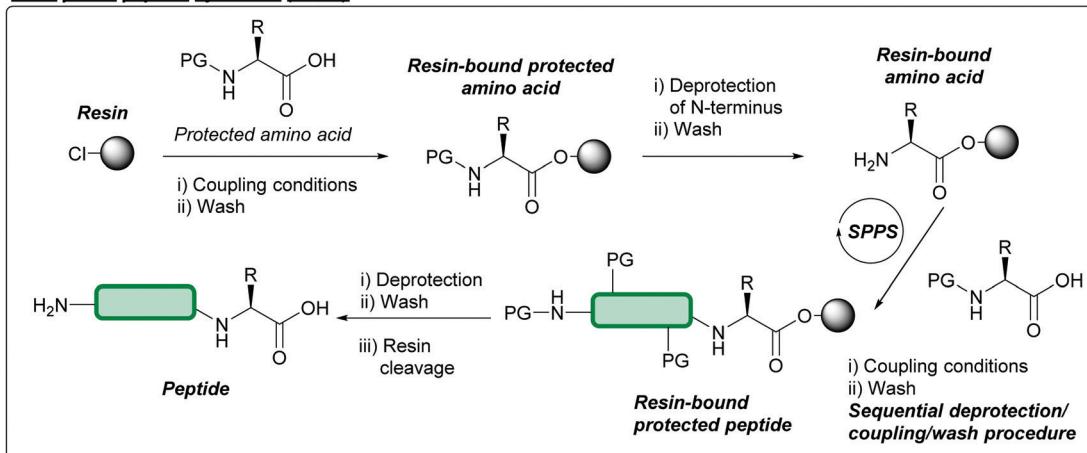
Solid phase peptide synthesis (SPPS)

Fig. 2 Outline of solid phase peptide synthesis (SPPS) procedure. Following loading of a desired amino acid onto a functionalised polystyrene resin, sequential deprotections of the N-terminal protecting group and amide coupling reactions yield a resin-bound, protected peptide of a desired sequence. Excess reagents/impurities can be removed by washing and filtration at each step. Removal of protecting groups and cleavage of the peptide off the resin with specific cocktails of reagents yields the final desired peptide.

3.2 Native chemical ligation and related ligation strategies

SPPS is now the standard for the chemical peptide synthesis; however, the process is generally limited to peptides of *ca.* 50 amino acids long.³⁵ As such, ligation reactions are usually employed when synthesising larger peptides,³⁶ the most common of which is the native chemical ligation (NCL) strategy. Introduced in 1994 by Dawson, Muir, Clark-Lewis, and Kent,³⁷ NCL is a ligation reaction between a C-terminal peptide thioester and an N-terminal cysteinyl peptide. An initial exchange reaction occurs between the thiol and the thioester linking the two peptides *via* a thioester bond. The molecule then spontaneously rearranges *via* an intramolecular *S,N*-acyl transfer, resulting in the formation of a native peptide bond (Fig. 3a).³⁸ A notable example of NCL is in the one-pot synthesis of Crambin reported in 2004, whereby three peptide fragments were ligated together using NCL, followed by folding to yield the desired protein.³⁹ Peptide fragments for NCL can be synthesised chemically *via* SPPS or, when significantly longer peptide fragments are desired, can be produced recombinantly in bacterial expression systems such as in *Escherichia coli* (*E. coli*) cells. In some cases, these recombinantly produced peptides contain an intein segment fused to the C-terminus, which can then undergo *N,S*-acyl shift and, following addition of an exogenous thiol such as sodium 2-mercaptoethanesulfonate (MESNa), cleavage to yield a thioester-containing peptide fragment that can subsequently participate in NCL; this process is known as expressed protein ligation (EPL, Fig. 3b).^{40,41} The resulting Cys residue post-NCL can then be converted to alanine through metal-based desulfurisation,⁴² or metal-free-based desulfurisation using radical initiators such as 2,2'-azobis[2-(2-imidazolin-2-yl)propane]dihydrochloride (VA-044) in combination with tris(2-carboxyethyl)phosphine (TCEP, Fig. 3c).⁴³ As a result, it is therefore common for alanine within a target peptide sequence to be the ligation site of choice.

Other common systems used for ligation of large peptides are *N,S*-acyl shift systems, one example of which is the

cysteinylprolyl ester (CPE) system.⁴⁴ Here, peptides containing a CPE unit at the C-terminus can undergo spontaneous *N* > *S* transformations into diketopiperazine thioesters. The resulting thioester can then undergo NCL in a one-pot process (Fig. 3d). A related system that uses cysteinylprolyl imide (CPI) peptides has more recently been described and used in the synthesis of proteins such as ZHER2 affibody.⁴⁵ In addition, peptides containing C-terminal hydrazides can be used as more chemically stable peptide thioester precursors.⁴⁶ In this strategy the hydrazide group can be chemically converted to a C-terminal azide or acyl pyrazole using nitrous acid or acetyl acetone, followed by conversion to a thioester through addition of 4-mercaptophenylacetic acid (MPAA, Fig. 3(e)).⁴⁷ This methodology has since been used in the synthesis of multiple proteins, including *Centruroides suffusus suffusus* toxin II protein (CstII)⁴⁶ and α -synuclein.⁴⁸ Peptide hydrazides can also be prepared through Cys cyanylation using 2-nitro-5-thiocyanatobenzoic acid (NTCB) followed by addition of hydrazine, as shown in the recently described activated Cys-directed protein ligation (APCL).⁴⁹ Another ligation strategy is the thioester method, whereby a silver (Ag^+) activated C-terminal alkyl thioester is directly displaced by an N-terminal amine to yield the desired amide bond.⁵⁰ A silver-free protocol has also been developed for the thioester method, which involves the use of aryl, as opposed to alkyl, thioesters (Fig. 3f).⁵¹ To ensure a successful peptide synthesis both thioester methods require peptide fragments with protected amino groups, such as Fmoc protection of N-terminal α -amino groups, or Boc/Z protection of Lys side chain ϵ -amino groups; alternatively, Lys side chains can be protected by using an azido-lysine analogue during peptide synthesis, followed by azide reduction to give the desired ϵ -amino group post-thioester ligation.⁵² Thioester methods have since been utilised for the synthesis of proteins such as chemokine CCL27⁵¹ and various glycoproteins.⁵³ For further reading on ligation methods, we direct the reader to extensive reviews on the subject.^{53–57}



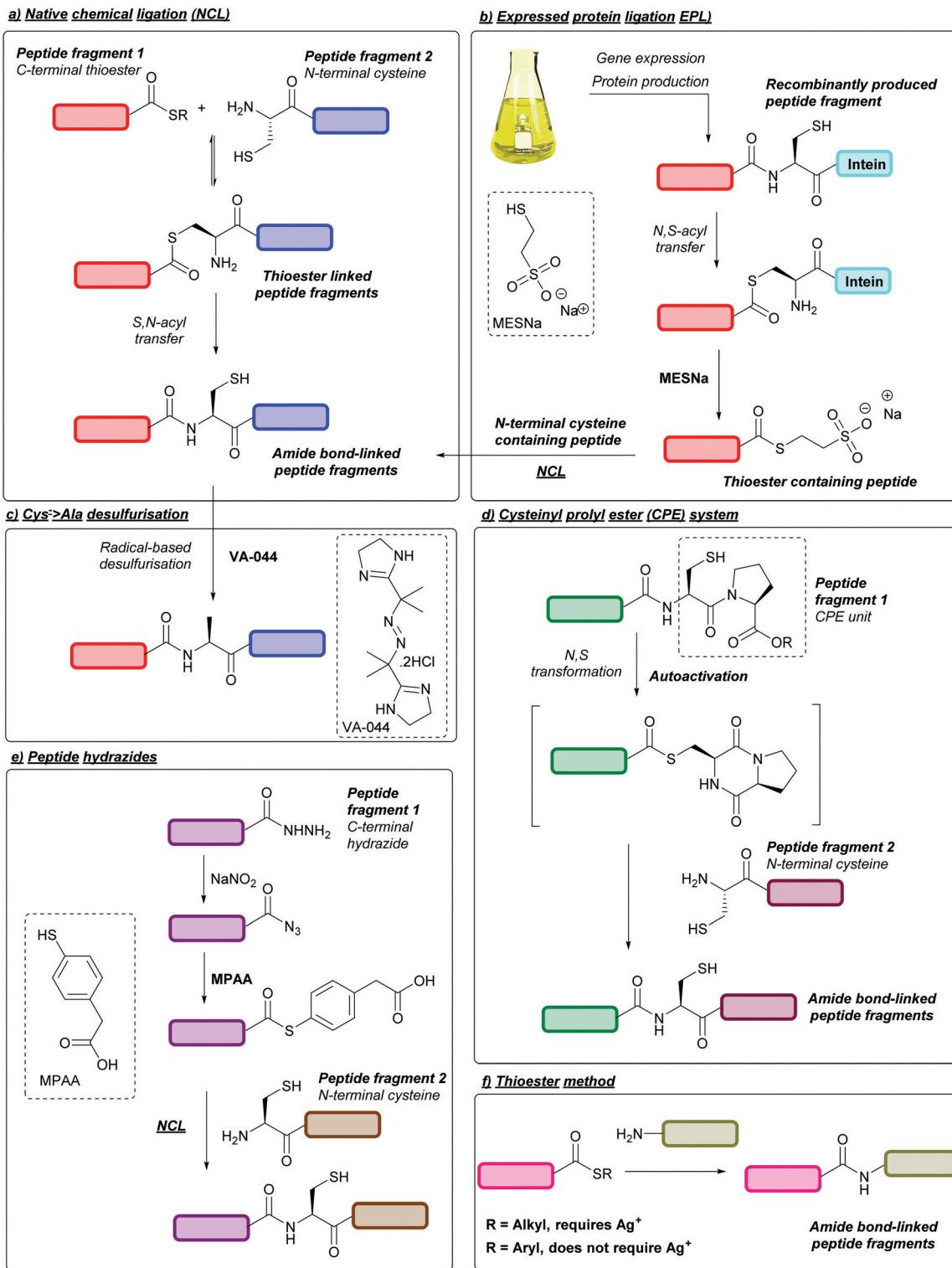


Fig. 3 Strategies related to peptide ligation. (a) Native chemical ligation (NCL), (b) expressed protein ligation (EPL), (c) radical-based desulfurisation of Cys to yield alanine using 2,2'-azobis[2-(2-imidazolin-2-yl)propane]dihydrochloride (VA-044), (d) cysteinyl prolyl ester(CPE) system, (e) ligation of peptides using peptide hydrazides, (f) thioester method for ligation of peptides.

3.3 Orthogonality and bioorthogonality

In 1977, Barany and Merrifield described the concept of “orthogonality”, which (as mentioned previously) describes

protecting groups that can be chemoselectively removed in the presence of one another without affecting/removing each other under certain sets of conditions.⁵⁸ This concept has



proved especially important in peptide synthesis when considering disulfide-containing peptides, where the use of protecting groups can avoid off-target and undesired disulfide formation (Fig. 4a).^{5,6} The concept of orthogonality would later be extended to chemical biology when Bertozzi coined the term “bioorthogonal”. First referenced by Bertozzi in 2003, along with Hang, Yu, and Kato,⁵⁹ bioorthogonal/bioorthogonality refers to chemical reactions that can be performed in biological systems without interfering with the native environment (Fig. 4b).^{60,61} This typically relies on incorporation of non-natural functionalities, which can be used as “handles” for selective, bioorthogonal reactions. The field

of bioorthogonal chemistry has grown rapidly over the last two decades, with *in vivo* applications such as metabolic labelling of developing zebrafish embryos.^{62,63} On the related subject of protein modification, advances in synthetic biology and genetic code expansion have enabled the incorporation of non-natural functionalities into proteins *via* unnatural amino acid mutagenesis. This typically involves expression of a gene (encoding for a protein of interest) containing an amber STOP codon (in *E. coli* cells), along with expression of an orthogonal tRNA/tRNA synthetase in the presence of an unnatural amino acid, to produce the unnatural amino acid-containing protein of interest (Fig. 4c).

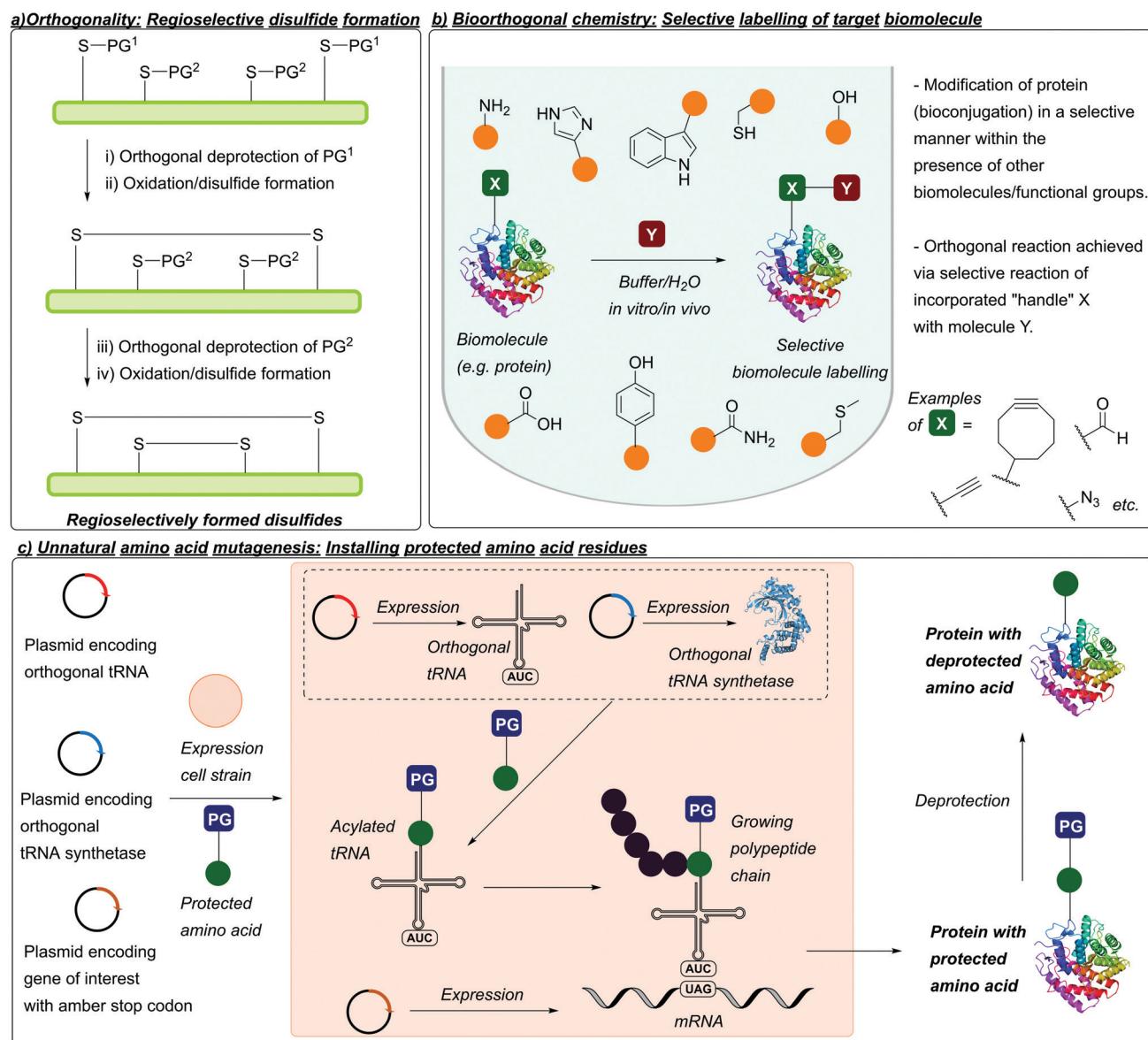


Fig. 4 (a) Concept of orthogonality and its relation to protecting group chemistry and disulfide formation. Using combinations of protecting groups that are orthogonal *i.e.* can be removed in the presence of one another, followed by disulfide bond formation in a sequential manner allows for controlled, regioselective disulfide bond formation. (b) Outline of bioorthogonal chemistry. Selective modification of a given biomolecule is carried out without off-target modification/perturbation of the native environment. (c) Outline of unnatural amino acid mutagenesis. Using a suitable cell strain, expression of a plasmid encoding for the desired protein (which contains an amber STOP codon) alongside an orthogonal tRNA synthetase/tRNA pair and unnatural amino acid allows for incorporation of said unnatural amino acid at the aforementioned STOP position.



Functionalities introduced into proteins in this manner include azides, alkynes, aldehydes, and tetrazines. Similar to the thiol side chain of Cys, these groups can subsequently be used as handles for site-selective bioconjugation to yield conjugates such as ADCs.⁶⁴ Alternatively, amino acids with modified or protected side chains can also be introduced; these include analogues that mimic post-translational modifications (PTMs) in proteins *e.g.* histones,⁶⁵ or photocaged analogues of inactive enzymes which can subsequently be activated *via* deprotection *e.g.* photocaged Tyr in β -galactosidase.⁶⁶

4. Table of cysteine protecting groups

Table 1 List of protecting groups for the Cys thiol that have been reported over the last several decades. The following for each protecting group is covered in this review: (i) name and abbreviations, (ii) the deprotection/lability classification (as mentioned previously in Section 2) (iii) deprotection conditions and relevant references (iv) conditions to which the protecting group is stable to/compatible with, and (v) the structure of Cys-protecting group conjugate as observed within a peptide chain

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Benzyl (Bzl, Bn); Section 5.1	Acid, reducing agents	Na/NH ₃ (liq.) ⁶⁷ HF (25 °C) ⁶⁸ TMSBr/TFA/thioanisole ⁶⁹	Standard Boc SPPS reagents ⁴	
Trityl (Trt); Section 5.2.1	Acid, oxidising agents	Ag(I) ⁷⁰ Hg(II) ⁷⁰ HBr/AcOH ⁷⁰ TFA/TIS (90 : 10) ⁷¹ HBF ₄ /scavengers ⁷² I ₂ ⁴ CuSO ₄ -cysteamine, Gdn-HCl/HEPPS buffer ⁷³	Standard Fmoc SPPS reagents ⁷⁴	
Diphenylmethyl (Dpm, Bzh, Bh); Section 5.2.2	Acid	TFA/TIS/H ₂ O/DCM (90 : 2.5 : 2.5 : 5) ⁷⁵	Cocktails of <25% TFA ⁷⁵ Standard Fmoc SPPS reagents ⁷⁵	
Tetrahydropyranyl (Thp); Section 5.2.3	Acid	Silver nitrate (aq., 0 °C) ⁷⁶ TFA/TIS/DCM (95 : 2.5 : 7.5) ⁷⁷	Na/NH ₃ (liq.) ⁷⁶ 1% TFA in DCM ⁷⁷ Standard Fmoc SPPS reagents ⁷⁷	
tert-Butyl (tBu); Section 5.2.4	Acid	NpsCl (2 h, RT), then NaBH ₄ ⁷⁸ HF (20 °C) ⁷⁹ DTNP/TFA ⁸⁰ Hg(OAc) ₂ /TFA/anisole ⁸¹ Silyl chloride-sulfoxide/TFA ⁸² Tl(TFA) ₃ ⁸³ DMSO/TFA ⁸⁴	I ₂ ⁷² TFA ⁸⁶ AgOTf/TFA ⁸⁷ Na/NH ₃ (liq.) ⁷⁸ Hydrazine ⁷⁸ Standard Fmoc SPPS reagents ⁸⁸	

5. Cysteine protecting groups in peptide and protein science

5.1 Benzyl (Bzl)

The benzyl (Bzl, Bn) protecting group (Fig. 5a) has been used for many years.^{67,167} One of the most noteworthy examples where the Cys(Bzl) protecting group has featured is in the landmark chemical synthesis of the hormone oxytocin in 1953 (Fig. 5b); this was the first example of a polypeptide hormone synthesis, and contributed towards Vincent du Vigneaud being awarded the Nobel Prize in Chemistry in 1955. Synthesis of other Cys-containing oxytocin analogues have also employed the Bzl protecting group.¹⁶⁸ Additionally, Cys(Bzl) protected tripeptides have been shown to display apoptotic activity.¹⁶⁹ Protocols for



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
4-Methoxybenzyl (Mob, MBzl); Section 5.2.5	Acid	PdCl ₂ , 50 mM Tris or urea buffer (37 °C) ⁸⁵ TFA (100 °C) ⁸⁹ HF ⁷⁹ DTNP or DTP/TFA/thioanisole ⁹⁰ TFA/TIS (12 h, 37 °C) ⁸⁶ Hg(TFA) ₂ ⁸¹ Tl(TFA) ₃ ⁸³ AgOTf/TFA/thioanisole ⁸⁷	HBr ⁸⁹ TFA (without scavengers) ⁸⁶ Standard Fmoc SPPS reagents ⁷⁵ Standard Boc SPPS reagents (for small peptides) ^{4,91} 50% TFA in DCM (23 h, 24 °C) ⁹² Standard Boc SPPS reagents ⁹²	
3,4-Dimethylbenzyl (DMB); Section 5.2.6	Acid	HF (10 min, 0 °C) ⁹²		
Methylbenzyl (Meb, 4-MeBn, 4-MeBzl); Section 5.2.7	Acid	HF/anisole (1 h, 0 °C) ⁹¹ Tl(TFA) ₃ ⁸³ DMSO/TFA (45 °C) ⁷⁴	AgOTf ⁸⁷ Standard Fmoc SPPS reagents ⁷⁴ Standard Boc SPPS reagents ⁹¹	
1-Adamantyl (Ad, 1-Ada); Section 5.2.8	Acid	Hg(OAc) ₂ /TFA ⁸¹ 1 M TFMSA/anisole/TFA ⁹³ Tl(TFA) ₃ ⁹³	TFA (2.5 h, 0 °C) ⁹³ AgOTf/TFA ⁸⁷ Standard Boc SPPS reagents ⁸⁷ Standard Fmoc SPPS reagents ⁴	
Benzoyloxymethyl (Bom); Section 5.2.9	Acid	AgOTf/anisole/TFA (1 h, 0 °C) ⁹⁴ 1 M TMSOTf/thioanisole/TFA (1 h, 0 °C) ⁹⁴ Tl(TFA) ₃ ⁹⁴	TFA (4 h, 0 °C) ⁹⁴ Hydrazine ⁹⁴ Piperidine/DMF ⁹⁴ NaBO ₃ ⁹⁴ Standard Fmoc SPPS reagents ⁹⁴	
2,4,6-Trimethoxybenzyl (Tmob); Section 5.2.10	Acid	≥ 6% TFA with TES or TIS (0.5%) in DCM (5 min, 25 °C) ⁹⁵ ≥ 30% TFA in DCM with phenol/thioanisole/H ₂ O (5% each) ⁹⁵ I ₂ /DMF (0 °C) ⁹⁵ Tl(TFA) ₃ /DMF/anisole (0 °C) ⁹⁵	Standard Fmoc SPPS reagents ⁹⁶	
4,4',4'',-Trimethoxy-triphenylmethyl (TMTr); Section 5.2.11	Acid	1% TFA in DCM ⁹⁶	Standard Fmoc SPPS reagents ⁹⁶	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Pseudoprolines (Ψ Pro); Section 5.2.12	Acid	TFA ($\Psi^{Me,Me}$ pro, 32–36 h, sequence dependant) ⁹⁷ TFMSA (15 min, 0 °C) ⁹⁸ TFA ($\Psi^{Me,Me}$ pro, 1–6 h, sequence dependant) ⁹⁹ TFA ($\Psi^{H,Dmp}$ pro, minutes) ⁹⁷ TFA ($\Psi^{H,Dmp}$ pro, C-terminal resin-bound, 1.5 h) ¹⁰⁰	Standard Fmoc SPPS reagents ⁹⁷ TFA ($\Psi^{H,H}$ pro) ⁹⁷ TFA/MeOH/TIS/H ₂ O (80:15:2.5:2.5, $\Psi^{Me,Me}$ pro, 1 h, cyclic peptides) ¹⁰¹	
4-Methyltrityl (Mtt); Section 5.2.13	Acid	1% TFA/scavengers ⁷⁵	Standard Fmoc SPPS reagents ⁷⁵	
4-Methoxytrityl (Mmt); Section 5.2.13	Acid	1–3% TFA in DCM/TES (95:5) ⁷¹ I ₂ ⁷¹	Bases, e.g. 30% piperidine in DMF (24 h, 22 °C) ⁷¹ Very weak acids, e.g. AcOH/TFE/DCM (1:2:7, 30 min) ⁷¹ Standard Fmoc SPPS reagents ⁷¹	
9H-Xanthen-9-yl (Xan); Section 5.2.15	Acid	TFA:DCM:TES (0.1:99.4:0.5) ¹⁰² TFA:DCM:BME (10:85:5) ¹⁰² TFA:DCM:TES (1:98.5:0.5) solid phase (25 °C, 2 h) ¹⁰² I ₂ /MeOH ¹⁰²	Piperidine/DMF (≥24 h, 25 °C) ¹⁰² HOEt/DMF (24 h, 25 °C); AcOH ¹⁰²	
2-Methoxy-9H-xanthen-9-yl (2-Moxan); Section 5.2.15	Acid	Tl(TFA) ₃ ¹⁰² TFA:DCM:TES (0.1:99.4:0.5) ¹⁰² TFA:DCM:BME (10:85:5) ¹⁰² TFA:DCM:TES (1:98.5:0.5) solid phase (25 °C, 2 h) ¹⁰² I ₂ /MeOH ¹⁰²	Piperidine/DMF (≥24 h, 25 °C) ¹⁰² HOEt/DMF (24 h, 25 °C); AcOH ¹⁰²	
4,5,6-Trimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-methyl (Tmbm); Section 5.2.16	Acid	TFA/TES/DCM (1:5:94) ¹⁰³	Standard Fmoc SPPS reagents ¹⁰³	
2,2,5,7,8-Pentamethyl-chroman-6-methyl (PmcM); Section 5.2.16	Acid	TFA/TES/DCM (1:5:94) ¹⁰³	Standard Fmoc SPPS reagents ¹⁰³	



Table 1 (continued)

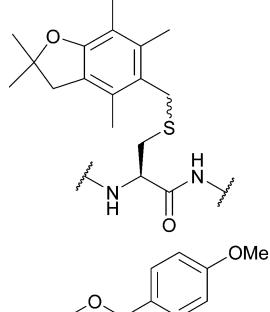
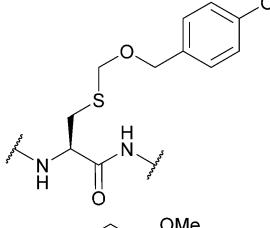
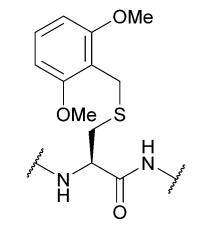
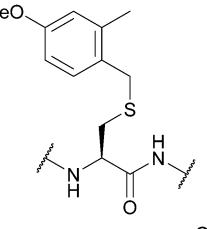
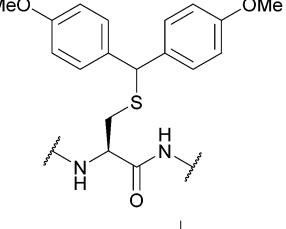
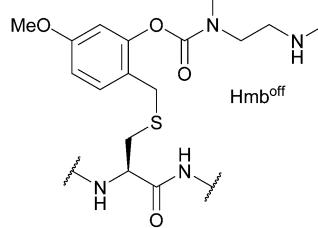
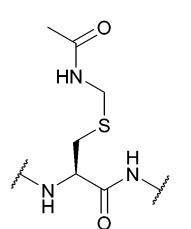
Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
2,2,4,6,7-Pentamethyl-2,3-dihydrobenzofuran-5-methyl (Pbfm); Section 5.2.16	Acid	TFA/DCM/TIS (1:5:94) ¹⁰³ I ₂ ¹⁰³ HFIP or TFE in DMF (15 min) ¹⁰³	Standard Fmoc SPPS reagents ¹⁰³	
4-Methoxybenzyloxymethyl (Mbom); Section 5.2.17	Acid	Reagent K/MeONH ₂ ·HCl ¹⁰⁴	Standard Fmoc SPPS reagents ¹⁰⁴	
2,6-Dimethoxybenzyl (2,6-diMeOBn); Section 5.2.18	Acid	TFA:DCM:TIS:H ₂ O (50:45:2.5:2.5, 1 h, 25 °C) ¹⁰⁵	Standard Fmoc SPPS reagents ⁷⁵	
4-Methoxy-2-methylbenzyl (4-MeO-2MeBn); Section 5.2.18	Acid	TFA:DCM:TIS:H ₂ O (50:45:2.5:2.5, 1 h, 25 °C) ¹⁰⁵	Standard Fmoc SPPS reagents ⁷⁵	
4,4'-Dimethoxydiphenylmethyl (Ddm); Section 5.2.19	Acid	TFA:DCM:TIS:H ₂ O (10:85:2.5:2.5, 1 h, 25 °C) ¹⁰⁵	Standard Fmoc SPPS reagents ¹⁰⁶	
Hmb ^{on/off} ; Section 5.2.20	Acid	TFA/TIS/H ₂ O (95:2.5:2.5, 2 h, 25 °C) in Hmb ^{on} form ¹⁰⁷	Standard Fmoc SPPS reagents in Hmb ^{off} form ¹⁰⁷ Standard NCL/desulphurisation/HPLC reagents in Hmb ^{on} form ¹⁰⁷	
Acetamidomethyl (Acm); Section 5.3.1	Oxidising agents	NpsCl (2 h, RT), then NaBH ₄ ⁷⁸ Hg ⁽ⁿ⁾ ¹⁰⁸ Ag ^(l) ⁸⁷ Pd ⁽ⁿ⁾ ¹⁰⁹ 6 M HCl (20 h, 110 °C) ¹¹⁰ 15 eq. DTNP in 97.5% TFA/thioanisole ^{78,90} 98% TFA with scavengers ⁸⁶ I ₂ ¹¹¹ Tl(TFA) ₃ ¹¹¹ Silyl chloride-sulfoxide/TFA ¹¹¹	TFA (25 °C) ¹¹⁰ HBr/AcOH (25 °C) ¹¹⁰ HCl/EtOH (25 °C) ¹¹⁰ HF (0 °C) ¹¹⁰ Pd(0) ¹¹³ TCEP ¹¹⁴ Standard Fmoc SPPS reagents ⁷⁴	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
5-Dibenzosuberyl (Dbs, Sub); Section 5.3.2	Oxidising agents	PdCl ₂ , aqueous/buffered conditions ¹¹² CuSO ₄ , aqueous/buffered conditions with aminothiol source ⁷³ Hg(OAc) ₂ ¹¹⁵ I ₂ /MeOH or AcOH ¹¹⁵ Tl(TFA) ₃ ⁸³	TFA ¹¹⁵	
Benzamidomethyl (Bam); Section 5.3.3	Oxidising agents	Hg(OAc) ₂ (1 h, RT) ¹¹⁶ Ag(OTf)/TFA/anisole (1 h, 0 °C) ⁸⁷ Silyl chloride-sulfoxide/TFA ⁸² 6 M HCl (24 h, 110 °C) ¹¹⁶	1 M HCl (25 °C) ¹¹⁶ 1 M NaOH (25 °C) ¹¹⁶ TFA (25 °C) ¹¹⁶ 90% Zn/AcOH (0 °C) ¹¹⁶ Standard Boc SPPS reagents ¹¹⁶	
(2-Oxo-1-pyrrolidinyl)-methyl (Pym); Section 5.3.4	Oxidising agents	HF ¹¹⁷ NaBO ₃ ¹¹⁷	Solution phase Boc reagents ¹¹⁷	
Dimethylphosphinothioly (Mpt); Section 5.3.5	Oxidising agents	AgNO ₃ (2–4 equiv., 20 min, 1 h, 0 °C) in H ₂ O ¹¹⁸ Hg(OAc) ₂ (1–3 equiv., 1 h, 0 °C) in H ₂ O ¹¹⁸ TBAF in THF (free thiol) ¹¹⁹ TBAF in DMF (disulfide) ¹¹⁹ TBAF in DCM (–S–CH ₂ –S– formation) ¹¹⁹	2 M HCl/EtOAc ¹¹⁸ 1 M HCl/MeOH ¹¹⁸ 2 M HCl/AcOH ¹¹⁸ 1 M HCl/H ₂ O ¹¹⁸ TFA ¹¹⁸	
Trimethyl-acetamido-methyl (Tacm); Section 5.3.6	Oxidising agents	I ₂ /EtOH in AcOH ¹²⁰	Solution phase Boc reagents ¹¹⁸ HF (1 h, 0 °C) ¹¹⁷ TFMSA/thioanisole/TFA (2 h, 0 °C) ¹¹⁷ 0.05 M NaOH in MeOH (aq., 1 h, 0 °C) ¹¹⁷ Hydrazine/MeOH (24 h, RT) ¹¹⁷ Zn in 90% AcOH (1 h, 25 °C) ¹¹⁷ Standard Boc SPPS reagents ⁹³	
9-Fluorenylmethyl (Fm); Section 5.4.1	Base	NH ₃ /MeOH ¹²² 50% Piperidine in DMF (2 h, RT) ¹²³	TFA ⁹³ TFMSA/TFA ⁹³ HCl (110 °C) ⁹³ HF/anisole (95:5, 1 h, 0 °C) ⁹³ 0.1 M I ₂ /DMF ¹²³ H ₂ , Pd/C ¹²² Standard Boc SPPS reagents ¹²³	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
2-(2,4-Dinitrophenyl)ethyl (Dnpe); Section 5.4.2	Base	50% Piperidine in DMF (30 min) ¹²⁴ Dilute DBU ⁶⁸	5% DIEA in DCM (2 h) ¹²⁴ 40% TFA in DCM (24 h) ¹²⁴ 90% HF/ <i>p</i> -cresol or anisole (1 h, 0 °C) ¹²⁴ Tl(TFA) ₃ /TFA ¹²⁴ I ₂ in 80% AcOH (aq.) ¹²⁴ Standard Boc SPPS reagents ¹²⁴	
9-Fluorenylmethyl-oxycarbonyl (Fmoc); Section 5.4.3	Base	Et ₃ N, then NH ₃ /MeOH or 50% Piperidine in DMF (2 h, RT) ¹²⁵	4 M HCl in dioxane ¹²⁵	
Phenyl-acetamidomethyl (Phacm); Section 5.5.1	Enzyme, oxidising agents	Penicillin G acylase (pH 7.9 buffer) ¹²⁶ Hg ^(II) ¹²⁷ Ag ^(II) ¹²⁷ I ₂ ¹²⁷ Tl(TFA) ₃ ¹²⁷	5% DIEA in DCM (24 h, 25 °C) ¹²⁶ 40% TFA in DCM (24 h, 25 °C) ¹²⁶ 25% piperidine in DMF (24 h, 25 °C) ¹²⁶ 0.1 M TBAF in DMF (24 h, 25 °C) ¹²⁶ 5% DBU in DMF (24 h, 25 °C) ¹²⁶ 90% HF/anisole or <i>p</i> -cresol (1 h, 0 °C) ¹²⁶ 90% TFA/scavengers (2 h, 25 °C) ¹²⁶ Standard Boc SPPS reagents ¹²⁶ Standard Fmoc SPPS reagents ¹²⁶ Standard Fmoc SPPS reagents ¹²⁸ Standard Boc SPPS reagents ¹²⁸	
Hydroxyglycine-Acm (Hgm); Section 5.6.1	Hydrazine	5% hydrazine in H ₂ O (pH 8.5, 3 days, 37 °C) ¹²⁸		
Hydroxyquinoline-Acm (Hqm); Section 5.6.1	Hydrazine	5% hydrazine in H ₂ O (pH 8.5, 8 h, 37 °C) ¹²⁸ I ₂ (30 min) ¹²⁸ AgOAc (30 min) ¹²⁸	Standard Fmoc SPPS reagents ¹²⁸ Standard Boc SPPS reagents ¹²⁸	
Allyloxycarbonyl (Alloc); Section 5.7.1	Pd, base	Pd(0) cat./Bu ₃ SnH/AcOH ¹²⁶ Piperidine (3 h, 30 °C) ¹²⁹	TFA/DCM (24 h, 50 °C) ¹²⁹ Standard Boc SPPS reagents ¹²⁹	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Allyloxy-carbonylamino-methyl (Allocam); Section 5.7.2	Pd	Pd(0) cat./Bu ₃ SnH/AcOH (10 min, RT) ¹³⁰ Pd(OAc) ₂ /NMM/AcOH in DMSO (2 h, disulfide) ¹³¹	Piperidine ¹³⁰ Acids (partially) ¹³⁰ Standard Fmoc SPPS reagents ¹³⁰	
[N-[2,3,5,6-Tetrafluoro-4-(N'-piperidino)-phenyl], N-allyloxycarbonyl]-aminomethyl (Fnam); Section 5.7.3	Pd, oxidising agents	Pd(0) cat./allyl scavenger then AcOH/BME ¹³² Heavy metal salts ¹³² Tl(TFA) ₃ ¹³²	Acid ¹³² Base ¹³² Standard Boc SPPS reagents ¹³² Standard Fmoc SPPS reagents ¹³²	
S-[N-[2,3,5,6-Tetrafluoro-4-(phenylthio)-phenyl], N-allyloxycarbonyl]-aminomethyl (Fsam); Section 5.7.4	Pd, oxidising agents	Pd(0) cat./allyl scavenger then AcOH/BME ¹³³ I ₂ and other oxidants ¹³³	Acid ¹³³ Base ¹³³ Standard Boc SPPS reagents ¹³³ Standard Fmoc SPPS reagents ¹³³	
Allyl (Sac); Section 5.7.5	Pd	Pd(tppts) ₄ ¹³⁴	Unnatural amino acid mutagenesis ¹³⁴	
S-Propargyl-cysteine (SprC); Section 5.7.6	Pd	Pd(tppts) ₄ ¹³⁵	Unnatural amino acid mutagenesis CuAAC, Sonagashira coupling (alkyne functionality can be used for conjugation without cleavage) ¹³⁵	
Succinimide (Suc); Section 5.7.7	Pd	PdCl ₂ and MgCl ₂ , 6 M Gdn.HCl/0.2 M phosphate buffer pH 5.5, 37 °C then DTT ¹³⁶	Aqueous solution phase conditions ¹³⁶ Desulphurisation conditions ¹³⁶	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Thiazolidine (Thz); Section 5.8.1	N-terminal Pd, oxidising agents, Cu	$\text{H}_2\text{O}_2^{137}$ I_2^{137} Iodoacetic acid/benzyl chloride (pH 10–11, RT) ¹³⁷ Air/ferric chloride (trace, pH 10) ¹³⁷ Excess methoxyamine at pH 4 (8 h) ¹³⁸ Pd(II) and MPAA/TCEP or GSH/6 M Gdn·HCl (pH ~6.5, 37 °C, 45 min) ^{85,138} CuSO_4 /sodium ascorbate/5 M Gdn·HCl/HEPPS buffer then DTT (pH 7.0, 1 h, 37 °C) ¹³⁹ 20 mM DPDS, 50% MeCN (0.1% TFA) ¹⁴⁰	$\text{PdCl}_2/\text{H}_2\text{O}^{85}$ Standard NCL reagents ¹³⁹	
Ninhydrin (Nin); Section 5.8.2	N-terminal Reducing agents	Excess Cys (pH 7.7, 30 min, 23 °C) ¹⁴¹ Cysteine O-methylester/DMF/DIEA (on resin) ¹⁴¹ Excess MPS, pH 7 ¹⁴¹ 10% TFA/ $\text{H}_2\text{O}/\text{Zn}$ dust, 1 h ¹⁴¹	Standard Boc SPPS reagents ¹⁴¹ Standard Fmoc SPPS reagents ¹⁴³ Standard Boc SPPS reagents ¹⁴³	
2-Nitrobenzyl (<i>o</i> NB); Section 5.9.1	Light	$h\nu \geq 350 \text{ nm}^{142}$	TFA ¹⁴⁴ Thiolysis ¹⁴⁴	
[7,8-Bis(carboxymethoxy)-coumarin-4-yl]methoxycarbonyl (7,8-BCMCMOC); Section 5.9.2	Light	$h\nu \geq 325 \text{ nm}^{144}$	TFA ¹⁴⁴ Thiolysis ¹⁴⁴	
[7-Bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl (BCMACMOC); Section 5.9.2	Light	$h\nu \geq 402 \text{ nm}^{144}$	TFA ¹⁴⁴ Thiolysis ¹⁴⁴ Piperidine ¹⁴⁴	
α -Carboxy-4-methoxy-2-nitrobenzyl (CDMNB); Section 5.9.2	Light	$h\nu \geq 325 \text{ nm}^{144}$		



Table 1 (continued)

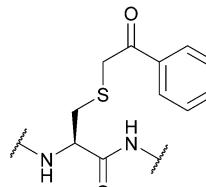
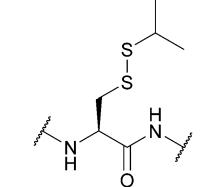
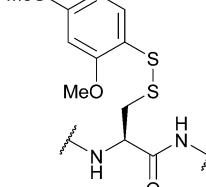
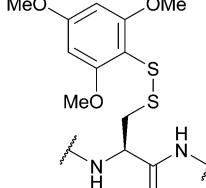
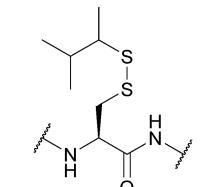
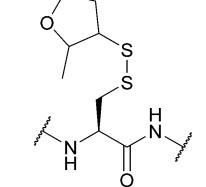
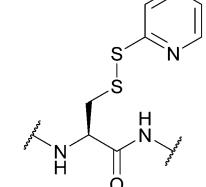
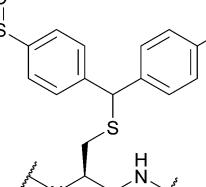
Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
2-Nitroveratryl 6-Nitroveratryl 4,5-Dimethoxy-2-nitrobenzyl (<i>o</i> NV, DMNB); Section 5.9.3	Light	$h\nu = 350$ nm (30 min) ¹⁴²	10% TFMSA/TFA/excess dipyridine disulfide ¹⁴² Standard Fmoc SPPS reagents ¹⁴²	
6-Bromo-7-hydroxy-coumarin (Bhc); Section 5.9.4	Light	$h\nu = 365$ nm in photolysis buffer (1 mM DTT in 50 mM PB, pH 7.2) ¹⁴⁵	Standard Fmoc SPPS reagents ¹⁴⁵	
Nitrodibenzofuran (NDBF); Section 5.9.5	Light	$h\nu = 365$ nm ¹⁴⁵	Standard Fmoc SPPS reagents ¹⁴⁵	
6-Bromo-7-hydroxy-3-methylcoumarin (mBhc); Section 5.9.6	Light	$h\nu = 365$ nm ¹⁴⁶	Standard Fmoc SPPS reagents ¹⁴⁶	
Methoxy-nitrodibenzofuran (<i>OMe</i> -NDBF); Section 5.9.7	Light	$h\nu \geq 350$ nm ¹⁴⁷	Standard Fmoc SPPS reagents ¹⁴⁷	
<i>para</i> -Nitrobenzyl (<i>p</i> NB); Section 5.10.1	Reducing agents	Zn/AcOH, then I ₂ (in solution) ¹¹¹ SnCl ₂ /HCl, then I ₂ (on resin) ¹¹¹ Excess CAN/Hopkins reagent ¹¹¹ H ₂ , Pd/C, then oxidant ¹¹¹	HF/ <i>p</i> -cresol (9 : 1, 1 h, 0 °C) ¹¹¹ TFA ¹¹¹ I ₂ /AcOH/2 M HCl ¹¹¹ Standard Boc SPPS reagents ¹¹¹	



Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Carbomethoxysulfenyl (Scm); Section 5.10.2	Reducing agents	DTT ¹⁴⁸	Strong acids – anhydrous HF, TFMSA ¹⁴⁹ Standard Boc SPPS reagents ¹⁴⁹	
(<i>N'</i> -Methyl- <i>N'</i> - phenylcarbamoyl)sulfenyl (Snm); Section 5.10.3	Reducing agents	DTT/NMM/CDCl ₃ ¹⁴⁹	Strong acids – anhydrous HF, TFMSA ¹⁴⁹ Standard Boc SPPS reagents ¹⁴⁹	
4-Picolyl; Section 5.10.4	Reducing agents	Zn/AcOH ¹⁵⁰ Electrolytic reduction in 0.5 M H ₂ SO ₄ ¹⁵¹	TFA ¹⁵¹ 32% HBr/AcOH (1 week, RT) ¹⁵¹ Standard Boc SPPS reagents ¹⁵¹	
Sulfonic acid/sulfonyl (SO ₃ H/SO ₂ R); Section 5.10.5	Reducing agents	Thiols ¹⁵² PBu ₃ ¹⁵³	Standard Fmoc SPPS reagents ¹⁵³ Standard Boc SPPS reagents ¹⁵³	
3-Nitro-2-pyridinesulfenyl (Nfps); Section 5.10.6	Reducing agents	Aliphatic thiols ¹⁵⁴ Tertiary phosphine/H ₂ O ^{155,156}	TFA (24 h, RT) ¹⁵⁵ HF (1 h, RT) ¹⁵⁵ 4 M HCl/dioxane (24 h) ¹⁵⁵ DCM ¹⁵⁷ DMF ¹⁵⁷ MeOH ¹⁵⁷ <i>N,N</i> -Dimethylacetamide ¹⁵⁷ <i>N</i> -Methylpyrrolidone ¹⁵⁷ Trifluoroethanol ¹⁵⁷ Pentafluorophenol ¹⁵⁷ Standard Boc SPPS reagents ¹⁵⁵	
5-Nitro-2-pyridinesulfenyl (5-Nfps); Section 5.10.7	Reducing agents	Thiols ¹⁵⁸	Standard Boc SPPS reagents (see Nfps) ¹⁵⁸	
<i>tert</i> -Butylsulphenyl (StBu); Section 5.10.8	Reducing agents	Thiols ¹⁵⁹ Phosphines ¹¹⁴ TFA/DTNP/thioanisole ⁸⁰	Acid ¹⁵⁹ Base ¹⁵⁹ TFA/DTNP ⁸⁰ Standard Fmoc SPPS reagents ⁷⁴	
<i>N</i> -Methyl-phenacyloxy- carbamidomethyl (Pocam); Section 5.10.9	Reducing agents, acid	Zn/AcOH (aq.) ¹⁶⁰ TFA (1 h, 50 °C) ¹⁶⁰	TFA (4 h, 4 °C) ¹⁶⁰ Standard Fmoc SPPS reagents ¹⁶⁰	

Table 1 (continued)

Protecting group, abbreviations and location within review	Lability	Deprotection conditions	Stable to/compatible with	Structure
Phenacyl (Pac); Section 5.10.10	Reducing agents	Zn powder, AcOH ¹⁶¹ TCEP in PBS pH 7.4 37 °C ¹¹⁴	Mild acid ¹⁶¹ Standard Fmoc SPPS reagents ¹⁶¹ Standard NCL reagents ¹⁶²	
<i>S</i> -Iso-Propyl (SiPr); Section 5.10.11	Reducing agents		Standard Fmoc SPPS reagents ¹¹⁴	
Dimethoxyphenylthio (<i>S</i> -Dmp); Section 5.10.12	Reducing agents	NMM (0.1 M) then either 20% BME/DMF or 5% DTT/DMF (5 min) ¹⁶³ DABDT, DIEA/H ₂ O/MeCN (3 : 3 : 94) ¹⁶⁴	20% piperidine in DMF (4 h) ¹⁶³ 95% TFA (1 h, RT) ¹⁶³ Standard Fmoc SPPS reagents ¹⁶³	
2,4,6-Trimethoxyphenylthio (<i>S</i> -Tmp); Section 5.10.12	Reducing agents	NMM (0.1 M) then either 20% BME/DMF or 5% DTT/DMF (5 min) ¹⁶³	20% piperidine in DMF (4 h) ¹⁶³ 95% TFA (1 h, RT) ¹⁶³ Standard Fmoc SPPS reagents ¹⁶³	
<i>Sec</i> -isoamyl mercaptan 3-methyl-2-butanethiol (SIT); Section 5.10.13	Reducing agents	BME in DMF (1 : 4), 0.1 M DIEA ¹⁶⁵ 20 equiv. DTT, MeCN/DIEA/ H ₂ O (90 : 5 : 5) ¹⁶⁵ 5 equiv. DTT × 3, DMF/DIEA/ H ₂ O (95 : 2.5 : 2.5) ¹⁶⁵	Standard Fmoc SPPS reagents ¹⁶⁵	
2-Methyloxolane-3-thiol (MOT); Section 5.10.13	Reducing agents	BME in DMF (1 : 4), 0.1 M DIEA ¹⁶⁵ 20 equiv. DTT, MeCN/DIEA/ H ₂ O (90 : 5 : 5) ¹⁶⁵ 5 equiv. DTT × 3, DMF/DIEA/ H ₂ O (95 : 2.5 : 2.5) ¹⁶⁵	Standard Fmoc SPPS reagents ¹⁶⁵	
2-Pyridinesulfenyl (<i>S</i> -Pyr); Section 5.10.14	Reducing agents	Thiols ⁴	1 M TFMSA in TFA-anisole (10 : 1, 2 h, 0 °C) ⁴ Standard Boc SPPS reagents ⁴	
4,4-Bis(dimethylsulfinyl)-benzhydryl (Msbh); Section 5.11.1	Safety-catch	NH ₄ I/DMS/TFA ¹⁶⁶	Acid (TFA, HF) ¹⁶⁶ Oxidants ¹⁶⁶ Reductants ¹⁶⁶ Standard Boc SPPS reagents ¹⁶⁶	

4,4-Bis(dimethylsulfinyl)-benzhydryl (Msbh); Section 5.11.1



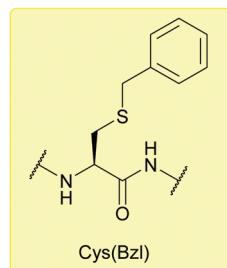
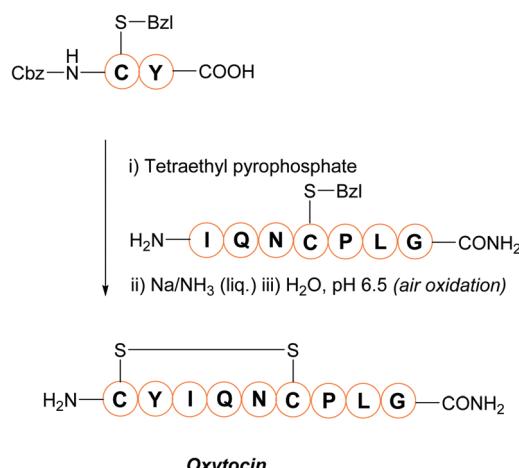
a) Benzyl**b) Oxytocin synthesis**

Fig. 5 (a) Cys thiol protection with the benzyl (Bn/Bzl) protecting group (b) the synthesis of oxytocin using Cys(Bzl).

removing Bzl with Na/NH_3 (liq.) have been described as far back as 1930,⁶⁷ and Bzl can also be removed by treatment with HF at 25 °C,⁶⁸ or with strong Lewis acids (e.g. TMSBr) in TFA-thioanisole.⁶⁹ However, these removal methods have a number of significant issues associated with them. For example, using Na/NH_3 (liq.) cleaves existing disulfide bonds alongside Bzl removal.⁷⁰ HF gas, in particular, is expensive, not widely available, and highly toxic. TMSBr been reported to undergo side reactions with peptides and has a relatively poor solubility in diethyl ether (Et_2O , a commonly used solvent for precipitation of a synthesised peptide once cleaved from the resin). TMSBr can thus precipitate with the peptide instead of being removed resulting in issues with handling following lyophilisation.^{90,170} Considering this, it is likely that Bzl will see diminishing use as a Cys protecting group in routine peptide synthesis, as it is superseded by newer protecting groups, benzyl-based or otherwise, that do not require such harsh conditions for removal.^{4,78}

5.2 Acid-labile protecting groups

5.2.1 Trityl (Trt). In 1962 the trityl (Trt) group (Fig. 6a) was proposed as an alternative Cys protecting group to protecting groups such as Bzl.⁷⁰ The key difference, in this case, was that cleavage of Trt could be accomplished without reduction of existing disulfide bonds which was a side effect of Na/NH_3 (liq.) treatment. Originally, metal salts such as $\text{Ag}(\text{i})$ or $\text{Hg}(\text{ii})$ were used to remove the group; provided the amino and carboxyl groups in the peptide were protected, cleavage of the disulfide bond was repressed, enabling the synthesis of unsymmetrical

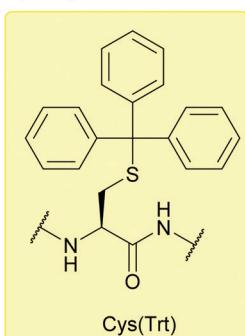
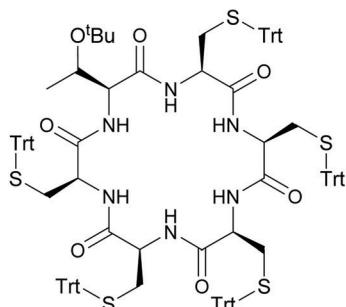
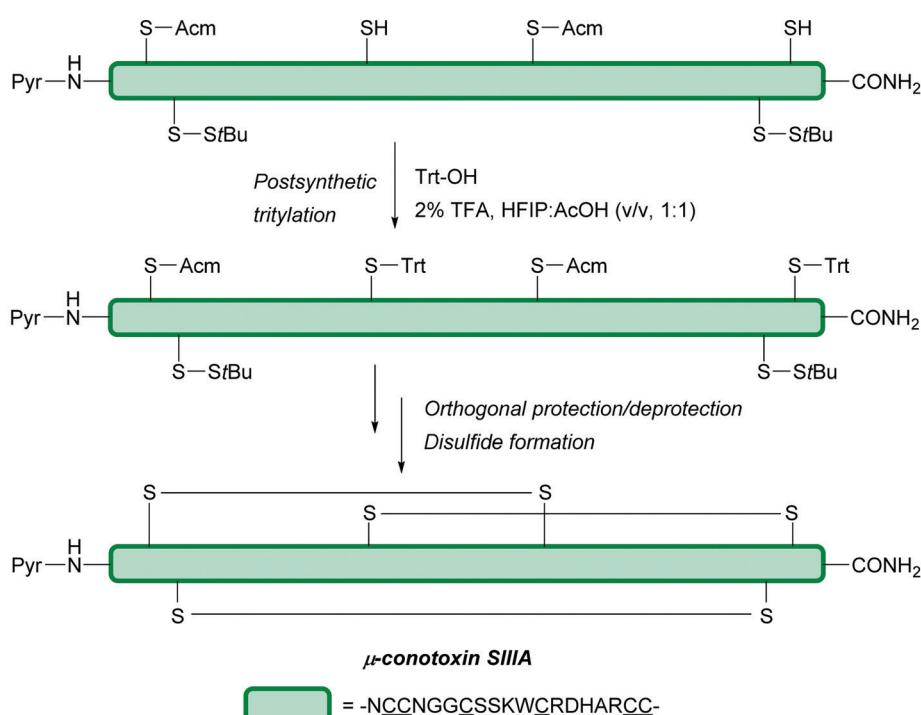
a) Trityl**b) Macrocylic Cys(Trt) peptides****c) Regioselective disulfide formation via post-synthetic tritylation strategy**

Fig. 6 (a) Cys thiol protection with the trityl (Trt) protecting group. Examples of Cys(Trt) use include (b) macrocyclic peptide synthesis and (c) regioselective disulfide formation in μ -conotoxin SIIIA via a post-synthetic tritylation strategy.



Cys-containing peptides containing two or more disulfide bonds.⁷⁰ Additionally, acids such as HBr/AcOH and TFA were noted to cleave the Trt group without affecting existing disulfide bonds.⁷⁰

Should the desired product of Trt cleavage be a new disulfide bond, oxidising agents such as I₂ may be used.⁴ The rate of Trt removal and subsequent disulfide formation by I₂ has previously been shown to depend on the choice of solvent.¹⁷¹ It is common to remove Trt using weak acids (*e.g.* HBF₄ or TFA) in the presence of scavengers such as triisopropylsilane (TIS) or triethylsilane (TES); these scavengers prevent the released Trt cations from adding back onto the synthesised peptide during cleavage and isolation.¹⁷² This method of Trt removal renders Trt orthogonal to other common protecting groups such as Acm or tBu, as shown in the regioselective synthesis of human insulin, *via* sequential disulfide formation.⁷² Other applications of Cys(Trt) in SPPS include synthesis of human relaxin,¹⁷³ and α -melanocyte stimulating hormone (α -MSH) analogues.¹⁷⁴ Additionally, macrocyclic peptides displaying *in vitro* anti-malarial properties have also been synthesised using Cys(Trt); in this example, the Trt protecting group is retained rather than removed in the final bioactive product (Fig. 6b).¹⁷⁵ Cys(Trt) has also very recently been reported to undergo complete deprotection in model peptides when treated with CuSO₄ and cysteamine in aqueous buffered conditions.⁷³

Cys(Trt) is routinely used in Fmoc SPPS. It is worth noting that Trt is highly hydrophobic and that the Trt cation-scavenger adducts formed during deprotection may not be removed completely during final TFA cleavage however. The presence of Trt can then mask the quality of the crude peptide due to its high UV absorbance.¹⁰³ To avoid incomplete detritylation, typical cleavage cocktails of >90% TFA with TIS/TES (typically *ca.* 5%) can be used. These conditions can, however, cause the reduction of the indole ring of Trp.^{71,172} Due to its lability to TFA, Trt is removed during cleavage of acid-labile resins (as commonly seen in Fmoc SPPS). It is still possible to use Trt as a protecting group when forming disulfide bonds in solution post-cleavage from the resin, however, the deprotected residues must be re-tritylated post-synthetically. This was exemplified in the regioselective syntheses of μ -conotoxin SIIIA (Fig. 6c) and human hepcidin, using combinations of StBu, Trt, Meb/Mob and Acm.⁷⁴

5.2.2 Diphenylmethyl (Dpm). The diphenylmethyl (Dpm) group (Fig. 7a) was introduced as a Bzl replacement by Zervas and Photaki alongside the Trt group in 1962.⁷⁰ It is also sometimes referred to as the benzhydryl (Bzh/Bh) protecting group in the literature,^{176,177} and has featured in Boc SPPS of peptides such as oxytoceine (which is oxidised to oxytocin post cleavage/deprotection).¹⁷⁸ The use of Dpm in Fmoc SPPS was first reported in 2012, where it was suggested as a replacement for the acid-labile Mob protecting group.⁷⁵ Dpm is stable to low concentrations of TFA (<25%) but can be cleaved with higher concentrations – up to 90% TFA in DCM (using 2.5% TIS and 2.5% H₂O as scavengers) is required for full removal. Due to its acid lability profile, Dpm is orthogonal to Trt and Mmt and fills a niche between groups that are labile to weak acids, *e.g.* Trt, and groups that are only removed using strong acids such as HF, *e.g.* Meb.^{75,105} Additionally, Cys racemisation (a known side effect during incorporation when using phosphonium and uronium salt-based coupling reagents) is attenuated considerably when using Dpm compared to Trt or Bzl: racemisation levels of 1.2%, 8.0% and 5.3% are seen under conventional Fmoc SPPS conditions, respectively.¹⁰⁶ The acid stability profile of Dpm was demonstrated in the synthesis of α -conotoxin ImI (in conjunction with Trt), along with synthesis of the hinge region of human immunoglobulin G1 (IgG1, 225–232/225'-232', in conjunction with Mmt, Fig. 7b).

5.2.3 Tetrahydropyranyl (Thp). The tetrahydropyranyl (Thp) group (Fig. 8) was first introduced as a Cys protecting group in 1958, when it was found to be slowly removed by Na/NH₃ (liq.) reduction yet rapidly removed by aqueous AgNO₃ at 0 °C.⁷⁶ Thp was further established as a Cys protecting group in 2015, where its use in Fmoc SPPS was discussed.⁷⁷ Thp is stable in mildly acidic conditions, but its acid-lability is strongly increased in the presence of TIS. It can be removed under conventional cleavage conditions, *e.g.* (i) 10% TFA and 2.5% TIS in DCM, (ii) 95% TFA and 2.5% TIS in H₂O or (iii) 0.1 M HCl and HFIP-TIS (99:1). Cys(Thp)-protected peptides exist as a diastereomeric mixture; however, once cleaved in concentrated TFA with a scavenger (*e.g.* 95% TFA, 2.5% TIS in DCM), a single pure product is obtained.⁷⁷ Thp protected tripeptides displayed greater solubility in H₂O/MeCN solvent systems (as assessed by reverse-phase HPLC) than

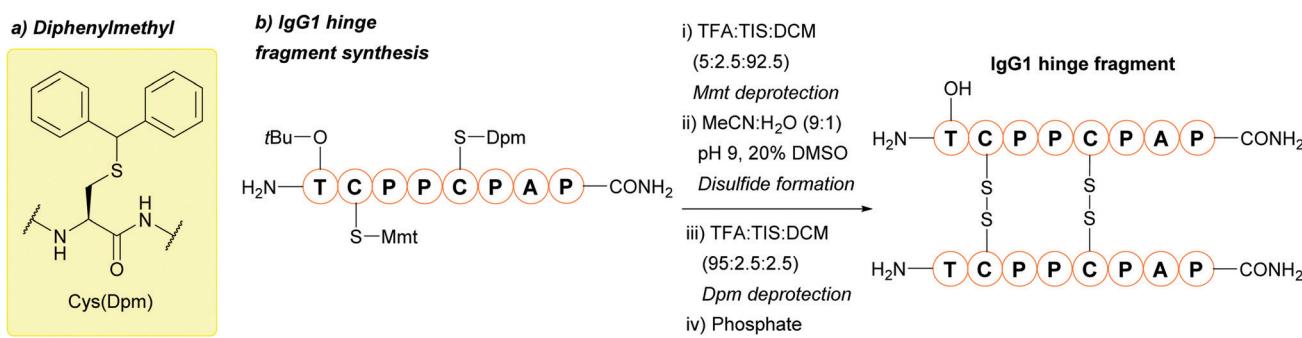


Fig. 7 (a) Cys thiol protection with the diphenylmethyl (Dpm) protecting group (b) synthesis of the IgG1 hinge region fragment using Cys(Dpm).



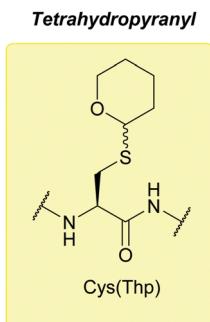


Fig. 8 Cys thiol protection with the tetrahydropyranyl (Thp) protecting group.

either Trt or Dpm protected tripeptides. Racemisation is also decreased compared to Trt, Dpm or StBu, and fewer side products, *e.g.* C-terminal 3-(1-piperidinyl)alanine adducts, are observed.⁷⁷ More recently, Thp has been explored as a protecting group for additional amino acid residues such as Ser and Thr.¹⁷⁹

5.2.4 *tert*-Butyl (*t*Bu). The use of the *tert*-butyl (*t*Bu) group to protect Cys (Fig. 9a) was first proposed in 1962.¹⁸⁰ It was then later discovered that 2-(nitrophenyl)sulfenyl chloride (NpsCl) (2 h, RT) could cleave the *t*Bu group. This could then be followed by treatment with NaBH₄, 2-mercaptoethanol (BME) or thioglycolic acid to obtain the free thiol. It should be noted that these conditions will also cleave Acm.⁷⁸ The Cys(*t*Bu) protecting group has been shown to be stable to oxidation by I₂⁷² and neat TFA treatment.⁸⁶ Cleavage of *t*Bu can be achieved with HF using anisole as a scavenger instead,⁷² and TFA in the presence of 2,2'-dithiobis(5-nitropyridine) (DTNP).⁸⁰ *t*Bu may also be cleaved using Hg(OAc)₂ in cold TFA-anisole (alternatively, Hg(TFA)₃ in AcOH (aq.)).⁸¹ To form the disulfide, cleavage may be performed using silyl chloride-sulfoxide in TFA,⁸² Ti(TFA)₃⁸³ or DMSO in TFA (with DMSO acting as an oxidant). The latter method has been used for the regioselective syntheses of various analogues of human insulin containing four disulfide bonds, in conjunction

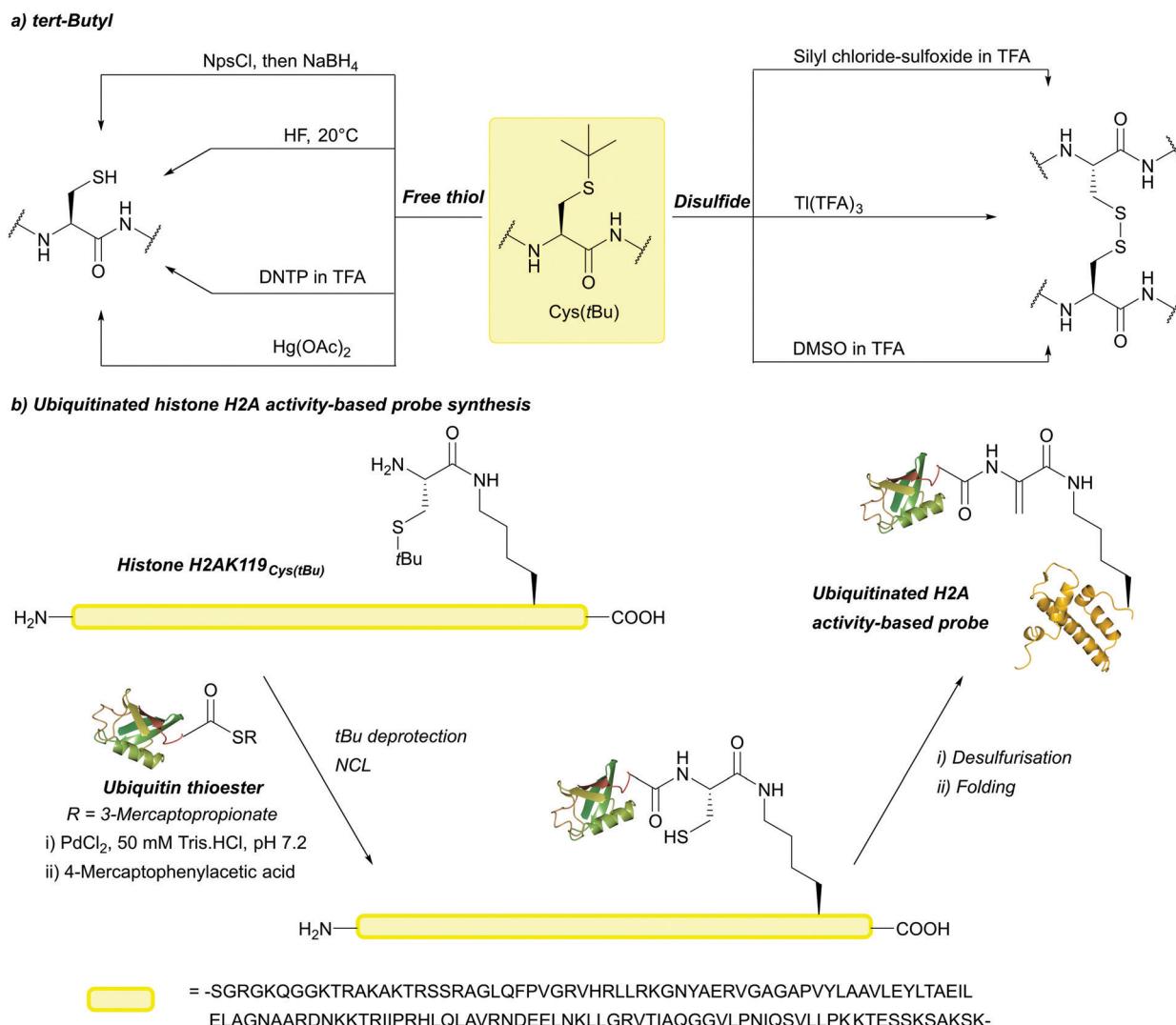


Fig. 9 (a) Cys thiol protection with the *tert*-butyl (*t*Bu) protecting group and different methods of deprotection to give the corresponding Cys or cystine. (b) Synthesis of a ubiquitinylated histone H2A activity-based probe using Cys(*t*Bu) and PdCl₂ for deprotection under aqueous conditions.



with Trt, Acm and Mmt.⁸⁴ If orthogonality to Meb is desired, DMSO/TFA may also be used for deprotection – *t*Bu is cleaved in DMSO/TFA at room temperature, whilst higher temperatures (45 °C) are required to cleave Meb. This has been used in the regioselective synthesis of an α -conotoxin dimer peptide with four disulfide bonds. Deprotection and oxidation were performed simultaneously in two one-pot procedures (the second procedure involved the Trt and Acm groups).⁸⁸ *t*Bu is stable to AgOTf in TFA, making it orthogonal to Mob and Acm under those conditions,⁸⁷ as well as to alkaline ester hydrolysis, hydrazine, and Na/NH₃ (liq.).⁷⁸

The above methods of deprotection are harsh,¹²⁸ and often result in the formation of side products and low yields.¹⁶⁶ Additionally, incubation in neat TFA causes ~20% deprotection.⁸⁶ In 2018, PdCl₂ in a 50 mM Tris or urea buffer at 37 °C was shown to cleave *t*Bu, providing a much milder way to remove the protecting group.⁸⁵ This is significant for *t*Bu, as the harsh conditions required for deprotection can hinder its practical use. *t*Bu is not removed by [Pd(allyl)Cl]₂, making it orthogonal to Thz and Acm under those conditions. This method of removal was successfully used to synthesise an activity-based probe of ubiquitinated histone H2A (Fig. 9b).⁸⁵

5.2.5 4-Methoxybenzyl (Mob). 4-Methoxybenzyl (Mob, MBzl) was introduced in 1964 as a Cys protecting group (Fig. 10a) that is labile to strong acids – originally boiling TFA,⁸⁹ but also HF⁷⁹ or TFA-thioanisole plus an electrophilic disulfide (DTNP, DTP).^{80,89,90} Mob can also be removed by heavy metal salts, *e.g.* Hg(TFA)₂,⁸¹ or AgOTf in TFA/anisole, followed by DTT to obtain the free thiol.⁸⁷ Tl(TFA)₃ can also be used for deprotection.⁸³ Additionally, AgOTf cannot cleave Meb, making Mob and Meb orthogonal under this treatment.⁸⁷ Mob is also stable to HBr.⁸⁹ Compared to Meb, the Mob group is much more acid-labile – it is at least 2700 times less stable in 50% TFA.⁹¹ Mob is however mostly stable to TFA without any scavengers at room temperature. At elevated temperatures and extended reaction times (12 h, 37 °C), in the presence of TIS, complete deprotection has been noted (with the resulting mixture existing as both the free thiol and the disulfide).⁸⁶ The conditions

typically required for full removal of Mob are harsh: relatively high concentrations of TFA (or HF), long reaction times and high temperatures.⁷⁵ Additionally, Mob is slightly labile to TFA when treated for extended periods – ~10% deprotection has been observed following treatment for 2.5 h at 0 °C. Partial conversion to *t*Bu can then occur, as Boc-derived *t*Bu cations may attack the Cys residue following partial Mob cleavage.⁹³ This means that Mob may not be suitable for Boc SPPS if large peptides that require repeated TFA treatment are being synthesised.⁹² Nevertheless, Mob has been demonstrated as a protecting group in the Boc solution phase synthesis of peptides, including oxytocin, urotensin II, and human calcitonin.⁸³ Cys(Mob) has also been incorporated into tripeptide benzyl esters for use as potential DNA intercalators, with the protecting group intact in the final product.¹⁸¹ Cys(Mob) is also compatible with Fmoc SPPS, as demonstrated in the synthesis of methylene thioacetal human insulin analogue (SCS-Ins),¹⁸² and of LaIT2, a β -KTx¹⁸³ peptide that is found in *Liocheles australasiae* scorpion venom, and displays antimicrobial activity.¹⁸⁴

Cys(Mob) can undergo oxidation to give the corresponding Mob-protected sulfone, Cys(Mob(O)) (Fig. 10b) with either NaBO₃¹⁸⁵ or H₂O₂.¹⁸⁶ Cys(Mob(O)) can in turn be incorporated into peptides *via* Fmoc-SPPS. Deprotection with TfOH : TFA : H₂O (50 : 45 : 5) leads to removal of the Mob protecting group, generating peptides bearing Cys sulfinic acid, a known PTM of Cys-containing proteins that can regulate protein function.¹⁸⁶ Additionally, Cys(Mob(O)) can be used for disulfide formation *via* sulfoxide-directed disulfide reactions¹⁸⁷ in an I₂-free manner (I₂ can otherwise oxidise amino acids such as Trp).¹⁸⁸ Example syntheses include oxytocin,¹⁸⁹ chicken calcitonin-gene-related peptide (cGRP),¹⁹⁰ and human insulin-like peptide-6 (INSL-6) (Fig. 10c).

5.2.6 3,4-Dimethylbenzyl (DMB). The 3,4-dimethylbenzyl (DMB) Cys protecting group (Fig. 10d) was developed in 1973 as an alternative to Mob for the synthesis of large peptides using Boc SPPS.⁹² DMB is noticeably more stable to TFA than Mob, with only 0.2% deprotection observed under 50% TFA in DCM for 23 h at 24 °C. The group is, however, easily cleaved

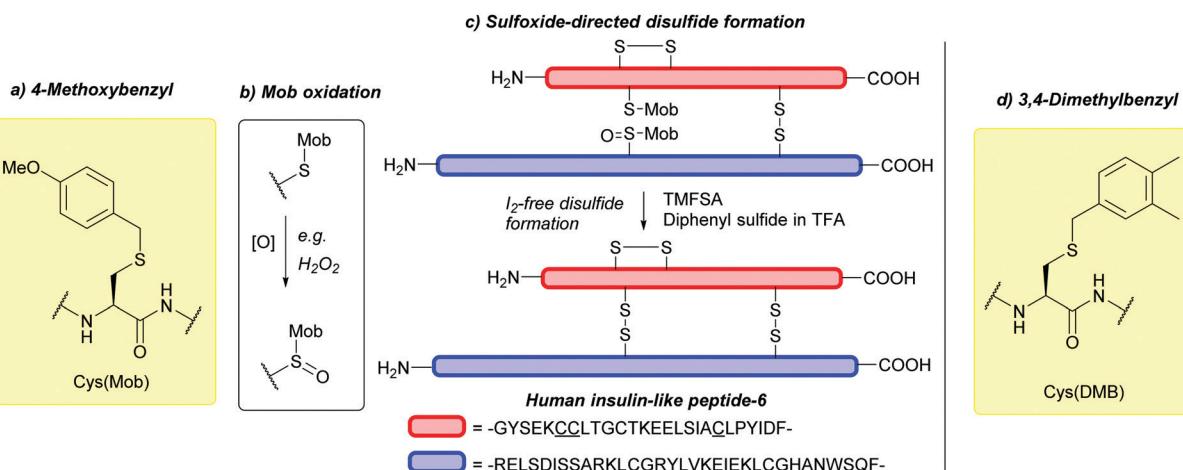


Fig. 10 (a) Cys thiol protection with the 4-methoxybenzyl (Mob) protecting group. (b) Oxidation of Cys(Mob) gives the corresponding Mob-protected sulfone, Cys(Mob(O)). (c) Synthesis of human insulin-like peptide-6 (INSL-6) using Cys(Mob) and Cys(Mob(O)) for sulfoxide-directed disulfide formation. (d) Cys thiol protection with the 3,4-dimethylbenzyl (DMB) protecting group.



using HF (10 min at 0 °C). Its use was demonstrated by the solid-phase synthesis of the C-terminal cyclic dodecapeptide¹⁹¹ of human pituitary growth hormone,⁹² oxytocin derivatives,¹⁹¹ and melanotropin analogues.¹⁹²

We note to the reader that the DMB protecting group is different to that of the similarly abbreviated 2,4-dimethoxybenzyl (Dmb) group, which is used as an amide backbone protecting group to prevent peptide aggregation and off-target reactions during peptide synthesis.⁴

5.2.7 Methylbenzyl (Meb). The methylbenzyl (Meb, 4-MeBn, 4-MeBzl) protecting group (Fig. 11a) is broadly similar to Mob but less labile to TFA. Meb can be removed using HF-anisole (50%, 1 h, 0 °C).⁹¹ Tl(TFA)₃ treatment of Boc-Cys(Meb)-OH will lead to cystine formation, along with minor by-products (anticipated to be sulfoxide species).⁸³ Oxidation may also be achieved using DMSO/TFA at 45 °C. Meb is orthogonal to Trt, Acm, *t*Bu and StBu.^{74,88} Consequently, these protecting groups have been used together, for example, in the regioselective synthesis of human hepcidin (Fig. 11b),⁷⁴ and in the synthesis of Cys-rich peptides such as protoxin I (ProTx-I), a three-disulfide-containing peptide isolated from tarantula (*Thrixopelma pruriens*) venom.¹⁹³

5.2.8 1-Adamantyl (Ad). The 1-adamantyl (Ad, 1-Ada) group (Fig. 12a) was first introduced as a Cys protecting group in 1978,

where it was noted that it could be cleanly removed using Hg(OAc)₂ in TFA.⁸¹ It is less labile to TFA than Mob, remaining intact under 2.5 h TFA treatment at 0 °C. It can, however, be removed in 1 M TFMSA-anisole/TFA in the presence of *m*-cresol, whereas application of Tl(TFA)₃ causes disulfide formation. Ad is less susceptible to sulfoxide formation than Mob – taking 28 h vs. 18 h for complete oxidation when treated with NaBO₃. This is advantageous for the synthesis of relatively large peptides.⁹³ It is also stable to AgOTf in TFA, and is thus orthogonal to Acm, Bam and Mob.⁸⁷ Cys(Ad) has previously been employed in synthesis of calcitonin-based peptides *via* Boc solution¹⁹⁴ and solid phase synthesis,⁸⁷ and in the synthesis of four-helix bundle proteins in Fmoc SPPS (Fig. 12b).¹⁹⁵

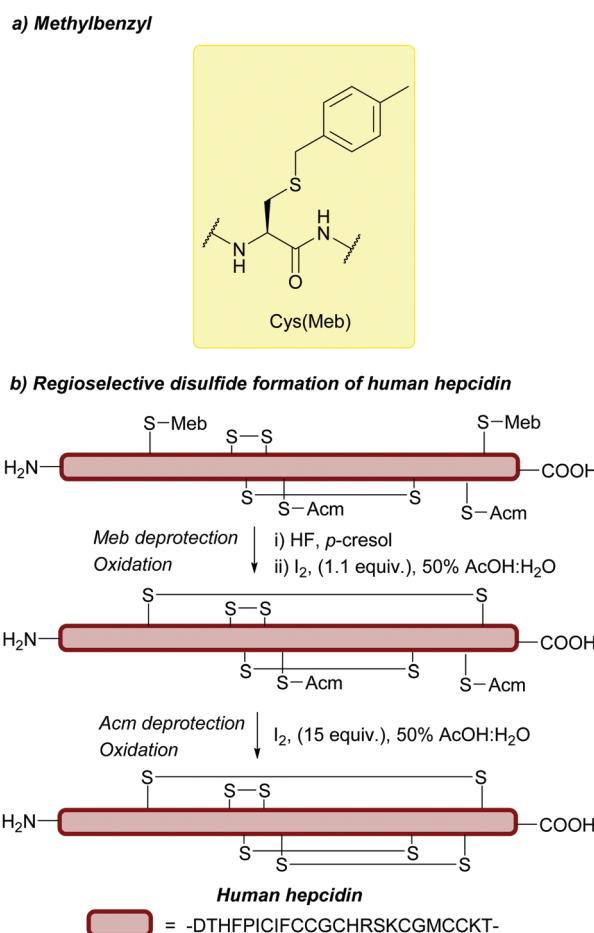
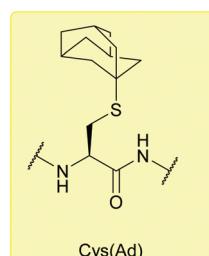


Fig. 11 (a) Cys thiol protection with the methylbenzyl (Meb) protecting group. (b) Synthesis of human hepcidin using Cys(Meb).

a) 1-Adamantyl



b) Four-helix bundle protein synthesis

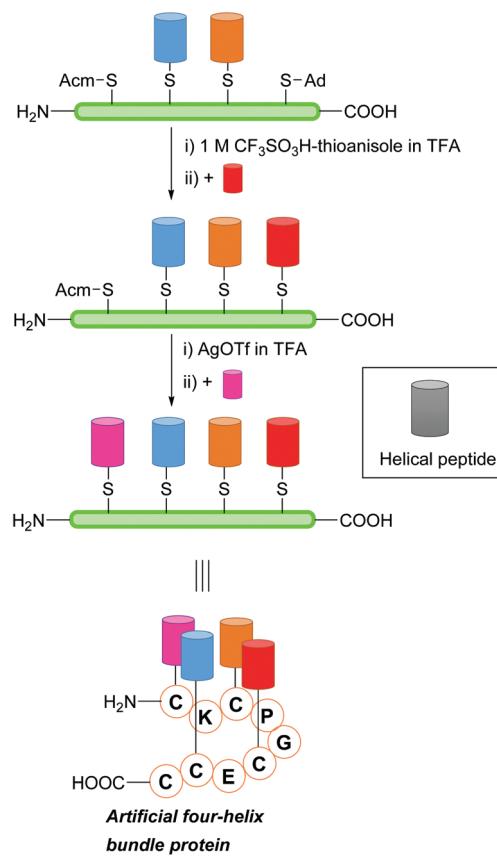


Fig. 12 (a) Cys thiol protection with the 1-adamantyl (Ad) protecting group. (b) Synthesis of four-helix bundle proteins using Cys(Ad).



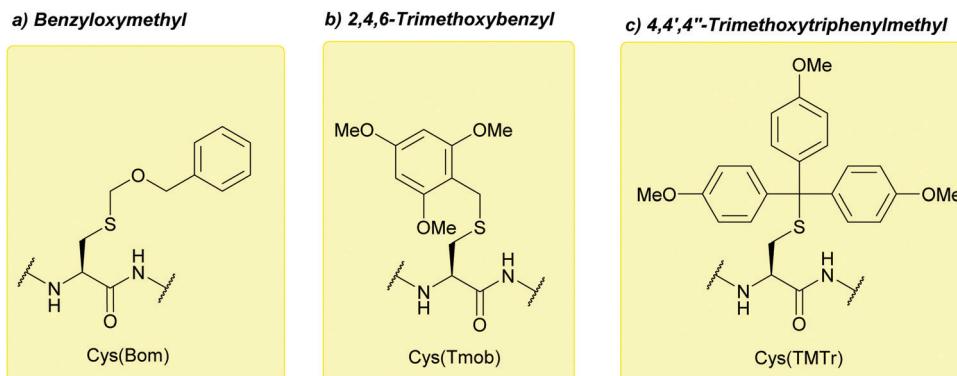


Fig. 13 (a) Cys thiol protection with the benzylxymethyl (Bom) protecting group. (b) Cys thiol protection with the 2,4,6-trimethoxybenzyl (Tmob) protecting group. (c) Cys thiol protection with the 4,4',4''-trimethoxytriphenylmethyl (TMTr).

5.2.9 Benzylxymethyl (Bom). Although it was already in use as a His protecting group,¹⁹⁶ benzylxymethyl (Bom) was introduced as a Cys protecting group (Fig. 13a) for use in Fmoc SPPS in 1989, where it was used in the synthesis of porcine brain natriuretic peptide (pBNP).⁹⁴ Deprotection can be achieved using AgOTf-anisole in TFA (1 h, 0 °C). It can also be removed using 1 M TMSOTf-thioanisole in TFA (1 h, 0 °C), although the former method gives a better yield of the deprotected Cys. To obtain the disulfide, Tl(TFA)₃ may be used (but not I₂). Bom is stable to TFA (4 h, 0 °C), hydrazine, piperidine/DMF and NaBO₃ oxidation.⁹⁴

5.2.10 2,4,6-Trimethoxybenzyl (Tmob). 2,4,6-Trimethoxybenzyl (Tmob) (Fig. 13b) was introduced in 1992 as a novel, acid-labile Cys protecting group suitable for use in Fmoc SPPS.⁹⁶ Tmob can be removed by a minimum of 6% TFA in DCM, in the presence of TES or TIS (5 min, 25 °C). Tmob can also be removed in a mixture of phenol, thioanisole and H₂O (5% each) but, in this case, at least 30% TFA is required. Tmob groups may be removed and the Cys thiol subsequently oxidised to the disulfide using I₂ in DMF (0 °C) or Tl(TFA)₃ in DMF-anisole (0 °C). Peptides synthesised using Tmob showed a marked improvement in purity when compared to identical peptides synthesised using Trt. The group is orthogonal to Acm; as such, the Tmob/Acm combination can be useful for the synthesis of two disulfide bond containing peptides.⁹⁵ However, modification of Trp residues by Tmob cations during deprotection has been reported.⁷¹

5.2.11 4,4',4''-Trimethoxytriphenylmethyl (TMTr). 4,4',4''-Trimethoxytriphenylmethyl (TMTr) (Fig. 13c) is removed by 1% TFA in DCM, making it more acid-labile than either Tmob or Trt. TMTr was designed to allow the selective generation of free Cys residues during Fmoc SPPS whilst the peptide is still on-resin.⁹⁶

5.2.12 Pseudoprolines (ΨPro). Pseudoprolines (ΨPro) were first introduced to SPPS in 1992 as a tool for disrupting unwanted secondary structure formation on resin.¹⁹⁷ The formation of such structures can negatively affect the solubility of a peptide in polar organic solvents and decrease coupling efficiency. By using ΨPro to simultaneously protect the side chains and amino group of Ser, Thr or Cys, a proline-resembling oxazolidine (or thiazolidine) is

formed.¹⁹⁷ These structures are typically incorporated into peptides using dipeptide building blocks *e.g.* Fmoc-aaa-Cys(Ψ^{R,R'}pro)-OH, where aaa = any amino acid and R/R' = identity of the C2 substituents (Fig. 14a).⁹⁷ ΨPro imparts similar conformational properties on the peptide to proline (which can adopt a *cis* conformation), preventing the aggregation of hydrophobic residues by disrupting backbone hydrogen bonding.^{99,197} A follow up study in 1996 investigated the differing stability of ΨPro derivatives to acid; by changing the R/R' groups of the ΨPro, the lability of the protecting group to acid changes significantly.⁹⁷ In the case where R/R' = Me (Ψ^{Me,Me}pro), a protected Cys can be deprotected by TFA within hours. This can be reduced to minutes if R = H and R' = 2,4-dimethoxyphenyl (Dmp) (Ψ^{H,Dmp}pro). Alternatively, when R/R' = H (Ψ^{H,H}pro, *i.e.*, Thz), the group is stable to strong acids. It should also be noted that the kinetics of deprotection appear to show some dependency on the acid and solvent system used.⁹⁷ The ΨPro derivatives are all stable to 20% piperidine in DMF, and are thus suitable for use in Fmoc SPPS.⁹⁷ As Cys(Ψ^{H,Dmp}pro) can be readily cleaved by 90% TFA, it has been suggested to be the most appropriate ΨPro protecting group for this strategy. The protecting group also shows stability to Pd(0), suggesting it may be orthogonal to allyl-based protecting groups.¹⁹⁷ It may also be possible exploit the differing stability of the various ΨPro derivatives by using them together as orthogonal protecting groups.⁹⁷ The acidic stability of Cys(Ψ^{Me,Me}pro) appears to be highly sequence dependant. For example, deprotection of linear 21-mer Sarafotoxin-S6b containing Cys(Ψ^{Me,Me}pro) required removal times of 32–36 h,⁹⁷ whereas a more recent publication observed complete deprotection of Cys(Ψ^{Me,Me}pro)-containing linear 4–10-mer peptides within 1–6 h.⁹⁹ In the case of protected head-to-tail cyclic peptides, high TFA stability has been observed, with required deprotection times of 13 days reported; complete Cys(Ψ^{Me,Me}pro) deprotection can alternatively be achieved with TFMSA at 0 °C within 15 min.⁹⁸ The use of Cys(Ψ^{Me,Me}pro) can enhance the rate of peptide macrocyclization, as the “kinks” induced in the peptide backbone by the ΨPro-protected residues may bring the reacting ends closer together. This was demonstrated by the synthesis of the α -conotoxins CnIB and A1.4 which cyclised significantly faster using Cys(Ψ^{Me,Me}pro) in place of Cys(Trt).⁹⁹ In the first reported synthesis of cyclogossine B,



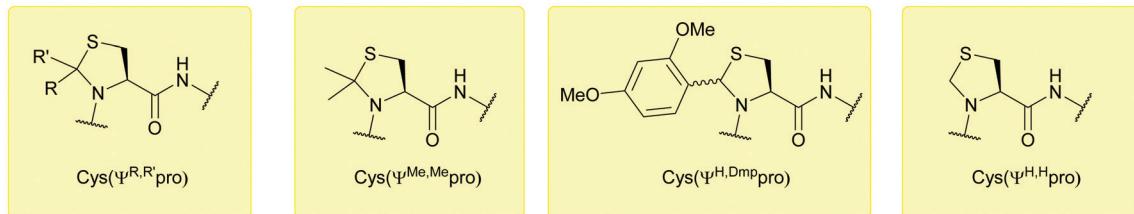
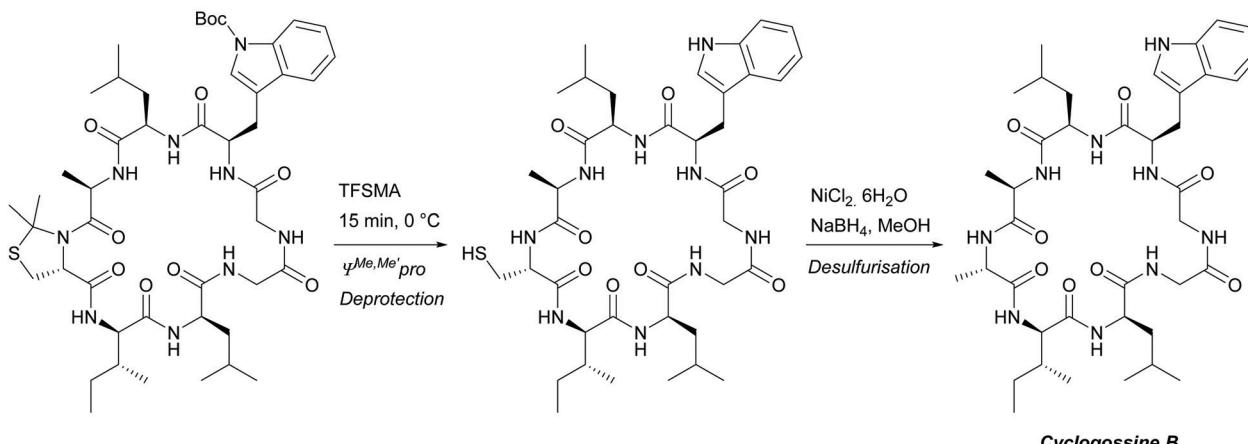
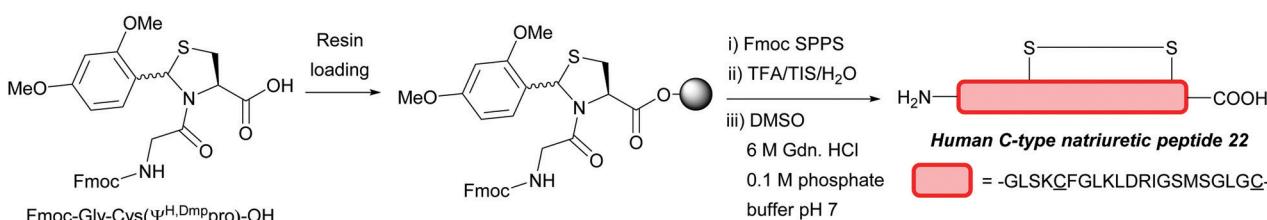
a) Pseudoprolines**b) Synthesis of cyclogossine B****c) Synthesis of human C-type natriuretic peptide 22**

Fig. 14 (a) Cys thiol protection with pseudoprolines bearing different substituents. (b) Synthesis of cyclogossine B using Cys(Ψ^{Me,Me'} pro). (c) Synthesis of human C-type natriuretic peptide 22 using a resin-bound C-terminal protected Gly-Cys(Ψ^{H,Dmp} pro) dipeptide.

Cys(Ψ^{Me,Me'} pro) was introduced in place of an Ala residue where it was used as a turn-inducer to improve cyclisation yields. Following cyclisation, a desulfurisation reaction was used to give the native Ala (Fig. 14b).⁹⁸ Additionally, replacement of Pro residues with Cys(Ψ^{Me,Me'} pro) in synthetic cyclic peptide phallistatin 19 leads to a peptide analogue with greater cytotoxicity *in vitro*.¹⁰¹ Additionally, it has recently been reported that the use of C-terminal resin-bound Cys(Ψ^{H,Dmp} pro) (Fig. 14c) can be used to suppress C-terminal epimerisation.¹⁰⁰ When short peptides were treated with 20% piperidine for 24 h at room temperature, epimerisation levels of <0.01% were observed. Deprotection can be achieved simultaneously with resin cleavage, using a standard cocktail of TFA/TIS/H₂O (95:2.5:2.5) for 1 h.¹⁰⁰

5.2.13 4-Methyltrityl (Mtt). The 4-methyltrityl (Mtt) protecting group (Fig. 15a) is a highly acid labile group that can be deprotected using 1% TFA and scavengers.⁷⁵ It has been utilised for the synthesis of glutathione (GSH) and associated analogues,^{198,199} and in the solid phase synthesis of bicyclic guanidinium oligomers.²⁰⁰ More recently, Cys(Mtt) has been used for the construction of peptide amphiphiles.²⁰¹ In this example,

dually palmitoylated peptides bearing Cys(Mtt) were first synthesised *via* Fmoc SPPS. Selective removal of Mtt (2.5% TFA, 5% TIS in DCM), followed by activation with 2,2'-dithiobis(5-nitropyridine) (DNTP) (Fig. 15b) enabled intermolecular disulfide formation with bioactive, cell penetrating peptides to construct peptide amphiphiles; these then self-assembled into the corresponding peptide amphiphile micelles. B cell lymphoma targeting aptamer (C10.36) could then be annealed to these structures to design aptamer-displaying micelles with anti-cancer properties.²⁰¹ The Mtt group has also been used to protect other amino acids such as Lys.²⁰²

5.2.14 4-Methoxytrityl (Mmt). 4-Methoxytrityl (Mmt) is a very acid-labile Cys protecting group (Fig. 16a) introduced in 1996. Mmt can be deprotected and cleaved from a resin using 1-3% TFA in DCM-TES. Under the removal conditions stated, deprotection of Mmt is irreversible.⁷¹ This is not always the case, as some groups can re-react with the thiol following deprotection in an unwanted side reaction (*e.g.* Trt).¹⁷² Mmt is stable to bases and very weak acids: 30% piperidine in DMF (24 h, 22 °C) and AcOH/TFE/DMF (1:2:7, 30 min). Most of its



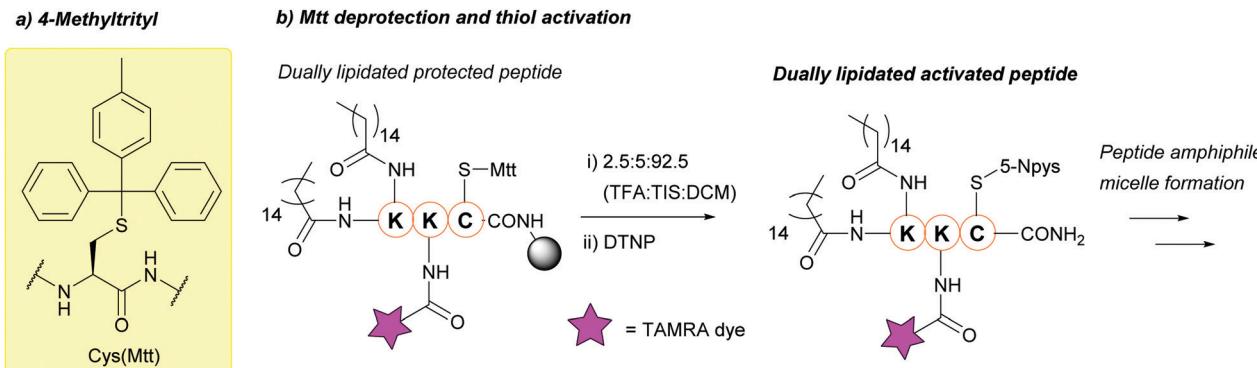


Fig. 15 (a) Cys thiol protection with the 4-methyltrityl (Mtt) protecting group. (b) Deprotection of Cys(Mtt) and activation with DTNP in preparation for peptide amphiphile micelle formation.

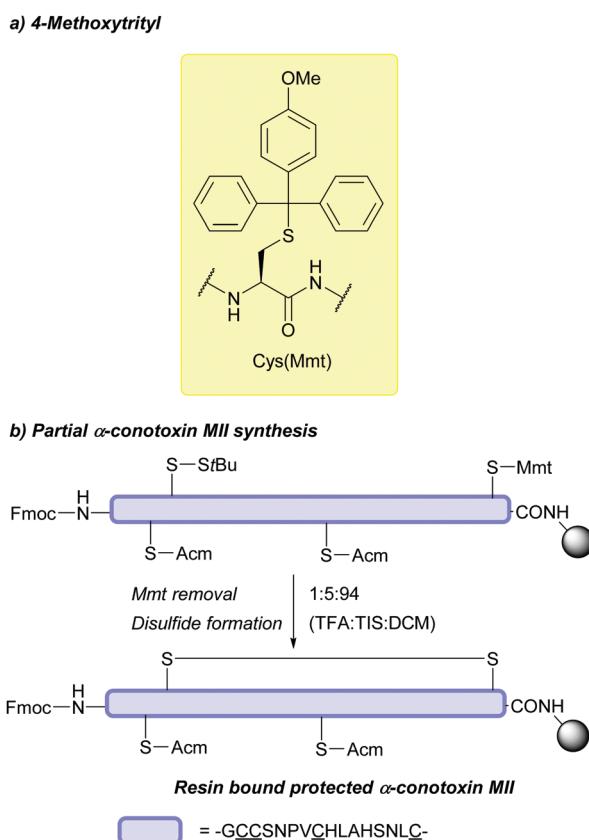


Fig. 16 (a) Cys thiol protection with the 4-methoxytrityl (Mmt) protecting group. (b) Cys(Mmt) deprotection and subsequent disulfide formation through displacement of StBu in the synthesis of α -conotoxin MII.

other properties, such as coupling rates, stability to piperidine, oxidative removal using I_2 , are identical to those of Trt. However, no modification of Trp residues is seen when using thiols or silanes as Mmt cation scavengers, which is advantageous when compared to using Tmob or Trt.⁷¹ The Mmt group displays orthogonality to multiple Cys protecting groups, including *t*Bu,⁸⁴ Dpm,⁷⁵ oNv,¹⁴² StBu,⁸⁴ and Acm.²⁰³ As a result, Cys(Mmt) has been frequently used in combination with other Cys protecting groups to synthesise disulfide containing peptides, such as α -conotoxin

MII (Fig. 16b).²⁰³ In addition, as it is more acid-labile than Trt, the two groups are technically orthogonal to each other; care, however, must be taken if using Mmt and Trt together to avoid an overlap in deprotection conditions (4–5% Trt deprotection is observed in 1% TFA for 30 min at 22 °C).^{71,75} Cys(Mmt) has also been used in the synthesis of cyclic tumour-homing peptides,²⁰⁴ and conopeptides in combination with Cys(Allocam).²⁰⁵ The protecting group also features in the synthesis of palmitoylated peptide fragments; these peptides can be subsequently used as building blocks in Ser/Thr ligation for the chemical synthesis of complex, palmitoylated membrane proteins, including *S*-palmitoylated rabbit sarcolipin (*S*-palm SLN),²⁰⁶ *S*-palmitoylated interferon-induced transmembrane protein 3 (*S*-palm IFITM3),²⁰⁷ and *S*-palmitoylated matrix-2 ion channel from influenza A virus (*S*-palm M2).^{206,207}

5.2.15 9H-Xanthen-9-yl (Xan) and 2-methoxy-9H-xanthen-9-yl (2-Moxan). The 9H-xanthen-9-yl (Xan)²⁰⁸ (Fig. 17a) and 2-methoxy-9H-xanthen-9-yl (2-Moxan) (Fig. 17b) groups were introduced for use in Fmoc SPPS in 1997.¹⁰² 2-Moxan is somewhat more acid-labile than Xan, but both groups are removed by 0.1% TFA in the presence of TES. Silane scavengers are highly efficient at aiding cleavage, whilst conventional aromatic scavengers, *e.g.* thioanisole, show no effect. Thiol scavengers, *e.g.* BME, may be used, but 10% TFA and a great excess of scavenger are needed. In the solid phase, more concentrated acid is required, *i.e.* 1% TFA for 2 h is sufficient. For oxidation to give a disulfide species, I_2 in MeOH

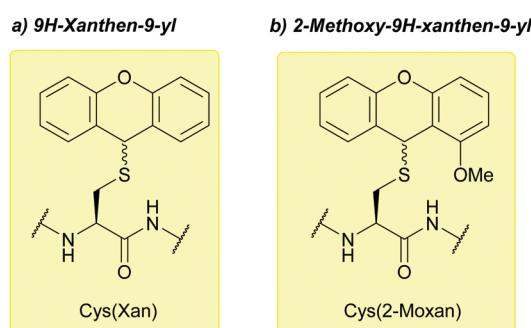


Fig. 17 (a) Cys thiol protection with the 9H-xanthen-9-yl (Xan) protecting group. (b) Cys thiol protection with the 2-methoxy-9H-xanthen-9-yl (2-Moxan).



or $\text{Ti}(\text{TFA})_3$ may be used.¹⁰² Both groups are stable to reagents used in Fmoc SPPS (piperidine in DMF at 25 °C for more than 24 h, 1-hydroxybenzotriazole (HOBt) in DMF at 25 °C for 24 h, *etc.*) and AcOH (even in the presence of silane scavengers). They can be selectively removed from acid-labile PAL (peptide-amide-linker) supports, further expanding their potential use. Both groups produced sample peptides of greater purity than the equivalent peptides synthesised using Cys(Trt). These groups may thus have potential as alternatives to Trt, Tmob or Acm.¹⁰² Xan has featured in the on-resin synthesis of cyclic peptides.²⁰⁹

5.2.16 4,5,6-Trimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-methyl (Tmbm), 2,2,5,7,8-pentamethylchroman-6-methyl (PmcM) and 2,2,4,6,7-pentamethyl-2,3-dihydrobenzofuran-5-methyl (Pbfm). 4,5,6-Trimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-methyl (Tmbm, Fig. 18a), 2,2,5,7,8-pentamethylchroman-6-methyl (PmcM, Fig. 18b) and 2,2,4,6,7-pentamethyl-2,3-dihydrobenzofuran-5-methyl (Pbfm, Pmbf, Fig. 18c) were reported as Cys protecting groups in 2010 in an attempt to find an alternative to Trt.¹⁰³ Cys(Tmbm) and Cys(PmcM) were all cleaved by TFA (although different concentrations were required). However, Pbfm was found to be a superior protecting group candidate, due to its lability and the desired solubility profile.¹⁰³ Pbfm shows promise as a less hydrophobic Trt replacement, with the greater solubility of Pbfm allowing for easier removal during work-up. Pbfm displays similar lability to Trt, and is removed by 1% TFA in the presence of either TES or TIS, although it should be noted that TES may not be used for Trp-containing peptides. Pbfm can also be removed oxidatively on the solid phase using I_2 . For oxidative

removal, fluorinated acidic solvents, such as HFIP or TFE in DMF, work well, requiring only 15 min of treatment.¹⁰³

5.2.17 4-Methoxybenzoyloxymethyl (Mbom). 4-Methoxybenzoyloxymethyl (Mbom) was introduced in 2012 as a Cys racemisation-suppressing replacement (Fig. 18d) for Trt or Acm for use in Fmoc SPPS.¹⁰⁴ Racemisation levels during the activation and coupling steps of conventional Fmoc SPPS were found to be just 0.4% *vs.* 8.0% for Trt¹⁰⁶ and 4.8% for Acm.¹⁰⁴ Mbom can be removed using reagent K (a standard cleavage cocktail composed of TFA/H₂O/phenol/thioanisole/ethane-1,2-dithiol (EDT), v/v 82.5:5.5:5:2.5. Both methoxybenzyl cations and formaldehyde are generated during TFA cleavage, which can undergo side reactions with the peptide; the methoxybenzyl cations can alkylate Cys residues, whereas formaldehyde can lead to hydroxymethylation, and react with N-terminal Cys residues producing Thz-capped peptides. Such side reactions are prevented by using a thiol as a methoxybenzyl cation scavenger, and $\text{MeONH}_2\text{-HCl}$ as a formaldehyde scavenger.¹⁰⁴

5.2.18 2,6-Dimethoxybenzyl (2,6-diMeOBn) and 4-methoxy-2-methylbenzyl (4MeO-2MeBn). 2,6-Dimethoxybenzyl (2,6-diMeOBn, Fig. 18e) and 4-methoxy-2-methylbenzyl (4MeO-2MeBn, Fig. 18f) were reported by Ramos-Tomillero *et al.* in 2012, when searching for protecting groups that fill the gap between Trt and Mob in Fmoc SPPS, *i.e.* labile to TFA concentrations of ~60–90%.⁷⁵ Both groups fulfil this requirement and are removed using 50% TFA (1 h, 25 °C). Despite this, Dpm was recommended for use instead, due to its similar properties and easier accessibility.¹⁰⁵

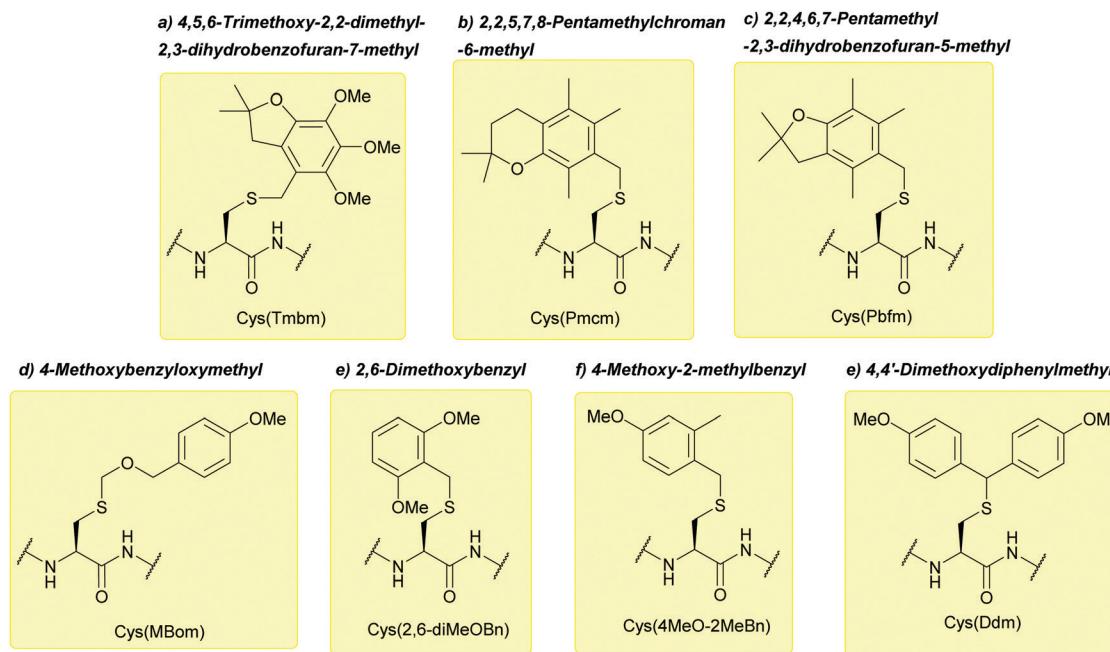


Fig. 18 (a) Cys thiol protection with the 4,5,6-trimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-methyl (Tmbm) protecting group. (b) Cys thiol protection with the 2,2,5,7,8-pentamethylchroman-6-methyl (PmcM) protecting group. (c) Cys thiol protection with the 2,2,4,6,7-pentamethyl-2,3-dihydrobenzofuran-5-methyl (Pbfm) protecting group. (d) Cys thiol protection with the 4-methoxybenzoyloxymethyl (Mbom). (e) Cys thiol protection with the 2,6-dimethoxybenzyl (2,6-diMeOBn) protecting group. (f) Cys thiol protection with the 4-methoxy-2-methylbenzyl (4MeO-2MeBn). (g) Cys thiol protection with the 4,4'-dimethoxydiphenylmethyl (Ddm) protecting group.



a) 2-Hydroxy-4-methoxybenzyl

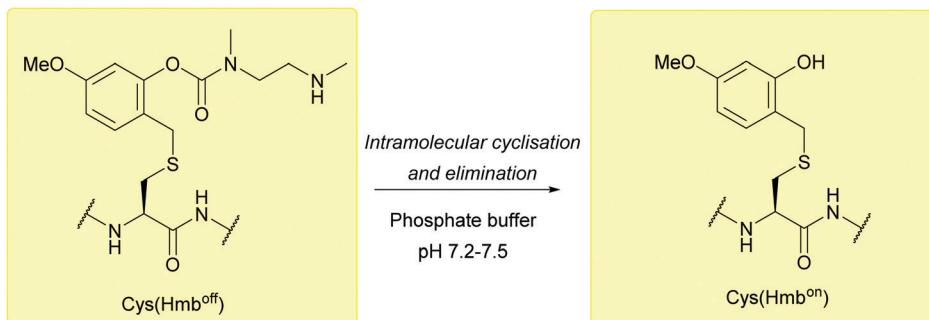
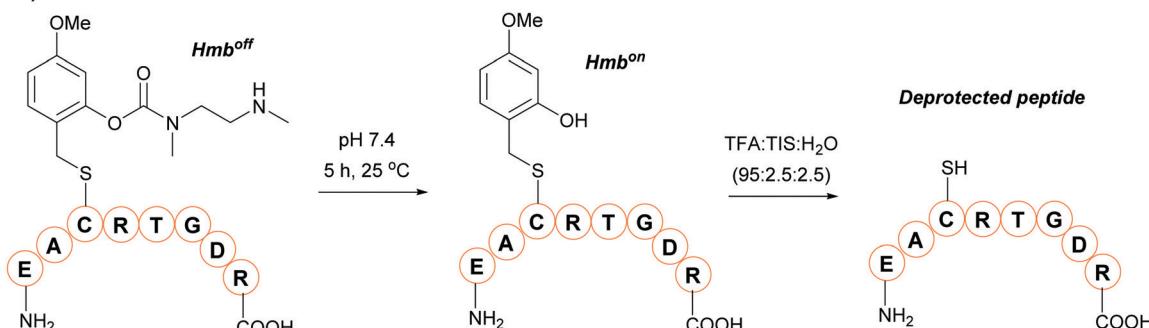
b) Conversion of Hmb⁰⁰ to Hmb⁰¹⁰

Fig. 19 (a) Cys thiol protection with the Hmb⁰⁰/¹⁰ protecting group. (b) Conversion of Cys(Hmb⁰⁰) to Cys(Hmb⁰¹⁰) and subsequent deprotection of a model peptide.

5.2.19 4,4'-Dimethoxydiphenylmethyl (Ddm). 4,4'-Dimethoxydiphenylmethyl (Ddm, 4,4'-diMeODpm, Fig. 18g) was introduced by Ramos-Tomillero *et al.* and can be removed in 10% TFA (5 min, 25 °C).¹⁰⁵ It is recommended as a racemisation-suppressing replacement for Trt, displaying lower rates of Cys racemisation than Trt or Dpm (0.8% vs. 8.0% vs. 1.2%, (respectively)) when used for conventional Fmoc SPPS.¹⁰⁶

5.2.20 Hmb⁰⁰/¹⁰. Hmb⁰⁰/¹⁰, a 2-hydroxy-4-methoxy benzyl derivative, is a novel protecting group with switchable activity (Fig. 19a). Hmb⁰⁰ is fully compatible with Fmoc SPPS. However, when treated with aqueous buffer at pH 7.2–7.5 the group is selectively converted to the Hmb⁰¹⁰ form. The Hmb⁰¹⁰ form is fully compatible with standard NCL protocols, including the post-ligation desulfurisation reaction and any HPLC handling steps but can be removed by TFA cocktails (Fig. 19b, 95% TFA, 2 h, 25 °C – conditions under which Hmb⁰⁰ is stable). To demonstrate its use in SPPS, a segment of erythropoietin (EPO) was synthesised (EPO[Cys⁹⁸-Arg¹⁶⁶]) using Hmb⁰⁰/¹⁰ as a Cys protecting group.¹⁰⁷

5.3 Oxidatively-labile protecting groups

5.3.1 Acetamidomethyl (Acm). Acetamidomethyl (Acm, Fig. 20a) was first described by Veber *et al.* in 1968.¹⁰⁸ This novel protecting group was noted to be stable to acidic conditions (TFA, HBr/AcOH and HCl/EtOH (all at 25 °C), as well as anhydrous HF at 0 °C). Acm was also noted to be stable to alkaline aqueous solutions at 25 °C but, crucially, could be removed by Hg(OAc)₂.^{108,110} Follow up literature reports further established that Acm shows stability to commonly used peptide synthesis protocols, can be removed under relatively mild conditions and

displays no major racemisation problems.¹¹⁰ Hg(II) is not the only heavy metal that can remove Acm–AgOTf in TFA (followed by DTT to obtain the free thiol) will also work,⁸⁷ as will AgBF₄ in TFA-thioanisole (also followed by DTT treatment).¹²¹ Alternative acidic conditions can also be used: 6 M HCl at 110 °C for 20 h¹¹⁰ or 97.5% TFA-thioanisole with an electrophilic disulfide (DTNP or DTP), with an excess of DTNP required (15 eq. for ~90% deprotection).⁹⁰ Partial Acm deprotection (70%) of a Cys(Acm)-containing peptide in 98% TFA-TIS has also been observed after 12 h at 37 °C, with 35% of the deprotected peptide in the disulfide form and 35% present as the free thiol. Replacing TIS with anisole or phenol resulted in similar levels of deprotection, whilst 80–90% deprotection was observed when using thioanisole. TES scavenger proved more effective at promoting Acm removal (TES can however reduce the indole ring of Trp). It should be noted here that whilst thioanisole and TES promote disulfide formation, as observed with TIS, anisole and phenol do not.⁸⁶ For Acm removal and subsequent oxidation to yield disulfides, I₂, Tl(TFA)₃,¹¹¹ or silyl chloride–sulfoxide in TFA may be used.⁸² Acm is stable to TCEP and is thus orthogonal to SiPr.¹¹⁴ The Acm protecting group also displays orthogonality to a large number of other Cys protecting groups; these include Trt, tBu, Meb,⁷⁴ Ad,⁸⁷ Hqm/Hgm,¹²⁸ Msbh,¹⁶⁶ Tmob, Mmt,²⁰³ and Dnpe.¹²⁴ As a result, Acm is widely used as a Cys protecting groups, as shown in the synthesis of proteins including chemokine CCL27 (using AgNO₃ for Cys(Acm) deprotection),⁵¹ EPO (using AgOAc for Cys(Acm) deprotection),²¹⁰ and HIV-1 Rev (Fig. 20b, using Hg(OAc)₂ for Cys(Acm) deprotection).²¹⁰ However, the methods described thus far to deprotect Cys(Acm)



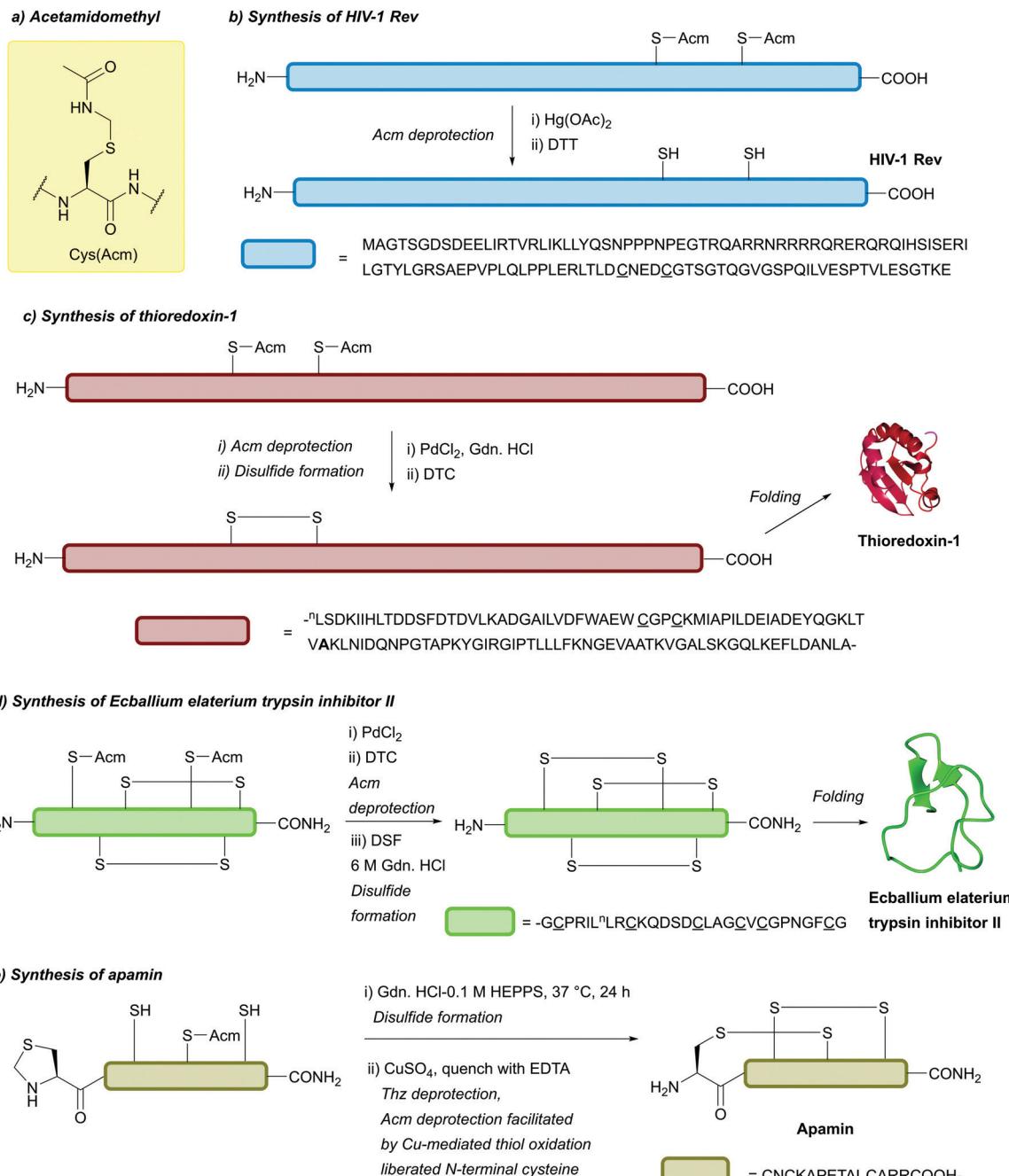


Fig. 20 (a) Cys thiol protection with the acetamidomethyl (Acm) protecting group. (b) Synthesis of HIV-1 Rev using Cys(Acm) and Hg-mediated deprotection. (c) Synthesis of thioredoxin-1 using Cys(Acm) and Pd-mediated deprotection. DTC is used for Pd quenching. (d) Synthesis of *Ecballium elaterium* trypsin inhibitor II (EETI-II) using Cys(Acm) and Pd-mediated deprotection. DSF is used for disulfide formation post-Acm removal. (e) Synthesis of apamin using Cys(Acm) and a Cu-mediated deprotection process.

have been reported to suffer from several issues over the years. The heavy metals used to remove Acm are toxic and harmful to the environment, and *S* to *O*(Ser, Thr) Acm shifts can occur upon deprotection in peptides with high Ser or Thr content. This can be avoided by using glycerol (with a molar ratio of glycerol:peptide, 5600:1) as a scavenger with Hg(II) or Tl(III) deprotection methods.²¹¹ I₂ can cause back-alkylation, resulting in the formation of residual products, which can be difficult to remove.¹²⁷ Other potential side-reactions include

the iodination of Trp and Tyr residues¹²⁸ or over-oxidation to the sulfonic acid.¹⁰⁹ Although mostly acid-stable, premature cleavage of Acm occasionally occurs in mildly acidic conditions in the presence of free thiol and thioanisole scavengers. Irreversible alkylation of Tyr residues with Acm groups can then occur. This reaction appears to be suppressed with scavengers (e.g. phenol) at comparatively high peptide dilution and may be sequence-specific.²¹² The preparation of Acm can also be problematic, as thiazolidine-2-carboxylic acid can be formed as a

byproduct. Activation using DCC/HOBt can also result in side reactions. The Bam and Tacm protecting groups have been reported in an attempt to address these issues.¹²⁰ Due to its partial instability to HF, Acm is not particularly suitable for use in Boc SPPS.¹¹¹ In addition, Acm reacts with strong electrophiles, such as the *t*Bu cation (which is generated during Boc removal), causing *S*-alkylation – although this reaction can be suppressed by the addition of dimethyl sulfide.¹¹⁰

More recently, it has been reported that Acm can be removed under significantly milder conditions using transition metal catalysts, such as Pd(II) complexes.^{109,112} For example, the synthesis of the two-Cys containing ubiquitin-like protein 5 (UBL5) could be achieved in a one-pot manner, with deprotection of Cys(Acm) in the final step performed using 30 equiv. PdCl₂ within 15 min (followed by DTT addition).¹¹² Treatment of Cys(Acm)-containing peptides with PdCl₂ in H₂O or guanidinium chloride (Gdn-HCl) pH 7 (30 min, 37 °C) followed by DTT addition led to total deprotection to yield the free thiol-containing peptide. Alternatively, using 100 equiv. of diethyldithiocarbamate (DTC) after Pd-mediated deprotection of multi-Cys(Acm)-containing peptides allows for oxidation to form disulfide bonds. Total synthesis of *E. Coli* thioredoxin (Trx-1) in a one pot manner has been reported using this strategy. First NCL was performed between an N-terminal fragment (bearing two Cys(Acm) residues and a C-terminal thioester, Trx(1-56)) and a C-terminal fragment (bearing an N-terminal Cys (Trx58-109)). This was then followed by desulfurisation, and finally sequential Acm deprotection and disulfide formation using PdCl₂ and DTC respectively to yield the target protein (Fig. 20c).¹⁰⁹ Moreover, whilst Acm and Thz are both labile to Pd(II) complexes, Acm is stable to the lower concentrations of [Pd(allyl)Cl]₂ compared to Thz, giving the two groups some orthogonality to one another. Following Thz deprotection, Acm can be deprotected within 5 h following the addition of an extra 10 equiv. of [Pd(allyl)Cl]₂. Additionally, Acm is orthogonal to *t*Bu under these conditions.⁸⁵ Acm is also stable to Pd(0)-mediated removal of N-terminal Alloc-protected α -amino groups. This, in tandem with a β -thiolactone-mediated NCL procedure,^{213,214} was demonstrated in the full chemical synthesis of histone H3 bearing an N ϵ trimethylated Lys residue ([Lys(Me3)9]H3.1).¹¹³ The use of PdCl₂ for Cys(Acm) deprotection, with DTC for Pd quenching and disulfiram (DSF) for disulfide formation, has very recently been

described in combination with photolabile Cys protecting groups for rapid deprotection/disulfide formation in multiple disulfide-rich peptides, including Linactotide and *Ecballium elaterium* trypsin inhibitor II (EETI-II, Fig. 20d).²¹⁵

In addition to Pd(II) chemistry, deprotection of Cys(Acm) using CuSO₄ has been reported.⁷³ Initially, it was noted that CuSO₄-mediated deprotection of Cys(Thz) would also lead to deprotection of Cys(Acm) in the same peptide scaffold if ascorbate was not added, but would leave Acm intact if ascorbate was added. In model peptides, CuSO₄ would only deprotect Cys(Acm) if the peptide contained an N-terminal Cys that was either unprotected or protected with Thz (which could undergo CuSO₄-mediated deprotection to reveal an N-terminal Cys). This instance of double deprotection has been hypothesised to result from Cu-mediated oxidation of the deprotected/unprotected N-terminal thiol to sulfenic acid, which then undergoes nucleophilic attack from the Cys(Acm) sulfur, leading to disulfide formation and loss of Acm. Excess Cu can then be quenched with DTT (leading to the free thiol-containing peptide) or ethylenediaminetetraacetic acid (EDTA, leading to the disulfide containing peptide). This protocol was demonstrated in the synthesis of the two-disulfide containing peptide apamin. Following formation of the first disulfide bond *via* Cys(Trt) deprotection and air oxidation, sequential deprotection of Cys(Thz) and Cys(Acm) with CuSO₄ (100 mM, 6 M Gdn.HCl, 0.1 M HEPPS) followed by quenching with EDTA (100 mM), could be used to engineer the second disulfide bond in a regioselective manner (Fig. 20e). Oxidation by-products were formed, however, if the order of disulfide bond formation in this procedure was reversed (with Cys(Mob) used as opposed to Cys(Trt)). In the case of peptides which lack an unprotected N-terminal Cys, Cys(Acm) can be deprotected by addition of CuSO₄ in the presence of an equimolar amount of aminothiol additive, such as cysteamine.⁷³

5.3.2 5-Dibenzosuberyl (Dbs). The 10,11-dihydro-5H-dibenzo-[*a,d*]cyclohepten-5-yl or 5-dibenzosuberyl (Dbs, Sub) protecting group (Fig. 21a) was proposed in 1976.¹¹⁵ The group was noted to be removed reductively with Hg(OAc)₂ or oxidatively with I₂ in MeOH or AcOH.¹¹⁵ Dbs-Protected Cys may also be cleaved using Tl(TFA)₃ to yield cystine.^{83,216} Dbs was observed to have “sufficient” stability to TFA but was partially removed by HBr/AcOH.¹¹⁵ Preliminary work has shown that Dbs may be a

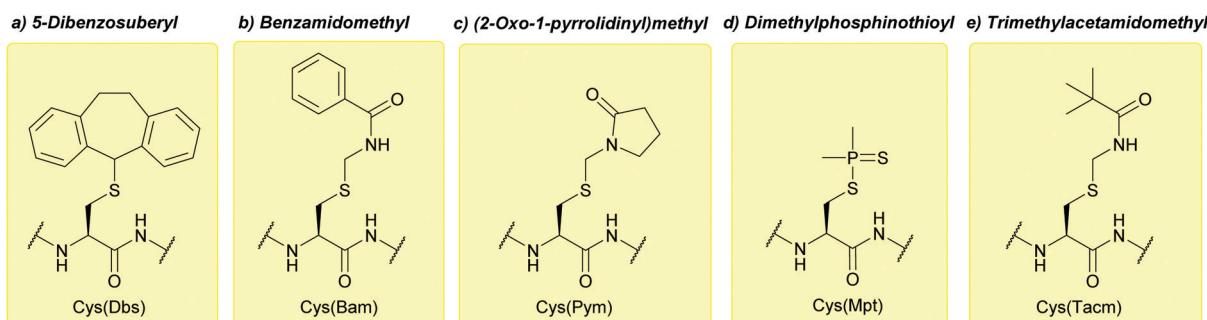


Fig. 21 (a) Cys thiol protection with the 5-dibenzosuberyl (Dbs) protecting group. (b) Cys thiol protection with the benzamidomethyl (Bam) protecting group. (c) Cys thiol protection with the (2-oxo-1-pyrrolidinyl)methyl (Pym) protecting group. (d) Cys thiol protection with the dimethylphosphinothioly (Mpt) protecting group. (e) Cys thiol protection with the trimethylacetamidomethyl (Tacm) protecting group.



promising protecting group for the guanidino function of Arg,²¹⁷ however, it is yet to find widespread use as a protecting group.⁴

5.3.3 Benzamidomethyl (Bam). The benzamidomethyl (Bam) protecting group (Fig. 21b) was proposed in 1978 as an alternative to Acm which could still be removed using $\text{Hg}(\text{OAc})_2$ (1 h, RT).¹¹⁶ Bam can also be removed oxidatively by AgOTf in TFA-anisole (1 h, 0 °C)⁸⁷ as well as by methyltrichlorosilane/tetrachlorosilane in the presence of diphenyl sulfoxide (a “silyl chloride-sulfoxide system”) in TFA.⁸² DTT may then be added to obtain the free thiol.⁸⁷ Compared to Acm and when no N-terminal protecting was present, preparation of Cys(Bam) was not accompanied by the formation of thiazolidine-2-carboxylic acid and side reactions were not observed during DCC/HOBt activation.¹²⁰ Bam has been shown to be stable to many commonly used reagents in peptide synthesis: 1 M NaOH, 1 M HCl, and TFA (all at 25 °C), as well as 90% Zn/AcOH at 0 °C. The group is however unstable to very strong acids, such as 6 M HCl (24 h, 110 °C),¹¹⁶ as well as HF cleavage and towards alkaline conditions.¹²⁰

5.3.4 (2-Oxo-1-pyrrolidinyl)methyl (Pym). The (2-oxo-1-pyrrolidinyl)methyl (Pym) functionality has been reported as a somewhat obscure Cys protecting group (Fig. 21c).¹¹⁷ Cys(Pym) shows instability when treated with HF, and is susceptible to oxidation with NaBO_3 to give the corresponding Cys sulfoxide species similar to Cys(Acm) and Cys(Bam). It has been noted to show stability towards 0.05 M NaOH or treatment with hydrazine. Complications arising from use of DCC-HOBt coupling were not observed when using Boc-Cys(Pym)-OH.¹¹⁷ It has been reported as a protecting group for the synthesis of hexapeptides, although its success in giving pure peptides during isolation was rather limited; this was rationalised by the Cys(Pym) group displaying increased solubility in solvents such as H_2O , acetone, and Et_2O .²¹⁸

5.3.5 Dimethylphosphinothioyl (Mpt). Initially reported as an N-terminal α -amino protecting group,²¹⁹ the dimethylphosphinothioyl (Mpt) protecting group was first investigated as a Cys protecting group in 1983 (Fig. 21d).¹¹⁸ Cys(Mpt) proved stable at room temperature to 2 M HCl in solvents such as EtOAc and AcOH, and to TFA. Partial cleavage was observed when using 25% HBr/AcOH, and dehydroalanine formation was noted upon treating Cys(Mpt)-containing peptides with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). The Mpt group can be cleaved with AgNO_3 or $\text{Hg}(\text{OAc})_2$ (1–4 equiv. 20–60 min), and

has been used in the Boc solution phase synthesis of glutathione.¹¹⁸ Alternatively, deprotection can also be achieved using tetrabutylammonium fluoride (TBAF)/THF to give the free thiol, or TBAF/DMF to yield the corresponding disulfide. If Mpt deprotection with TBAF is carried out in DCM, however, methylenedithioether formation between two Cys thiols occurs; this was subsequently demonstrated in the Boc solution phase synthesis of a cyclic enkephalin analogue.¹¹⁹

5.3.6 Trimethylacetamidomethyl (Tacm). The trimethylacetamidomethyl (Tacm) group (Fig. 21e) was proposed in 1989 as an alternative to Bam.¹²⁰ Similar to Bam, preparation and activation when using Tacm are not accompanied by side reactions; in contrast, however, Tacm is also stable to acidic conditions (HF, 1 h, 0 °C, or TFMSA-thioanisole in TFA, 2 h, 0 °C) and a variety of basic conditions (0.05 M NaOH in MeOH, 1 h, 0 °C or hydrazine in MeOH, 24 h, RT). Tacm is also stable to 90% Zn/AcOH (1 h, 25 °C), and displays a higher resistance to air oxidation than Acm or Bam. Partial cleavage is observed, however, when treated with 25% HBr/AcOH.¹¹⁷ Tacm can be removed using $\text{Hg}(\text{OAc})_2$, or I_2/EtOH in AcOH (aq.) for oxidation to the disulfide.¹²⁰ Much like Acm, Tacm is also cleaved by AgBF_4 in TFA-thioanisole (followed by DTT treatment)¹²¹ and silyl chloride-sulfoxide in TFA, the latter of which gives the disulfide.⁸²

Care must be taken when using I_2 in AcOH, as partial oxidation of methionine (Met) residues to methionine sulfoxide (Met(O)) can occur. Modification of Trp residues has also been observed.¹²¹ Despite its higher resistance to acid than Bam, Tacm can still show instability in HF and TFA/heat. It is therefore not particularly suitable for Boc SPPS,¹¹¹ although it has been used successfully in Boc solution phase synthesis of pBNP using this strategy.¹²⁰ Furthermore, Cys(Tacm) has been used in Fmoc SPPS to synthesise oxytocin in combination with the silyl chloride-sulfoxide system.²²⁰

5.4 Base-labile protecting groups

5.4.1 9-Fluorenylmethyl (Fm). The 9-fluorenylmethyl (Fm) group is a base-labile Cys protecting group (Fig. 22a) first described in 1982¹²² and introduced to SPPS in 1986.¹²³ Fm can be removed by NH_3 in MeOH¹²² or 50% piperidine in DMF (2 h, RT).¹²³ Fm displays favourable properties for Boc SPPS; it is stable to TFA, TFMSA/TFA, boiling HCl (at 110 °C)¹²² as well as HF-anisole

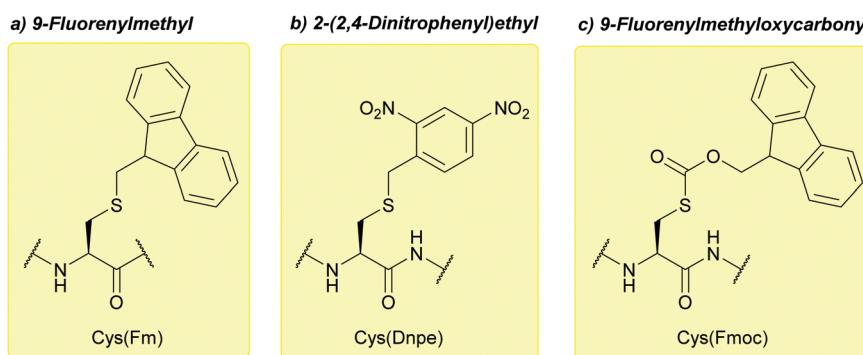


Fig. 22 (a) Cys thiol protection with the 9-fluorenylmethyl (Fm) protecting group. (b) Cys thiol protection with the 2-(2,4-dinitrophenyl)ethyl (Dnpe). (c) Cys thiol protection with the 9-fluorenylmethyloxycarbonyl (Fmoc) protecting groups.



(95 : 5, 1 h, 0 °C). It is also stable to 0.1 M I₂ in DMF,¹²³ and catalytic hydrogenation.¹²² As with all of the base-labile protecting groups described here, Fm is incompatible with Fmoc SPPS.¹²³ Some Fm-protected peptides can display poor solubility in polar media, and a low peptide yield is observed upon final HF cleavage from the resin when the C-terminal amino acid is Cys(Fm). Dnpe is an alternative protecting group that may be used to avoid these complications.¹²⁴

5.4.2 2-(2,4-Dinitrophenyl)ethyl (Dnpe). 2-(2,4-Dinitrophenyl)ethyl (Dnpe) was introduced in 1992 as a replacement for the Fm group in Boc SPPS (Fig. 22b).¹²⁴ Compared to Fm, superior yields were obtained following HF cleavage when the C-terminal amino acid is Cys; this is attributed to the reduced steric hindrance encountered during cleavage when using Dnpe. Dnpe is more base-labile than Fm and cleavage using 50% piperidine in DMF can yield the desired disulfide-containing peptide within 30 min. Alternatively, the free thiol-containing peptide can be obtained within 1 h if this process is done in the presence of 2% BME under an argon atmosphere.¹²⁴ Deprotection can also be accomplished using DBU (2% v/v in DMF).⁶⁸

Dnpe is stable to a wide variety of reagents, both basic and acidic. These include: 5% DIEA in DCM (2 h), 40% TFA in DCM (24 h), 90% HF in the presence of *p*-cresol or anisole (1 h, 0 °C), and TFMSA-*p*-cresol in TFA (1 : 3 : 10, 2 h, 25 °C). It is also stable to oxidative conditions, *e.g.* Tl(TFA)₃ in TFA, I₂ in 80% AcOH (aq.) and is thus orthogonal to protecting groups including Meb, Acm and StBu.¹²⁴

5.4.3 9-Fluorenylmethyloxycarbonyl (Fmoc). Although widely used for N-protection of the α -amino group in SPPS, it was not until 2001 that 9-fluorenylmethyloxycarbonyl (Fmoc) as a protecting group for the Cys thiol was demonstrated (Fig. 22c).¹²⁵ Cys(Fmoc) can be converted to Cys(Fm) by treatment with Et₃N. Fm may then be removed as described previously. Furthermore, *S*-Fmoc can be removed preferentially over *N*-Fmoc through choice of base, allowing the two groups to be used together. Although Fmoc still has not become widely used as an *S*-protecting group, it provides a simple way of synthesising Fm derivatives. Additionally, *S*-Fmoc could be useful in synthetic strategies that require selective deprotection of the thiol group in the presence of *N*-Fmoc.¹²⁵

5.5 Enzyme-labile protecting groups

5.5.1 Phenylacetamidomethyl (Phacm). Phenylacetamidomethyl (Phacm, Fig. 23a) is an environmentally-friendly alternative to Acm, first described in 1991 by Greiner and Hermann.²²¹ The protecting group was then introduced to SPPS in 1995 by Royo *et al.*¹²⁶ Phacm has very similar stability and lability to Acm but is additionally cleaved by *E. coli* penicillin G acylase (PGA, E.C. 3.5.1.1).¹²⁶ PGA can be immobilised on amino-acrylic resin (iPGA, Fig. 23b), which allows the enzyme to be recycled for repeated use; total enzymatic activity is still retained after five reaction cycles. Immobilisation of the enzyme is beneficial as it decrease the environmental impact and increase the cost-effectiveness of the enzyme. Immobilised enzymes also tend to have enhanced stability and display activity over a wider range of conditions.¹²⁷ Cys(Phacm) deprotection can be performed under mild conditions; the optimal conditions for using iPGA are 0.1 mM phosphate buffer, pH 7.9, in

DMSO (95 : 1), at 37 °C. DMSO is the best-tolerated solvent, but enzymatic activity remains almost completely intact when DMSO is replaced by any of a variety of organic co-solvents: MeCN, DMF, EtOH, various other alcohols and Et₂O. The pH range under which deprotection can occur is also broad, with clean removal still observed at pH 5.9.¹²⁷ If enzymatic hydrolysis is performed in the presence of BME, the free thiol is obtained, otherwise, the Cys is oxidised directly to the disulfide.¹²⁶ The efficiency of iPGA can depend on the peptide sequence containing Cys(Phacm), as some peptide sequences appear to tolerate a broader range of conditions than others. Care must therefore be taken to choose the optimal conditions for a given sequence.¹²⁷ Phacm may also be removed using Hg(II) or Ag(II) salts, or under conventional oxidative conditions, *e.g.* using I₂ or Tl(TFA)₃. However, removal under enzymatic conditions circumvents the problems with such reagents, as there is no need to use toxic heavy metals or reagents (*e.g.* I₂) which can favour peptide chain modifications (*e.g.* back alkylation), have difficult to remove residual products and are damaging to the environment.¹²⁷ Phacm is stable to acidic and basic conditions, including 5% DIEA in DCM, 40% TFA in DCM, 25% piperidine in DMF, 0.1 M TBAF in DMF and 5% DBU in DMF (all for 24 h at 25 °C). Phacm is also stable to 90% HF in the presence of anisole or *p*-cresol (1 h, 0 °C) and 90% TFA in the presence of a number of scavengers (*i.e.* phenol, ethane-1,2-dithiol (EDT), *p*-cresol, anisole, 2 h, 25 °C). This makes Phacm suitable for both Fmoc and Boc SPPS. However, it is more useful for Fmoc SPPS, as it is partially cleaved (<20%) by TFMSA-TFA-*p*-cresol (1 : 10 : 0.3, 2 h, 25 °C).¹²⁶ Phacm is orthogonal to a wide variety of protecting groups, including Fm, Dnpe, Meb, Trt and Tmob.¹²⁶ In addition to those mentioned, Phacm is orthogonal to many acid-labile protecting groups.¹²⁷ It is also partially orthogonal to Acm, provided Phacm is removed enzymatically prior to Acm deprotection.¹²⁶ This has been demonstrated on model tripeptides containing Cys(Phacm) and Cys(Acm) (Fig. 23c).¹²⁷ Cys(Phacm) derivatives, which have been used as protecting groups/solubilising tags in the chemical synthesis of proteins such as histone H4, can also be removed using PdCl₂ under aqueous conditions.²²² Additionally, the orthogonality of Cys(Phacm) can be used to facilitate multi-interchain disulfide formation in the final step of three-disulfide containing peptides synthesis, such as in the I₂ free synthesis of a porcine insulin analogue (Fig. 23d).²²³ Here, the A chain (containing four c) can be synthesised using a combination of Cys(S-Tmp), Cys(Mmt), Cys(Trt) and Cys(Phacm). Selective deprotection, followed by activation, yields the Cys(Trt), Cys(Phacm), disulfide containing resin bound A chain. Simultaneous Trt removal and resin cleavage could then be achieved with a cleavage cocktail of TFA : TIS : H₂O (92.5 : 5 : 2.5). Incubation of this A chain peptide with a Cys(Phacm), Cys(5-Npys) activated B chain peptide in ligation buffer (0.2 M NH₄OAc, 6 M urea, pH 4.5) lead to formation of one of the interchain disulfides. Finally, selective removal of the Phacm protecting group with immobilised PGA and activation with 3 equiv. 5,5'-dithiobis-(2-nitrobenzoic acid) (DTNB) lead to formation of the second interchain disulfide to give the desired product. Optimisation of activation with DTNB proved critical to minimise misfolding and disulfide scrambling;

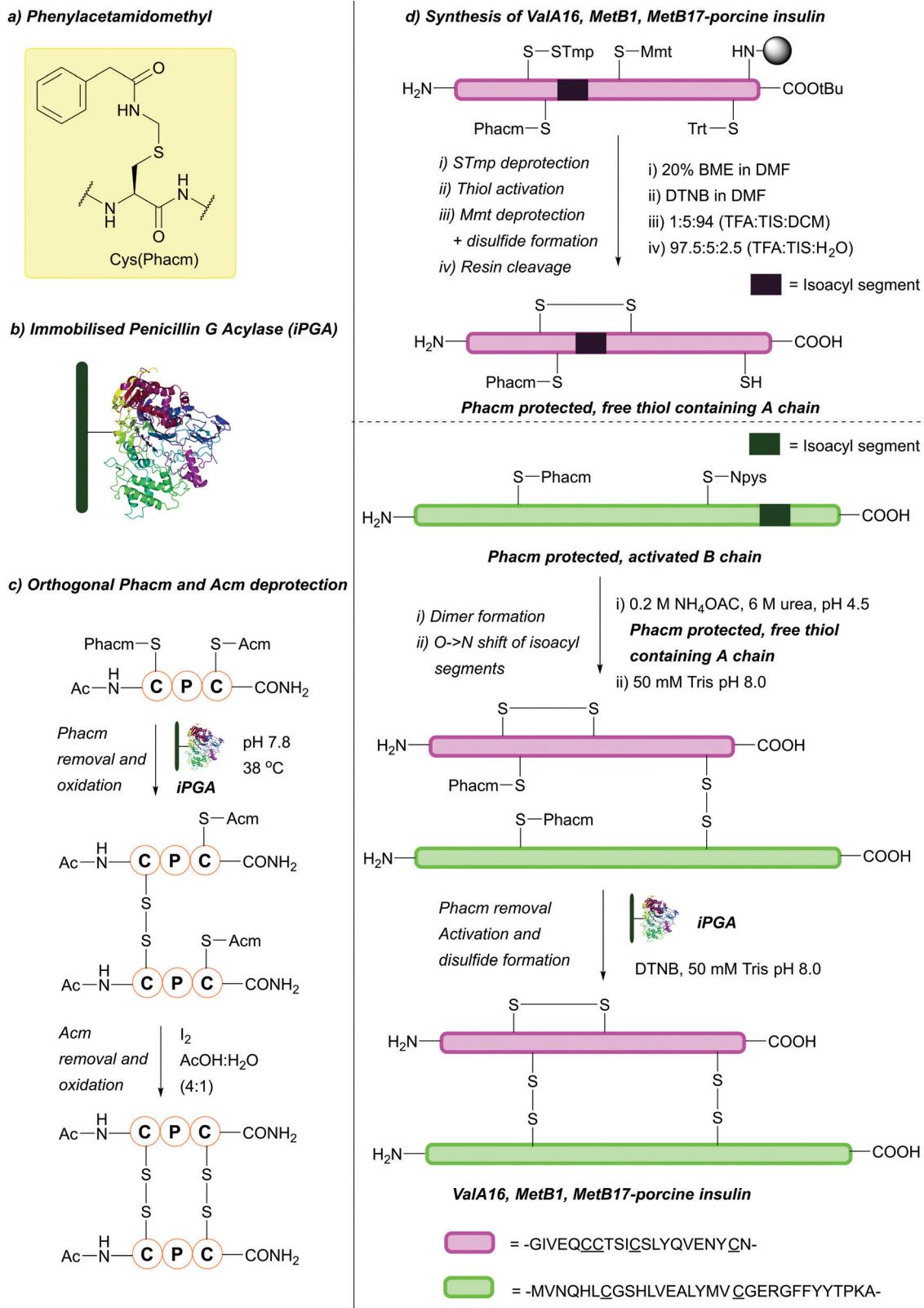


Fig. 23 (a) Cys thiol protection with the phenylacetamidomethyl (Phacm) protecting group. (b) Schematic of immobilised Penicillin G Acylase (iPGA) used for Cys(Phacm) deprotection. (c) Orthogonal deprotection of Cys(Phacm) and Cys(Acm) in a model tripeptide. (d) Synthesis of a porcine insulin analogue using Cys(Phacm).

oxidation with no DTNB or in 10% DMSO led to only scrambled side products, whereas double-DTNB side products were observed when using >4 equiv. DTNB.²²³ A similar strategy was adopted for the synthesis of human relaxin-2 using Cys(Phacm) and Cys(*t*Bu); here, DTNB was replaced with activating agent bis(5-(2-methoxyethoxy)-2-pyrimidinyl disulfide (BMPD) post-Phacm-removal to give an improved peptide yield.²²⁴

5.6 Hydrazine-labile protecting groups

5.6.1 Hydroxyglycine-Acm (Hgm) and hydroxyquinoline-Acm (Hqm). Hydroxyglycine-Acm (Hgm, Fig. 24a) and hydroxyquinoline-Acm (Hqm, Fig. 24b) were devised by Shen *et al.* in 2011.¹²⁸ Both groups are stable to Fmoc and Boc SPPS and are removable by hydrazine (5% v/v in H₂O) under mild conditions

(pH 8.5, 37 °C). In both cases, hydrazine removes the OAc moiety, triggering an internal deprotection step. Hqm is removed within 8 h, while Hgm takes 72 h for full removal; Hqm is therefore recommended for practical use. Treatment with standard oxidative reagents (*i.e.* I₂ or AgOAc) removes Hqm within 30 min. Hqm can be considered orthogonal to (and subsequently removed in the presence of) Acm due to the latter's stability towards treatment with hydrazine. This orthogonality was demonstrated in a synthesis of human neutrophil defensin hNP2 using Hqm, Acm and Trt as three orthogonal protecting groups (Fig. 24c). An improved final yield of the peptide was observed when compared to previous reports that used the StBu, Acm and Trt groups.¹²⁸

5.7 Palladium-labile protecting groups

5.7.1 Allyloxycarbonyl (Alloc). The allyloxycarbonyl (Alloc) group has been previously described for the protection amino acids, including the thiol group of Cys (Fig. 25a).²²⁵ Alloc groups can be deprotected using tributyltin hydride (Bu₃SnH) and a Pd(0) catalyst. Removal can be achieved within 10 min using PdCl₂(PPh₃)₂ in DCM and AcOH with Bu₃SnH. The Alloc group is stable in TFA/DCM (24 h, 50 °C), but base-labile – piperidine treatment (30% in DMF, 3 h, 30 °C) of Boc-Cys(Alloc)-OH results in complete removal of the Alloc group. Additionally, under Fmoc conditions, the Alloc group is prone to undergoing $\beta \rightarrow \alpha$ shifts, and intramolecular acylation reactions may also occur.¹²⁹ These issues associated with the Alloc group hinder its suitability as a Cys protecting group. As such, other allyl-based Pd-labile protecting groups, such as Allocam, are recommended instead.¹³⁰

5.7.2 Allyloxycarbonylaminomethyl (Allocam). The allyloxycarbonylaminomethyl (Allocam) group was reported in 1994 as a replacement for Alloc in Cys protection chemistry (Fig. 25b).¹³⁰ The Allocam group can be removed using Bu₃SnH and a Pd(0) catalyst in AcOH (10 min, RT). Following deprotection, the crude reaction mixture contains a mixture of the tributyltin salt, the free thiol, and additionally minor amounts of the corresponding disulfide. 0.5 equivalents of I₂ may then be added to isolate the deprotected Cys residues as their disulfide derivatives.¹³⁰ In the presence of Pd, Cys(Allocam) derivatives can rearrange into allyl thioethers with a corresponding loss of CO₂ and methylenimine. This is prevented by adding a high concentration of a weak nucleophilic species, such as AcOH, into the reaction to trap the π -allyl entity prior to rearrangement. Without addition of AcOH, ~5–10% formation of allyl thioethers is observed.¹³⁰ Cys(Allocam) displays stability towards piperidine,²²⁶ but is slightly unstable to the acidic conditions used for Boc removal,²²⁷ with ~10% degradation seen following 20 h of treatment with 25% TFA in DCM.¹³⁰

After its initial documentation, the Allocam group saw little use as a protecting group for Cys in the literature. More recently, however, it has seen a revival as an orthogonal Cys protecting group. Here, alternative deprotection protocols that lead directly to the disulfide formation on-resin have been developed: Pd(OAc)₂ (1.5 equiv.), 3% NMM and 5% AcOH in DMSO for 2 h. Under these conditions, complete removal of Allocam could be achieved to yield the disulfide-containing

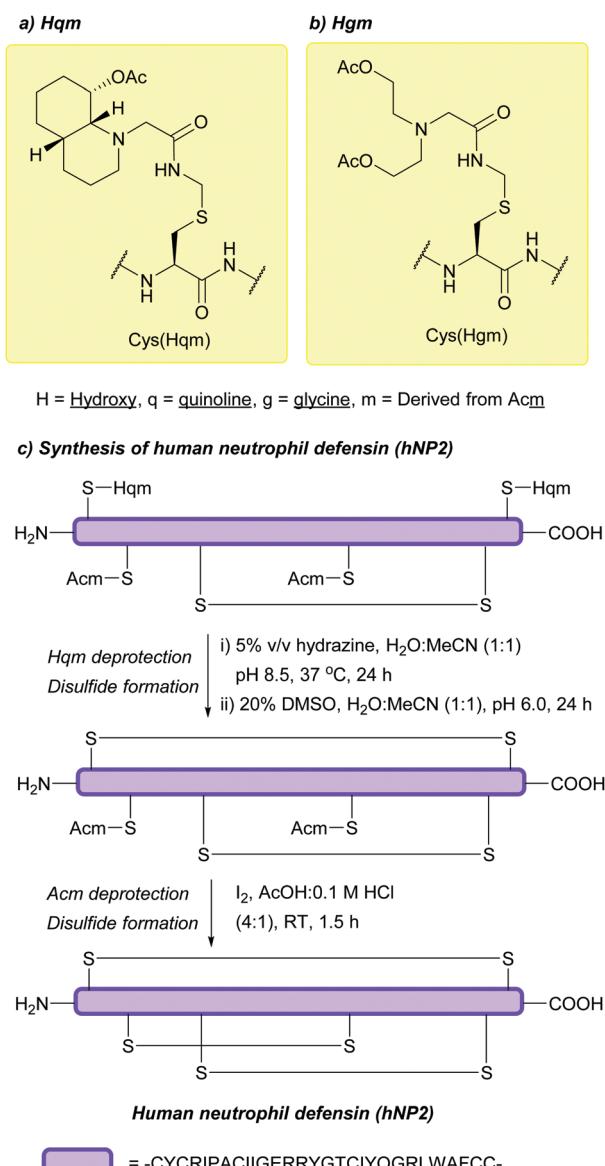


Fig. 24 (a) Cys thiol protection with the Hqm protecting group. (b) Cys thiol protection with the Hgm protecting group. (c) Synthesis of human neutrophil defensin (hNP2) using Cys(Phacm).



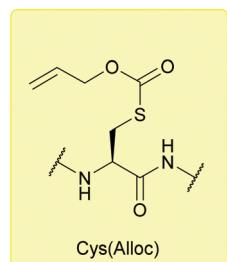
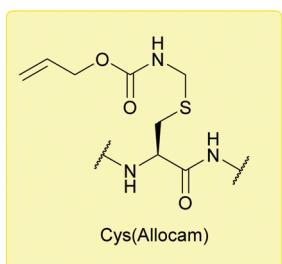
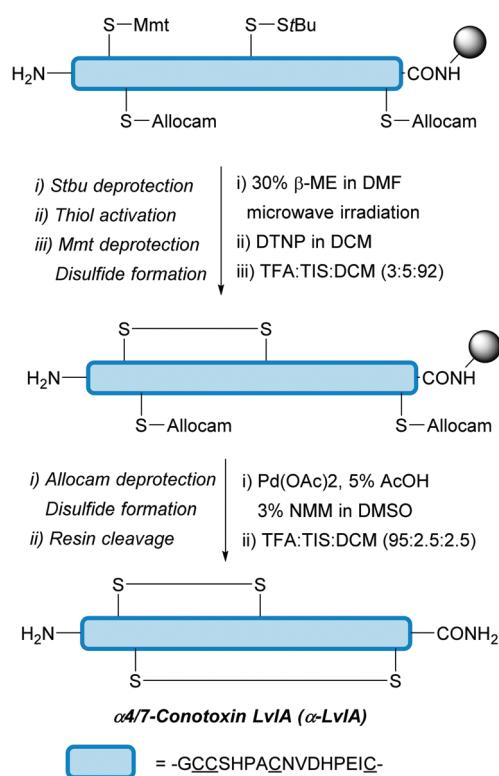
a) *Allyloxycarbonyl*b) *Allyloxycarbonylaminomethyl*c) *Synthesis of α 4/7-Conotoxin LvIA (α -LvIA)*

Fig. 25 (a) Cys thiol protection with the allyloxycarbonyl (Alloc) protecting group. (b) Cys thiol protection with the allyloxycarbonylaminomethyl (Allocam) protecting group. (c) Synthesis of α 4/7 Conotoxin LvIA (α -LvIA) using Cys(Allocam).

resin-bound peptide.¹³¹ The use of Cys(Allocam) has since been expanded towards higher-yielding, on-resin synthesis of α 4/7-Conotoxin LvIA (α -LvIA, Fig. 25c).²⁰⁵ Orthogonality of Cys(Allocam) to other protecting groups was also further established.

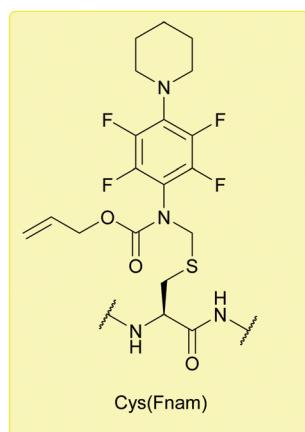
For example, treatment of peptides containing Cys(Trt) and Cys(*t*Bu) with $\text{Pd}(\text{OAc})_2$ (1.5 equiv.), 3% NMM and 5% AcOH in DMSO for 2 h, followed by resin cleavage, led to no removal of either protecting group, whereas treatment of Cys(Mmt) with the same conditions gave a mixture of products. Peptides containing two Cys(Allocam) residues could be fully deprotected to give the corresponding disulfide when using I_2 , whereas the Allocam protecting groups remained intact when using conditions typically used for *StBu*/Mmt removal (20% BME, DTNP, 1% TFA, 5% TIS). Depending on the combination of Cys protecting groups used, Cys(Allocam) could be orthogonally deprotected first or last in a given sequence to perform regioselective synthesis of disulfide-containing α -LvIA on-resin.²⁰⁵

5.7.3 [N-[2,3,5,6-Tetrafluoro-4-(N'-piperidino)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fnam). The [N-[2,3,5,6-tetrafluoro-4-(N'-piperidino)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fnam) group (Fig. 26a) was synthesised in 1999, whilst looking for a replacement to the Allocam group that was more stable to TFA.¹³² The decomposition of Allocam in the presence of acid was hypothesised to be an acid-catalysed fragmentation reaction, which led to the formation of a reactive acylium cation. One way which was theorised to increase the stability of Allocam to TFA was to add an electron-withdrawing group to the nitrogen atom, which would disfavour acylium formation. Fnam can be removed using $\text{Pd}(0)$ complexes in the presence of allyl scavengers, *e.g.* Bu_3SnH in DCM in the presence of 5 mol % $\text{PdCl}_2(\text{PPh}_3)_2$ and AcOH, followed by AcOH/BME to obtain the free thiol. Alternatively, following up with I_2 treatment will give the disulfide. $\text{Pd}(\text{PPh}_3)_4$ in the presence of either PhSiH_3 or NDMBA also caused deprotection within 15 min and 60 min, respectively (these systems fail to deprotect *S*-Allocam).¹³² As with their Allocam homologues, a scavenger (Bu_3SnH , PhSiH_3 or NDMBA) is needed to avoid rearrangement to allyl thioethers. Fnam is completely acid and base stable, and is compatible with both Boc and Fmoc SPPS. Fnam has thus been hypothesised to be compatible with most acid- and base-labile protecting groups. However, Fnam is not stable to the deprotection conditions used for Acm, *i.e.* heavy metal salts or oxidants such as $\text{Ti}(\text{TFA})_3$.¹³²

5.7.4 *S*-[N-[2,3,5,6-Tetrafluoro-4-(phenylthio)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fsam). *S*-[N-[2,3,5,6-Tetrafluoro-4-(phenylthio)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fsam, Fig. 26b) is an easier to handle analogue of Fnam.¹³³ Conditions for its removal are identical: a $\text{Pd}(0)$ complex in the presence of allyl scavengers, *e.g.* PhSiH_3 (or NDMBA) in DCM, followed by $\text{Pd}(\text{PPh}_3)_4$ (inert atmosphere, 10 min, 25 °C). This gives a mixture of the free thiol and thioaminals – AcOH/BME can then be added to give the free thiol as the sole product. As with Fnam, $\text{PdCl}_2(\text{PPh}_3)_2/\text{Bu}_3\text{SnH}$ can also be used, but is more difficult to handle. I_2 may be added to remove the Fsam protecting group, yielding a disulfide bond.¹³³

Fsam is stable to acidic and basic conditions, and is compatible with both Boc and Fmoc SPPS. Fsam is labile to similar oxidative conditions to Acm and Phacm. A side reaction was observed during SPPS, which was suggested to be due to *N*-allyl peptides forming *via* nucleophilic attack of the neighbouring α -amino function at the allyl group. This reaction was proposed

a) *N*-[2,3,5,6-Tetrafluoro-4-(*N*[′]-piperidino)-phenyl], *N*-allyloxycarbonyl]-aminomethyl



b) *S*-[2,3,5,6-Tetrafluoro-4-(phenylthio)-phenyl], *N*-allyloxycarbonyl]-aminomethyl

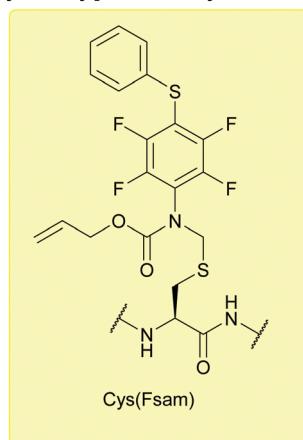


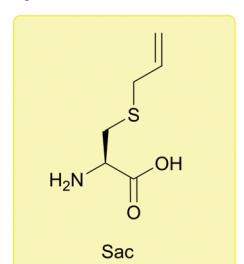
Fig. 26 (a) Cys thiol protection with the *N*-[2,3,5,6-tetrafluoro-4-(*N*[′]-piperidino)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fnam) (b) Cys thiol protection with the *S*-[2,3,5,6-tetrafluoro-4-(phenylthio)-phenyl], *N*-allyloxycarbonyl]-aminomethyl (Fsam) protecting group.

to occur under the basic conditions present during Fmoc removal or during the coupling step. This phenomenon has also been observed with the Alloc group.¹³³

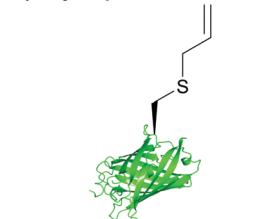
5.7.5 Allyl (Sac). *S*-Allyl-cysteine (Cys(All), Sac, Fig. 27a) is a protected Cys variant that is naturally found in garlic.²²⁸ Recently it has been shown that Sac can be incorporated *via* unnatural amino acid mutagenesis into Cys-free superfolder GFP (cfsfGFP(R2Sac)).¹³⁴ In contrast to other UAA incorporation strategies, which rely on addition of the UAA to the growth medium during protein biosynthesis, Sac incorporation was achieved by addition of allyl mercaptan; this precursor could be biosynthetically converted to Sac, and subsequently incorporated into the target GFP. The allyl group can be subsequently deprotected overnight using Pd(TPPTS)₄ followed by addition of DTT to yield the free thiol-containing GFP in PBS (Fig. 27b). The allyl group could further be used in thiol-ene chemistry to fluorescently label hydrogels with cfsfGFP(R2Sac).¹³⁴

5.7.6 *S*-Propargyl-cysteine (SprC). *S*-Propargyl-cysteine (SprC) is a Cys derivative where the thiol has been capped with a

a) Allyl



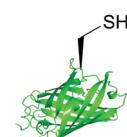
b) Allyl deprotection



Sac-containing cysteine-free superfolder GFP cfsfGFP(R2Sac)

i) Pd(TPPTS)₄
PBS pH 7.4
Overnight
37 °C

ii) DTT
PBS pH 7.4
20 min
37 °C



Deprotected superfolder GFP

Fig. 27 (a) *S*-allyl cysteine (Sac). (b) Pd-mediated deprotection of Sac-containing cysteine-free superfolder GFP (cfsfGFP(R2Sac)).

propargyl group (Fig. 28a). Similarly to Sac, SprC has been used in unnatural amino acid mutagenesis to generate proteins bearing a protected Cys, such as SprC-containing human thioredoxin (Trx73SprC). SprC could then be deprotected with Pd(TPPTS)₄ followed by DTT addition to give the free-thiol containing protein (in PBS, pH 7.4, 37 °C). Control of catalytic Cys activity *via* SprC Cys protection/deprotection could also be achieved, as shown with SprC-containing human rhinovirus-14 3C (HRV 3C(147SprC)) protease. HRV 3C(147SprC) protease showed no proteolytic activity against substrates containing a relevant HRV 3C protease cleavage site; upon *in situ* addition of Pd however, substrate cleavage was initiated as confirmed by SDS-PAGE analysis, suggesting activation of protease activity and thus deprotection of the catalytic Cys (Fig. 28b). This was further confirmed by ESI-MS analysis. SprC-containing proteins could additionally undergo bioconjugation reactions using the alkyne group as a reactive handle, including thiol-ene click reactions, and Cu(i)-catalysed azide-alkyne cycloaddition (CuAAC). In particular, SprC can participate in Pd-catalysed Sonogashira coupling, the product of which can be cleaved/deprotected with a different



Pd catalyst to give the free Cys containing protein. For example, Sonogashira coupling could be performed between SprC-containing enhanced GFP (EGFP(182SprC)) and biotin-iodobenzene using $\text{Pd}(\text{NO}_3)_2$ to yield biotinylated GFP; this species could then be deprotected with $\text{Pd}(\text{TPPTS})_4$ to release the conjugated biotin and reveal EGFP(182Cys, Fig. 28c).

5.7.7 Succinimide (Suc). The reaction of maleimides with Cys to yield succinimide (Suc) conjugates is one of the most widely used methods for a variety of applications, such as surface modification,²²⁹ ADC synthesis,²³⁰ and fluorescent bioconjugates.²³¹ Very recently, Suc has been applied as a Pd-labile Cys protecting group (Fig. 29a) for use in protein semisynthesis.¹³⁶ Suc undergoes deprotection using PdCl_2 similar to *t*Bu and Acm, with deprotection significantly accelerated by addition of MgCl_2 (giving total Suc deprotection within 45 min as opposed to 4 h). Additionally, Cys(Suc) remains stable to treatment with $[\text{Pd}(\text{allyl})\text{Cl}_2]$, giving a degree of orthogonality to Thz (Thz is partially labile to PdCl_2 treatment). Furthermore, Cys(Suc) shows stability to conditions both for NCL and desulfurisation, as demonstrated in the synthesis of

disulfide-containing Trx-1. Here, an N-terminal fragment of Trx-1 (containing a C-terminal thioester) was synthesised *via* expressed protein ligation (EPL), and the two Cys residues capped with *N*-methyl maleimide for Cys(Suc) protection. Capping was carried out at $-18\text{ }^\circ\text{C}$ to avoid hydrolysis of the succinimide ring. Subsequent NCL of a C-terminal fragment of Trx-1 (containing an N-terminal Cys), followed by desulfurisation, led to the Cys(Suc) protected Trx-1. Deprotection of Cys(Suc) with PdCl_2 , followed by oxidation with DTC yielded the desired disulfide-containing Trx-1 (Fig. 29b). Maleimides for Suc protection of Cys can also be functionalised for further applications; for example, a Suc-based protecting group could act both as a protecting group and a linker to a solid phase resin (PEGA resin) in the synthesis of ubiquitin activity-based probes.¹³⁶

5.8 N-terminal cysteine protecting groups

5.8.1 Thiazolidine (Thz). The thiazolidine group (Thz) was introduced as far back as 1937, where it was noted that formaldehyde reacts with Cys residues to form thiazolidinecarboxylic

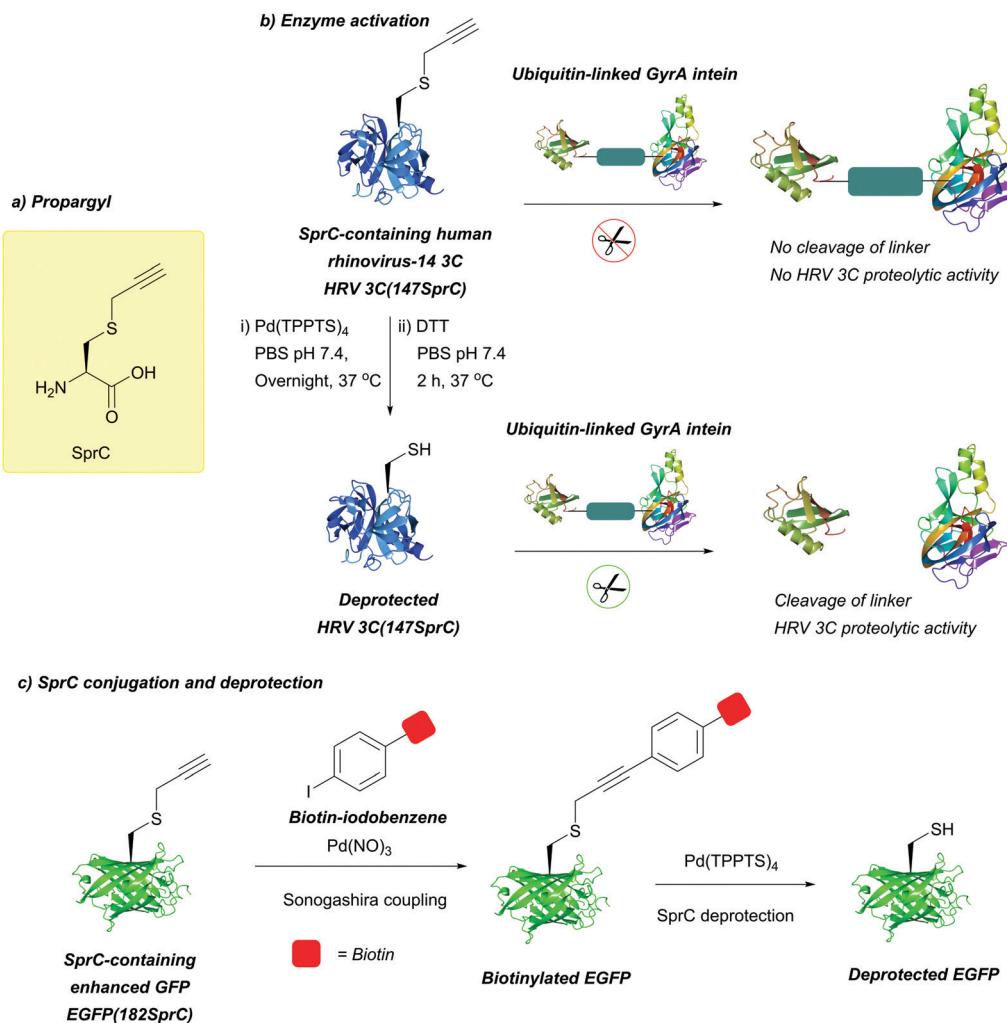


Fig. 28 (a) S-Propargyl-cysteine (SprC). (b) Pd-Mediated deprotection of SprC-containing human rhinovirus-14 3C (HRV 3C(147SprC)). Upon SprC deprotection, HRV 3C proteolytic activity is restored. (c) Sonogashira coupling of SprC-containing enhanced GFP (EGFP(182SprC)), followed by subsequent Pd-mediated deprotection to yield the free-thiol containing EGFP.



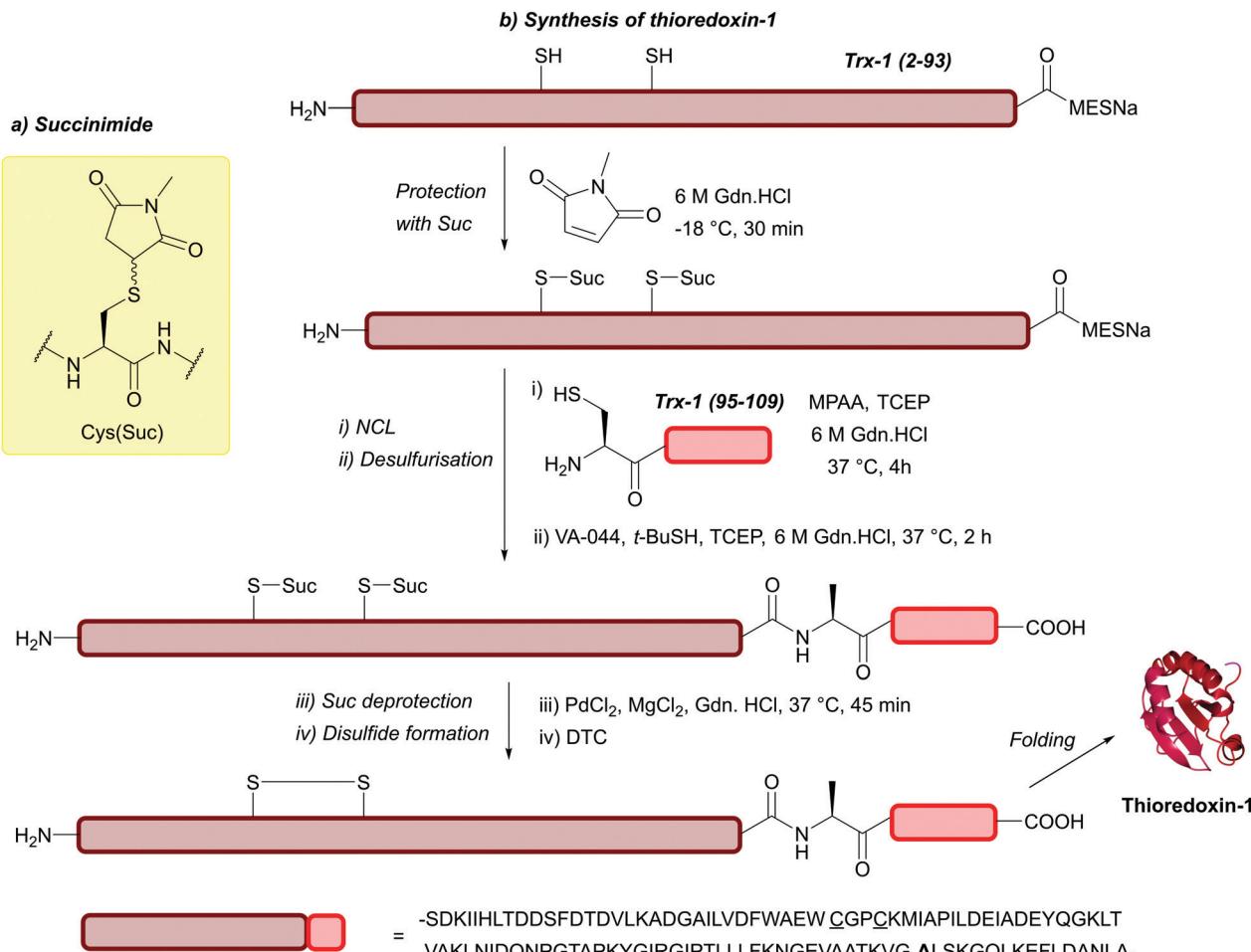


Fig. 29. (a) Cys thiol protection with *N*-methyl maleimide yielding a thiol-succinimide conjugate (Suc). (b) Synthesis of thioredoxin-1 using Cys(Suc).

acids.¹³⁷ The Thz group simultaneously protects the thiol and the amino group of Cys (Fig. 30a), and can be removed using oxidants such as H_2O_2 and I_2 . Removal will also occur following treatment with iodoacetic acid and benzyl chloride (pH 10–11, RT), or ferric chloride in air (pH 10).¹³⁷ Alternatively, deprotection of Thz can be achieved by adjusting the reaction mixture to *ca.* pH 4 in the presence of a large excess of methoxyamine. Due to the ease of deprotection using this strategy, the Thz protecting group has seen widespread use in chemical protein synthesis, with one of the first examples being the total chemical synthesis of Crambin reported in 2004 (Fig. 30b).³⁹ The group has also been employed in the synthesis of other proteins such as ubiquitinated proteins,²³² histones,²³³ and HIV-1 protease.²³⁴ The use of methoxyamine to deprotect Thz has proven, however, to be incompatible with one-pot ligations involving thioesters (undesired reaction at/ hydrolysis of the thioester group).²³³ Thz has also been shown to be unstable towards NaNO_2 treatment at pH 3–4 during activation of peptide hydrazides; this issue can be circumvented by using a 2-(*tert*-butyldisulfanyl)ethyloxycarbonyl protected Thz group (Tbeoc-Thz) in place of Thz, which is stable to NaNO_2 hydrazide activation, and can be converted to Thz upon reduction with TCEP.⁴⁷

More recently, alternative strategies for the deprotection of Thz have been described; these have primarily been transition-metal

based.²³⁵ For example, deprotection of Thz can be achieved using water-soluble Pd(II) complexes, such as $[\text{Pd}(\text{allyl})\text{Cl}]_2$, followed by treatment with DTT to both obtain the free thiol and quench remaining Pd species (Fig. 30c). This is performed under native chemical ligation (NCL) conditions and in the presence of MPAA and TCEP, with complete removal obtained within 15 min.¹³⁸ MPAA and TCEP appear to be crucial for efficient removal (100% removal in 15 min *vs.* 40% removal after 4 h). It has been hypothesised that this is due to MPAA and TCEP chelating to Pd(II), or possibly reducing it to Pd(0). To demonstrate the usage of this deprotection method, Lys34-ubiquitinated H2B and several other sample peptides have been synthesised using Pd(II) to deprotect Thz.¹³⁸ In further work, it was found that $[\text{Pd}(\text{allyl})\text{Cl}]_2$ and GSH (1:1) in 6 M Gdn-HCl (pH 6.5, 37 °C, 45 min) were sufficient for full removal, along with its orthogonality demonstrated to both Acm and *t*Bu.⁸⁵ Pd-mediated Thz deprotection has also been successfully applied towards *in vivo* systems for triggered release/chemical activation of peptides/proteins.²³⁶ Furthermore, Thz analogues have also been employed in within the field of protein bioconjugation; Pd-mediated²³⁷ (or Ag-mediated)²³⁸ “unmasking” of unnatural Thz side chains leads to generation of an α -oxo aldehyde side chain, which can be used for downstream site-selective protein modification.²³⁹ Aside from

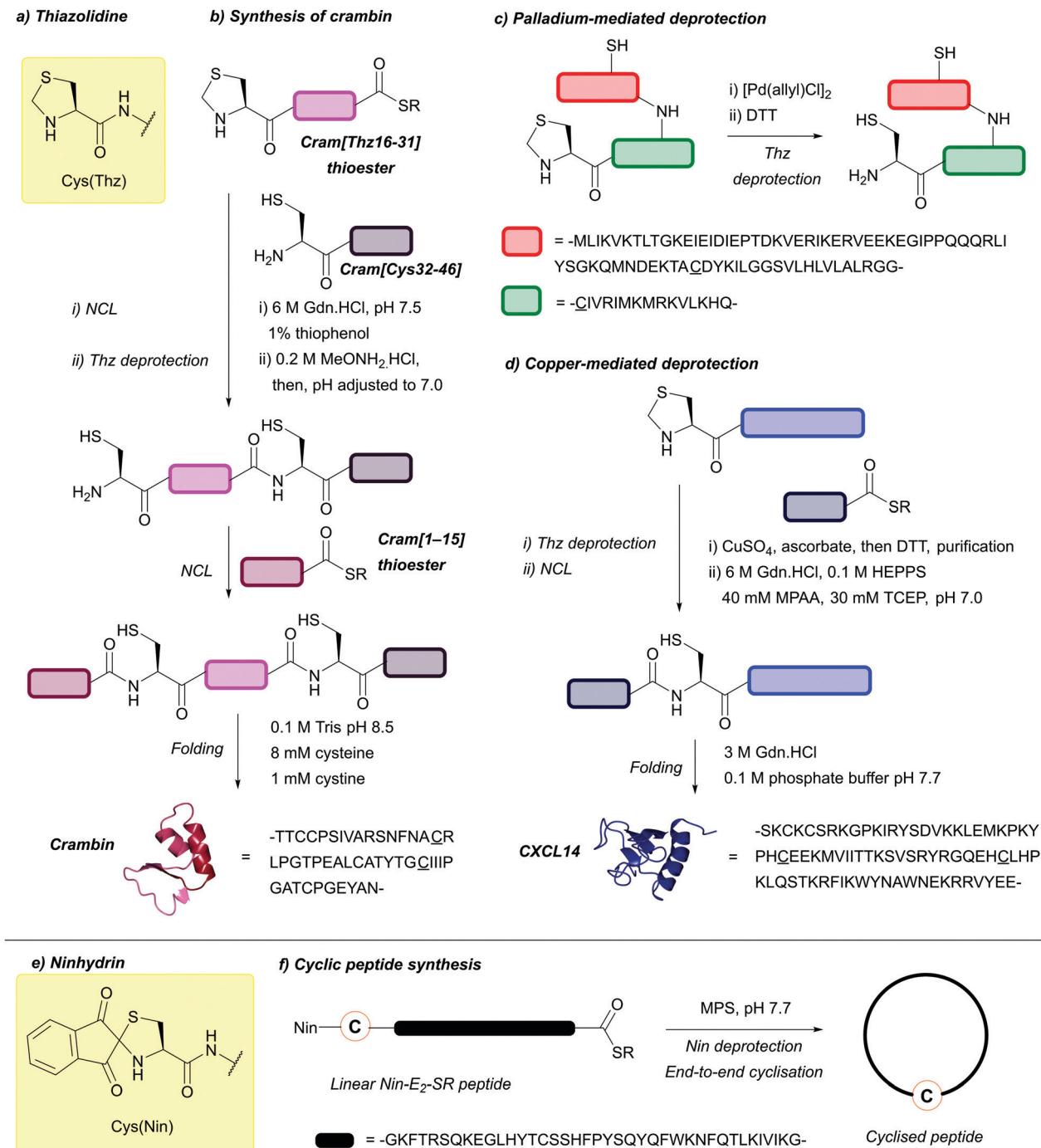


Fig. 30 (a) N-terminal Cys protection with the thiazolidine (Thz) protecting group. (b) Synthesis of Crambin using Cys(Thz) with methoxyamine-mediated deprotection. (c) Peptide synthesis using Cys(Thz) with Pd-mediated deprotection. (d) Synthesis of CXCL14 using Cys(Thz) with Cu-mediated deprotection. (e) N-terminal Cys protection with the ninhydrin (Nin) protecting group. (f) Cyclic peptide synthesis using Cys(Nin).

Pd, Cu complexes can also be used to deprotect Thz.^{139,240} Thz is removed by CuSO₄ in the presence of sodium ascorbate (critical for avoiding oxidation by-products), in 5 M Gdn.HCl in HEPES buffer (pH 7.0, 1 h, 37 °C). This was demonstrated in the synthesis of CXCL14 (Fig. 30d).¹³⁹ As discussed previously, the reaction can then be quenched with DTT or EDTA.⁷³ No epimerisation or side products are observed using this method of

deprotection, and the reaction can be performed under standard NCL conditions.¹³⁹ Outside of transition-metal based strategies, 2,2'-dipyridyl disulfide (DPDS) in 50% MeCN (0.1% TFA) as a reagent for Thz deprotection has also been described.^{140,241}

5.8.2 Ninhydrin (Nin). The 1,2,3-indanetrione monohydrate (ninhydrin, Nin) group can be used to modify N-terminal Cys residues, protecting both the amine and thiol moiety as a

thiazolidine ring (Fig. 30e).²⁴² Nin has since been used as an N-terminal Cys protecting group used in Boc SPPS.¹⁴¹ The Nin group can be converted back to the Cys in the presence of an excess of Cys (pH 7.7, 30 min, 23 °C). Cysteine *O*-methylester in DMF/DIEA will remove the group while the peptide is still attached to the resin. However, using Cys deprotection is not possible for thioester-containing peptides as Cys can form amide bonds with thioesters. Deprotection can be achieved in this case using excess 3-mercaptopropiosulfonic acid (MPS) at pH 7.7 (which is nearly as effective as Cys-mediated deprotection) or under reducing conditions (10% TFA/H₂O/Zn dust, 1 h).¹⁴¹

Protection using the Nin group avoids the formylation side reactions normally found during TFA and HF cleavage when His(Bom) groups are present, without the need for additional scavengers. Additionally, in thioester-containing peptides, the products will cyclise under deprotection conditions, enabling a one-step process. As proof of concept, a Nin-E₂-SR peptide was synthesised and cyclised in one-step (Fig. 30f), using an excess of MPS (where E₂ refers to a 40-residue long sequence of the chemokine receptor CCR5's second extracellular loop).¹⁴¹

5.9 Photo-labile protecting groups

5.9.1 2-Nitrobenzyl (*o*NB). 2-Nitrobenzyl (*o*NB) is a photo-cleavable Cys protecting group (Fig. 31a) first described in 1981,²⁴³ and can be removed by irradiation at ≥ 350 nm.¹⁴² The protecting group is compatible with Boc and Fmoc SPPS, and can be cleaved under aqueous conditions; for example, in deoxygenated MeCN/0.05 M PBS, 1:1 at pH 6, in the presence of semicarbazide and L-(-)-ascorbic acid.¹⁴³ The *o*NB protecting group also shows a high one-photon efficiency, and a high yield of the free thiol is obtained upon photolysis.¹⁴⁵

The protecting group has since featured in the synthesis of a thioester-containing HCDLP pentapeptide; this peptide can then undergo NCL to semisynthesise a variant of a nickel-dependant superoxide dismutase (NiSOD). Critically, Cys(*o*NB) remained intact after acidic deprotection of other amino acid residues (95% TFA) of the pentapeptide, and subsequent NCL to a recombinant *Streptomyces coelicolor* NiSOD bearing an N-terminal Cys. Photochemical deprotection of *o*NB could then be achieved by irradiation at 365 nm (100 mM NaOAc, 20 mM TCEP, 10 mM semicarbazide, pH 5.8).²⁴⁴ Cys(*o*NB) can also be

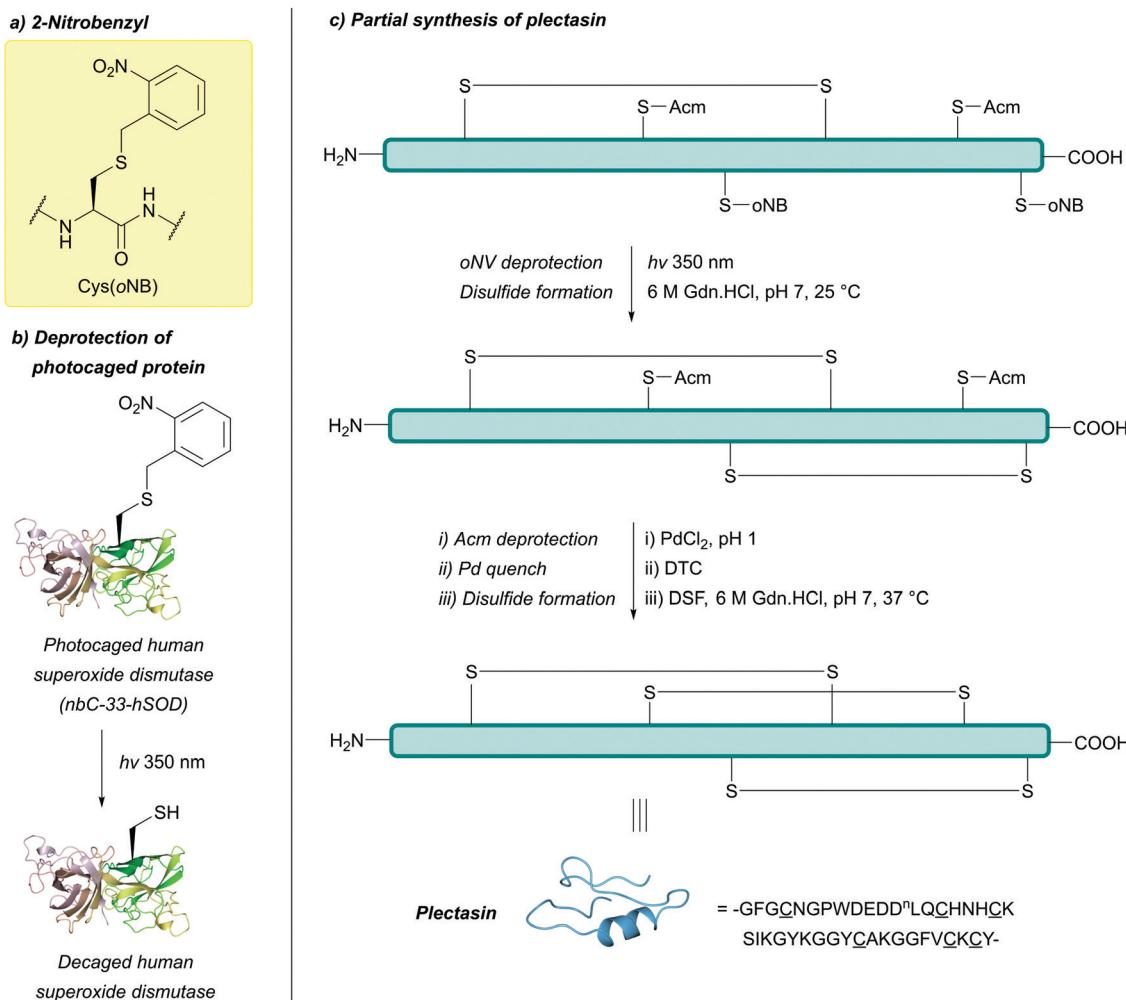


Fig. 31 (a) Cys thiol protection with the 2-nitrobenzyl (*o*NB) protecting group. (b) Photodecaging of a photocaged human superoxide dismutase containing Cys(*o*NB) as an unnatural amino acid (nbC-33-hSOD). (c) Partial synthesis of plectasin using Cys(*o*NB).



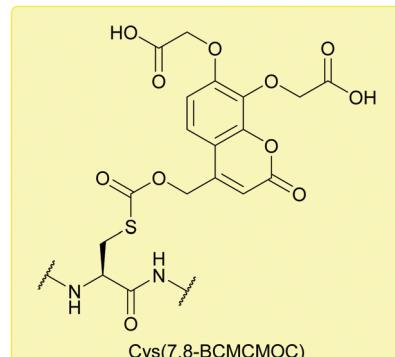
incorporated into proteins *via* unnatural amino acid mutagenesis^{245,246} as demonstrated with a photocaged human superoxide dismutase (nBC-33-hSOD, Fig. 31b),²⁴⁶ along with being used to study protein activity.^{247,248} As discussed previously, Cys(*o*NB) is also orthogonal to Pd-mediated deprotection of Acm, as recently displayed in the synthesis of Linactide and plectasin (Fig. 31c).²¹⁵ The *o*NB protecting group is, however, a poor chromophore and displays low two-photon sensitivity. Coumarin-based protecting groups have since been described in an attempt to address some of these issues.¹⁴⁵

5.9.2 [7,8-Bis(carboxymethoxy)coumarin-4-yl]methoxycarbonyl (7,8-BCMCMOC), [7-bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl (BCMACMOC), and α -carboxy-methoxy-2-nitrobenzyl (C4MNB). [7,8-Bis(carboxymethoxy)coumarin-4-yl]methoxycarbonyl (7,8-BCMCMOC, Fig. 32a), [7-bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl (BCMACMOC, Fig. 32b), and α -carboxy-4-methoxy-2-nitrobenzyl (C4MNB, Fig. 32c) were reported for use as H_2O soluble, photocleavable Cys protecting groups in 2009.¹⁴⁴ The 7,8-BCMCMOC and BCMACMOC groups are based on (coumarin-4-yl)methyl chromophores, whereas the C4MNB group is based on a 2-nitrobenzyl chromophore (along with a α -carboxy-4,5-dimethoxy-2-nitrobenzyl (CDMNB) group that was also reported). All groups were reported to show stability towards TFA and thiolysis, and all three protected-Fmoc-Cys derivatives showed good solubility in HEPES buffer: MeCN (95 : 5, pH 7.2). The 7,8-BCMCMOC and BCMACMOC groups were, however, unstable when treated with piperidine, resulting in intramolecular *S* > *N* acyl shifts in the case of N-terminal Cys; an alternative Fmoc removal protocol (1% DBU in DMF, acidic washing) and acetylation of the N-terminus was therefore utilised. The BCMACMOC group can be removed by irradiation at ≥ 402 nm whilst the 7,8-BCMCMOC and C4MNB groups can be removed by irradiation at ≥ 325 nm, allowing for orthogonal deprotection (provided BCMACMOC is photolysed using long-wavelength irradiation first). These groups were subsequently used to synthesise an *N*-acetylated resact peptide (Ac⁰-resact).¹⁴⁴

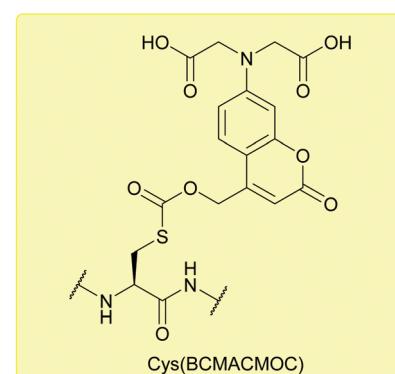
5.9.3 2-Nitroveratryl (*o*NV). Originally described as a photolabile group for other functional groups,^{249–251} the 2-nitroveratryl/6-nitroveratryl (*o*NV), or 4,5-dimethoxy-2-nitrobenzyl (DMNB) group was first introduced as a Cys protecting group (Fig. 33a) for use in Fmoc SPPS in 2014.¹⁴² Removal of this group was achieved by irradiation at 350 nm for 30 min in aqueous media without the need for additional reagents, and displayed a stronger molar absorptivity at 350 nm than *o*NB. No significant racemisation (<0.5%) was observed upon the incorporation of Cys(*o*NV) during SPPS using diisopropylcarbodiimide (DIC) and HOBt activation.¹⁴²

*o*NV is fully compatible with Fmoc SPPS, including stability to 10% TFMSA/TFA in the presence of excess dipyridine disulfide, the conditions necessary to convert the *t*Bu protecting group to the activated *S*-Pyr group. The two groups may, therefore, be used together – photolysis of the *o*NV is followed by thiolysis in the presence of Cys(S-Pyr), selectively forming a disulfide bond. This strategy has been used for the solid-phase synthesis of several Cys-rich peptides, including human insulin and α -conotoxin

a) [7,8-Bis(carboxymethoxy)coumarin-4-yl]methoxycarbonyl



b) [7-Bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl



c) α -Carboxy-4-methoxy-2-nitrobenzyl

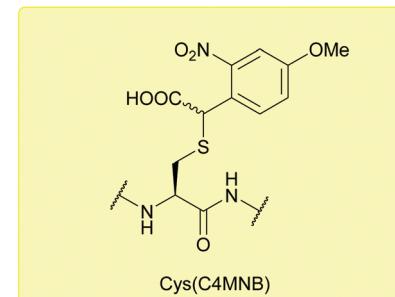


Fig. 32 (a) Cys thiol protection with the [7,8-bis(carboxymethoxy)-coumarin-4-yl]methoxycarbonyl (7,8-BCMCMOC) protecting group. (b) Cys thiol protection with the [7-bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl (BCMACMOC) protecting group. (c) Cys thiol protection with the α -carboxy-4-methoxy-2-nitrobenzyl (C4MNB) protecting group.

ImI (Fig. 33b).¹⁴² *o*Nv photocaged Cys has since been utilised in the synthesis of multi-Cys-containing peptide fragments.²⁵² The protected amino acid has also been incorporated into proteins *via* unnatural amino acid mutagenesis to yield photocaged eGFP (EGFP^{Y39DMNB-Cys}),²⁵³ and photocaged glutathione peroxidase 3 (caged Gpx3 Cys32); the latter can then be oxidised with H_2O_2 to generate the sulfenic acid analogue (caged Gpx3 Cys32O, Fig. 33c).²⁵⁴

5.9.4 6-Bromo-7-hydroxycoumarin (Bhc). 6-Bromo-7-hydroxycoumarin (Bhc) was first described as a thiol-protecting group in 2008,²⁵⁵ and described as a Cys protecting group (Fig. 34a)



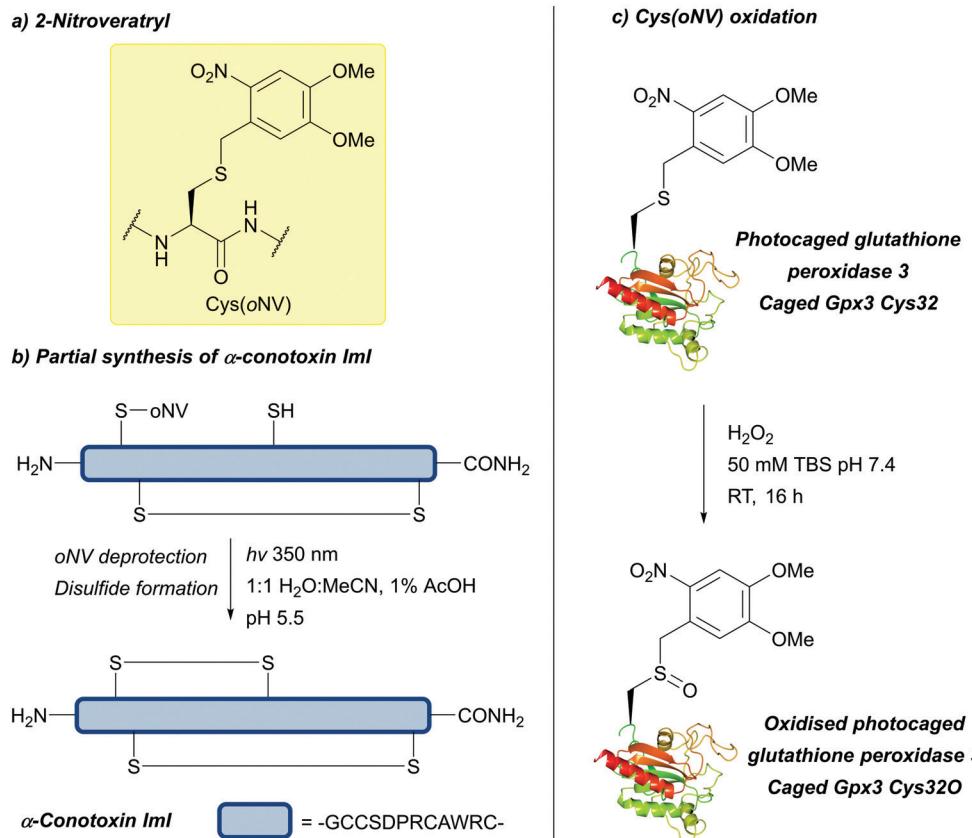


Fig. 33 (a) Cys thiol protection with the 2-nitroveratryl (oNV) protecting group. (b) Partial synthesis of α -conotoxin Iml using Cys(oNV). (c) Photocaged glutathione peroxidase 3 (caged Gpx3 Cys32) and subsequent oxidation to yield the the sulfenic acid analogue (caged Gpx3 Cys32O).

in 2016.¹⁴⁵ Irradiation at 365 nm in buffer (1 mM DTT in 50 mM PB, pH 7.2) causes deprotection. Unlike oNB, Bhc has a high two-photon sensitivity; for two-photon excitation, wavelengths of 800 nm may be used.

Although incorporation into a peptide using Fmoc SPPS is not an issue, the photocleavage efficiency of Bhc-protected thiols is context-dependent. This is because the major product of irradiation is typically an unwanted photoisomer (a 4-methylcoumarin-3-yl thioether, Fig. 34b) instead of the free thiol, which limits the applications of Bhc as a Cys protecting group.

5.9.5 Nitrodibenzofuran (NDBF). Nitrodibenzofuran (NDBF) was proposed as an alternative Cys protecting group (Fig. 34c) to Bhc in 2016.¹⁴⁵ Like Bhc, NDBF is removed from Cys *via* irradiation at 365 nm; two-photon deprotection is also possible at 800 nm. The two-photon cross-section of NDBF is comparable to that of Bhc-protected acetate. Additionally, NDBF deprotection results in clean conversion to the free thiol without the occurrence of *S*-to-*N* shifts, and displays a higher uncaging efficiency than that of oNV.¹⁴⁵ NDBF was also found to be compatible with Fmoc SPPS, allowing for the synthesis of Cys(NDBF) photocaged K-Ras-derived peptides. These photocaged peptides could then be decaged with irradiation at 800 nm, and the free thiol enzymatically farnesylated *in situ* in the presence of protein farnesyltransferases (PFTase) and farnesyl diphosphate; as anticipated, farnesylation did not occur if the Cys residue was protected with NDBF.

The NDBF protecting group has been additionally used for live cell applications. A fluorescent, farnesylated peptide which can undergo enzymatic palmitoylation by palmitoyl acyltransferase was synthesised and protected as a NDBF thioether (Fig. 34d).¹⁴⁵ Incubation of this peptide with human ovarian carcinoma SKOV3 cells led to localisation of the peptide to the cytosol and the Golgi apparatus. Upon irradiation, the peptide migrated to the plasma membrane, indicating that enzymatic palmitoylation had occurred (Fig. 34e).

5.9.6 6-Bromo-7-hydroxy-3-methylcoumarin (mBhc). The 6-bromo-7-hydroxy-3-methylcoumarin (mBhc) protecting group (Fig. 35a) is an analogue of the Bhc protecting group.¹⁴⁶ Compared to Bhc, the C3 position of mBhc is alkylated, which prevents photoisomerisation upon irradiation allowing for decaging to occur. Photolysis can be achieved using with one or two-photon excitation. Controlled prenylation of K-ras derived peptides was also demonstrated in a manner similar to that described for the Cys(NDBF) group. Furthermore, mBhc caged thiols could be used to design 3D patterns in hydrogel matrices.¹⁴⁶

5.9.7 Methoxy-nitrodibenzofuran (OMe-NDBF). Very recently, methoxy-nitrodibenzofuran (OMe-NDBF) has been suggested as an alternative to NDBF for the protection of the Cys thiol (Fig. 35b) with a higher two-photon photolysis efficiency.¹⁴⁷ Additionally, in-depth analysis into suppressing Cys racemisation in the coupling of both Fmoc-Cys(NDBF) and Fmoc-Cys(OMe-NDBF) was performed;



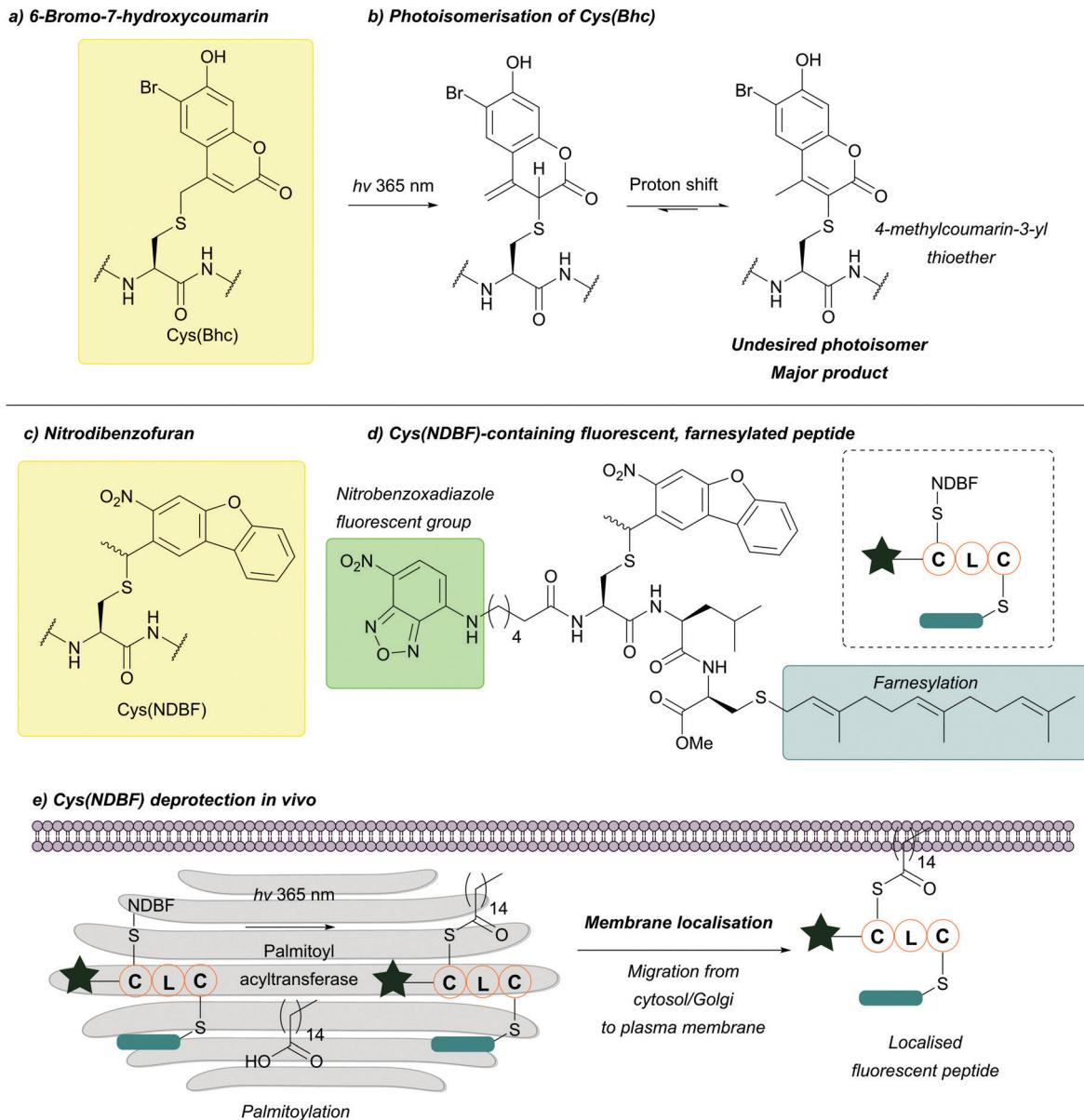


Fig. 34 (a) Cys thiol protection with the 6-bromo-7-hydroxycoumarin (Bhc) protecting group. (b) Irradiation of Cys(Bhc) and subsequent formation of a 4-methylcoumarin-3-yl thioether photoisomer. (c) Cys thiol protection with the nitrodibenzofuran (NDBF) protecting group. (d) Fluorescent, farnesylated peptide containing Cys(NDBF). (e) Incubation and subsequent localisation *in vivo* of the aforementioned peptide within the cytosol and Golgi apparatus. Irradiation of the cells leads to deprotection of Cys(NDBF) which can then under enzymatic palmitoylation, leading to membrane localisation of the peptide.

employing benzotriazole-1-yl-oxy-tris-pyrrolidino-phosphonium hexa-fluorophosphate/1-hydroxy-7-azabenzotriazole (PyBOP/HOAT) coupling (using DIEA as a base) lead to <2% racemisation observed when either of these were used in Fmoc SPPS. Irradiation of α -factor-derived peptides containing Cys(OMe-NDBF) at 350 nm for less than 30 sec proved sufficient for deprotection. As for Cys(NDBF), Cys(OMe-NDBF) caging and decaging can be used to control farnesylation of photocaged K-ras derived peptides.¹⁴⁷

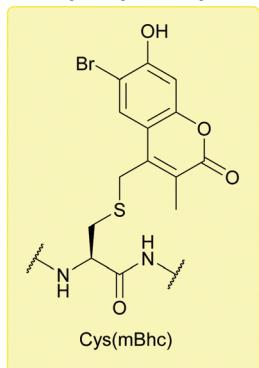
5.10 Reducing agent-labile protecting groups

5.10.1 *para*-Nitrobenzyl (pNB). The use of the *para*-nitrobenzyl (pNB) group for protecting Cys (Fig. 36) was first proposed

in 1957.²⁵⁶ *p*NB was originally removed by catalytic hydrogenation in the presence of 10% palladium on carbon (3 h, RT, atmospheric pressure).²⁵⁶ However, it was later reported that $\text{H}_2/\text{Pd/C}$ reduction of pNB can lead to *para*-aminobenzyl (pAB) formation instead.²⁵⁷ To avoid this, the group can be removed by a reducing agent, followed by an oxidising agent to remove pAB and form a disulfide. Zn/AcOH followed by I_2 has been reported to be the most effective agent in solution, while SnCl_2/HCl followed by I_2 is the preferred agent for cleavage on solid support. On-resin, I_2 oxidation resulted in complex mixtures and low yields. Other methods are less effective but still viable; oxidative removal of pAB can be achieved using an excess of ceric ammonium nitrate (CAN) and Hopkins reagent (10% HgSO_4 /5% H_2SO_4) but I_2 in AcOH gives both a faster



a) 6-Bromo-7-hydroxy-3-methylcoumarin



b) Methoxy-nitrodibenzofuran

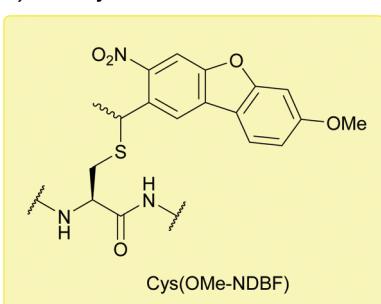


Fig. 35 (a) Cys thiol protection with the 6-bromo-7-hydroxy-3-methylcoumarin (mBhc) protecting group. (b) Cys thiol protection with the methoxy-nitrodibenzofuran (OMe-NDBF) protecting group.

para-Nitrobenzyl

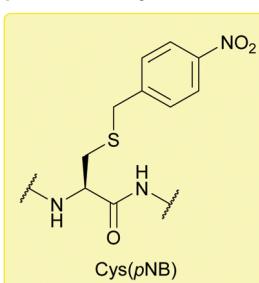


Fig. 36 Cys thiol protection with the *para*-nitrobenzyl (pNB) protecting group.

and cleaner reaction in solution.¹¹¹ *p*NB is stable to HF/*p*-cresol (9 : 1, 1 h, 0 °C), TFA and I₂/AcOH/2 M HCl. No side products are observed during cleavage. *p*NB has been proposed as an alternative to Acm for use in Boc SPPS due to its greater stability to acid.¹¹¹

5.10.2 Carbomethoxysulfenyl (Scm). Carbomethoxysulfenyl (Scm) was first proposed in 1970, as a thiol protecting group (Fig. 37a) that could be used to form unsymmetrical disulfides.²⁵⁸ Scm can be removed using thiols or other reducing agents,⁶⁸ *e.g.* DTT.¹⁴⁸ Scm is stable to strong acids, including anhydrous HF and TFMSA.¹⁴⁹ Cys(Acm) can be converted to Cys(Scm) *via* treatment with methoxycarbonylsulfenyl chloride (Fig. 37b), where upon Cys(Scm) can be displaced by free thiols to form disulfides.¹⁴⁸ However, there is some evidence that side

reactions involving *S*-to-*N* acyl migrations occur during coupling. The related derivative Snm has been recommended for use in Boc SPPS instead as side reactions are minimised.¹⁴⁹ Both Cys(Scm) and Cys(Snm) have both been used in the synthesis of disulfide and trisulfide-containing oxytocin and deaminoxytocin.²⁵⁹

Cys(Scm) has recently used in protein bioconjugation to facilitate the modification of MB23-Cys (an Alphabody – a trihelical peptide with potential as an anti-cancer therapeutic) *via* disulfide linkages. MB23-Cys was first reduced using DTT (to remove any protein dimer), then modified with a folic acid, Cys(Scm)-containing peptide in 10 mM Tris-HCl, pH 7.4, 37 °C (Fig. 37c).¹⁴⁸

5.10.3 (N'-Methyl-N'-phenylcarbamoyl)sulfenyl (Snm).

(N'-Methyl-N'-phenylcarbamoyl)sulfenyl (Snm) is an Scm derivative synthesised in 1989 for Cys thiol protection.¹⁴⁹ Snm can be removed under mild thiolytic conditions, *e.g.* DTT in the presence of *N*-methylmorpholine (NMM) in CDCl₃, which results in a mixture of the free thiol and the cyclic disulfide. If treated with 2-mercaptopuridine Snm is converted to the 2-pyridyl disulfide. Snm is stable to strong acids (anhydrous HF, TFMSA) and is less prone to undergoing side reactions than Scm – although a terminating side reaction is still observed when coupling of glycine is carried out in DMF. Snm is suitable for use in Boc SPPS.¹⁴⁹ With regards to Fmoc SPPS, upon treatment with piperidine the Snm group is converted to a *S*-(*N*-piperidylcarbamoyl)sulfenyl group (*-S*(C=O)Piperidine), referred to as the Snip protecting group (Fig. 38a). These derivatives can be used for intramolecular disulfide formation both on and off resin akin to peptides containing Cys(Snm).²⁵⁹

5.10.4 4-Picoly. The 4-picoly protecting group (Fig. 38b) was originally removed by electrolytic reduction in a 0.5 M sulfuric acid solution.¹⁵¹ However, it can be removed in a more convenient manner by Zn/AcOH.¹⁵⁰ The group is completely stable in TFA or 32% HBr in AcOH (1 week, RT).¹⁵¹ However, the group is rarely used in SPPS.¹⁵⁰

5.10.5 Sulfonic acid (SO₃H) and sulfonyl (SO₂R). The sulfonic acid (SO₃H) group (Fig. 38c) is removed by thiols,¹⁵² *e.g.* DTT, BME, or phosphines, *e.g.* tributylphosphine.¹⁵³ However, it is very acid sensitive and, as such, has little use in peptide synthesis.¹⁵² The sulfonate derivative (SO₃Na) has, however, been shown to have sufficient stability to be used in both Boc and Fmoc SPPS. As proof of concept, Arg⁸-vasopressin was successfully synthesised using Cys(SO₃Na) *via* Fmoc SPPS. Use of *p*-cresol as the sole scavenger during TFA cleavage from the resin presented premature removal of SO₃Na from Cys.¹⁵³

Sulfonyl (SO₂R) protecting groups (Fig. 38d) have recently found some use in the synthesis of enantiomerically-enriched α -hydroxy and α -chloro acid building blocks. The sulfonyl group is first introduced to the Cys residue, and diazotisation is subsequently used to generate the α -hydroxy or α -chloro acid (depending on whether H₂SO₄ or HCl is used).²⁶⁰

5.10.6 3-Nitro-2-pyridinesulfenyl (Npys). The 3-nitro-2-pyridinesulfenyl (Npys)²⁶¹ protecting group (Fig. 38e) is a reducing agent-labile Cys protecting group.¹⁵⁵ Npys can be removed in under 10 min using aliphatic thiols (*e.g.* 3-mercaptopropionic acid (MAA), BME).¹⁵⁴ It can also be removed at room temperature using



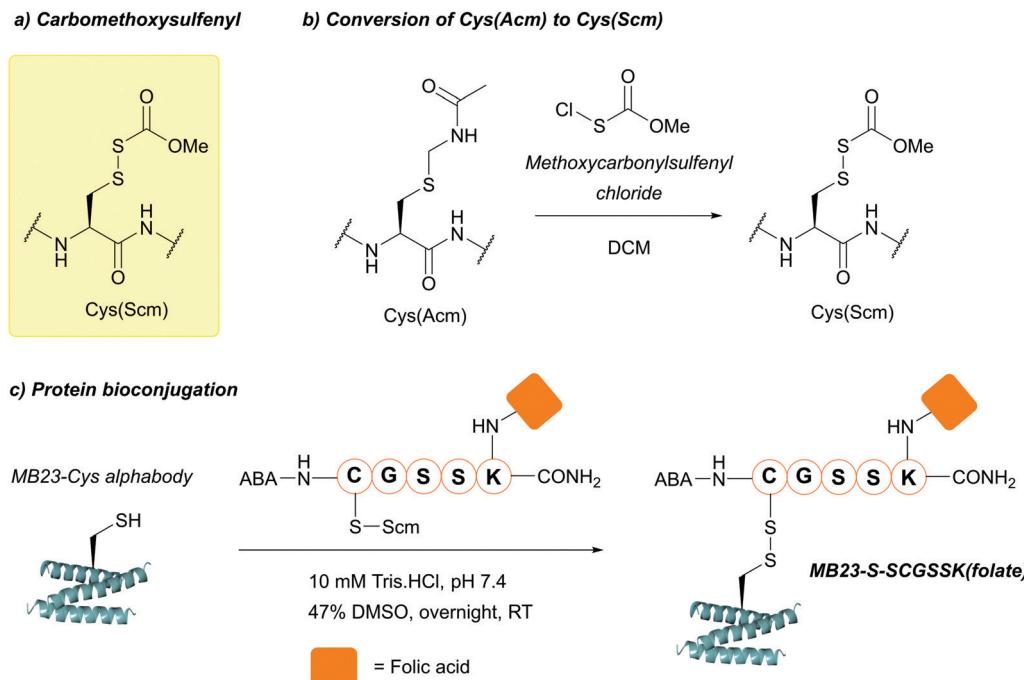


Fig. 37 (a) Cys thiol protection with the carbomethoxysulfenyl (Scm) protecting group. (b) Conversion of Cys(Acm) to Cys(Scm) using methoxycarbonylsulfenyl chloride. (c) Protein bioconjugation with Cys(Scm)-containing peptides.

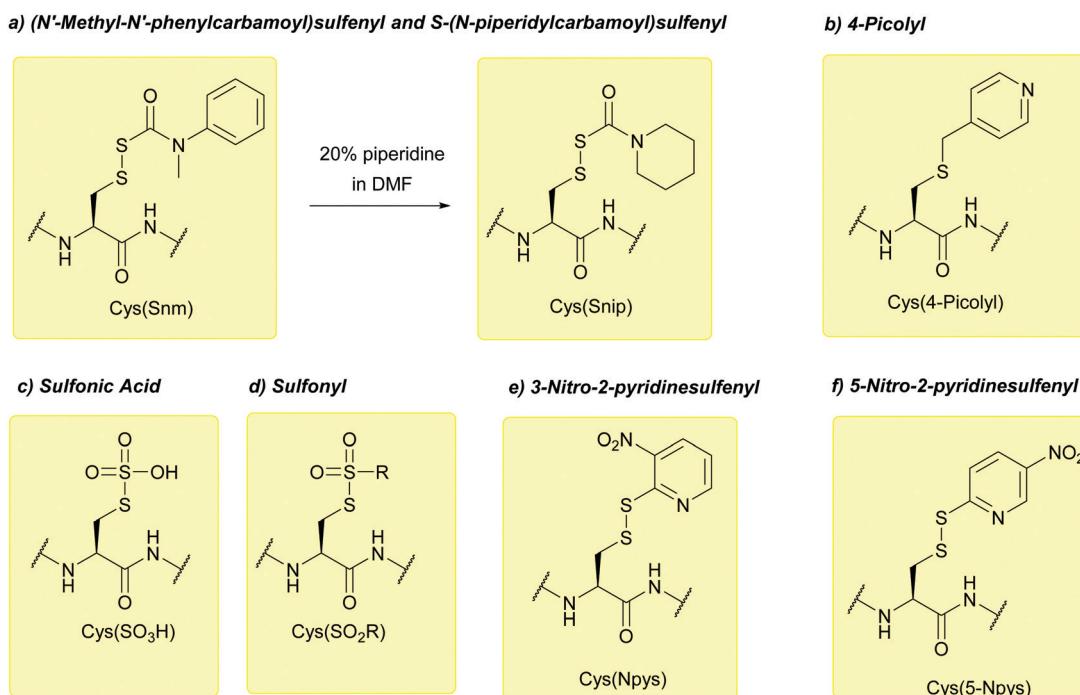


Fig. 38 (a) Cys thiol protection with the (N'-methyl-N'-phenylcarbamoyl)sulfenyl (Snm) protecting group. Conversion of Cys(Snm) to Cys(Snip) occurs upon treatment with piperidine (b) Cys thiol protection with the 4-picoly protecting group. (c) Cys thiol protection with the sulfonic acid (SO₃H) protecting group. (d) Cys thiol protection with the sulfonyl (SO₂R) protecting group. (e) Cys thiol protection with the 3-nitro-2-pyridinesulfenyl (Npys) protecting group. (f) Cys thiol protection with the 5-nitro-2-pyridinesulfenyl (5-Npys) protecting group.

tertiary phosphines in the presence of H₂O.^{155,156} Cys(Npys) is stable to strong acids such as TFA (24 h, RT), HF (1 h, RT) and 4 M HCl/dioxane (24 h) and is thus suitable for Boc SPPS.¹⁵⁵ It is also

stable to a wide variety of other reagents commonly used in Boc SPPS: DCM, DMF, *N,N*-dimethylacetamide, *N*-methylpyrrolidone, MeOH, trifluoroethanol, pentafluorophenol.¹⁵⁷ S-Npys is somewhat

stable towards aromatic thiols, which can cleave the *O*-Npys and *N*-Npys derivatives, enabling a degree of selectivity in its deprotection.¹⁵⁴ It is relatively stable to the photolytic cleavage conditions used for peptide-(*o*-nitrobenzyl ester) resin bonds (350 nm).¹⁵⁷ Npys can also act as an activating group for disulfide formation as it is displaced by the free thiol.¹⁵⁵

Npys is not compatible with Fmoc SPPS, as it is unstable to piperidine (81% decomposition following treatment with 50% piperidine in DCM for 10 min). It is also unstable to TBAF⁻, an alternative to piperidine for Fmoc deprotection. Additionally, while treatment with HF in the presence of anisole or *p*-cresol leaves Npys unaltered, HF in the presence of *p*-thiocresol or DMS (HF/DMS/*p*-cresol, 25 : 65 : 10 or HF/DMS/*p*-cresol/*p*-thiocresol, 25 : 65 : 5 : 5), has been shown to cause significant loss of the protecting group.¹⁵⁷ Npys has been used in many syntheses.¹⁵⁴ An early example of this is the synthesis of [Lys]⁸vasopressin, which was chosen as a model peptide to display the use of Npys in Boc SPPS.¹⁵⁶ More recently, the Npys protecting group has been the focus of a solid phase disulfide ligation (SPDSL) system.²⁶² Here, Npys-Bn is loaded onto a solid support and converted to resin-bound Npys-Cl through chlorosulfonylation. Cys(*t*Bu)-containing peptides can then be loaded onto the resin *via* Npys-mediated displacement of the *t*Bu protecting group. Peptide release, along with disulfide bond formation, can then be achieved through addition of a Cys-containing peptide. Subsequent intramolecular amide formation then yields a disulfide containing peptide, as demonstrated in the synthesis of oxytocin.²⁶² A similar platform that replaces the Npys-Cl group for a more stable Npys-OPh(*para*-fluoro) group has very recently been reported in the literature.²⁶³

5.10.7 5-Nitro-2-pyridinesulfenyl (5-Npys). 5-Nitro-2-pyridinesulfenyl (5-Npys, *p*-Npys, Fig. 38f) is an analogue of Npys.¹⁵⁸ 5-Npys retains almost all the properties of Npys and is also removed by thiols.¹⁵⁸ It can also be partially removed (70–75%) under mild conditions by a large excess of ascorbic acid in the presence of DTNP (pH 7, 35 °C, 24 h).²⁶⁴ Much like Npys, 5-Npys can be used as an activating group. The *para*-nitro group increases the acidity of the corresponding thiol and it is thus able to react at a lower pH than Npys.¹⁵⁸ As with Npys, 5-Npys is incompatible with Fmoc SPPS.⁹⁰

5.10.8 *tert*-Butylsulphenyl (StBu). The *tert*-butylsulphenyl (StBu) Cys protecting group (Fig. 39a) has been described for use in both Boc²⁶⁵ and Fmoc¹⁵⁹ peptide synthesis. StBu can be removed under organic or aqueous conditions with reducing agents such as thiols, *e.g.* BME,¹⁵⁹ DTT,²⁶⁶ or phosphines (*e.g.* PBu₃,²⁶⁷ PPh₃,²⁶⁸ TCEP²⁶⁹) The StBu protecting group is stable to acidic conditions (*e.g.* TFA:thioanisole:phenol, 95 : 2.5 : 2.5 v/v) provided no thiol scavenger is added. In cases such as for tryptophan-containing peptides, 2-methylindole and anisole can be used as alternative scavengers to avoid StBu deprotection.¹⁵⁹ The group is also compatible with basic conditions for Fmoc SPPS; extended incubations of resin-bound C-terminal Cys(StBu)-containing peptides in 20% piperidine in DMF can lead to 3-(1-piperidinyl)alanine by-products however.⁷⁷ StBu can also be removed by TFA in the presence of DTNP-thioanisole. Interestingly, StBu exhibits no lability to TFA/DTNP without the addition of thioanisole to the mixture, making it orthogonal

to groups which are removed by TFA/DTNP, such as *t*Bu.⁸⁰ Partial removal in HF has also been reported.¹⁵⁹ The StBu protecting group is orthogonal to other protecting groups, such as Trt, Acm, Meb/Mob, *t*Bu,^{74,163} and Allocam.²⁰⁵ Protected Cys(StBu) has featured in the synthesis of somatostatin,²⁶⁸ coumarin-based probes,²⁷⁰ and cryptophane-based probes.²⁷¹ Additionally, peptides bearing Cys(StBu) and perfluoroaryl-modified Cys residues can undergo cyclisation to form macrocyclic peptides; this was achieved with *in situ* reduction of Cys(StBu) with TCEP in the presence of glutathione *S*-transferase (GST, which facilitates conjugation of the newly released thiol and perfluoroaryl group, Fig. 39b).²⁷² In the case of N-terminal Cys protected with StBu, *in situ* reduction/protecting group removal followed by NCL can be achieved in the presence of a suitable peptide thioester substrate.^{273,274} Alternatively, the N-terminal Cys can react with 2-cyano-6-aminobenzothiazoles (CBTs), as demonstrated in the synthesis of imaging agents for positron emission tomography (PET).^{269,275} For formation of disulfide bonds using an orthogonal protecting group strategy, StBu must be removed before other protecting groups to avoid cleaving or scrambling existing disulfides (as would occur upon treatment with a reducing agent). This is typically done on-resin prior to TFA acidolysis, which can result in side products and low yields. As discussed previously, one solution to this problem that has been reported was to perform post-synthetic tritylation; multiple disulfide bonds could then be regioselectively formed in solution using combinations of StBu, Trt, Acm and Meb/Mob, all of which survive the final cleavage step in Fmoc SPPS, bar Trt.⁷⁴

Cys(StBu) has been used in the synthesis of a range of different peptides, including μ -SIIIA (Fig. 39c),⁷⁴ α -LVIa (Fig. 39d),²⁰⁵ and Linactotide (Fig. 39e).²⁷⁶ The removal of StBu with reducing agents has previously been shown to be sequence-dependent and challenging;¹⁶⁶ additionally, the lengthy times required for deprotection are undesirable when using the group in routine SPPS.¹⁶³ Alternative disulfide-based protecting groups such as dimethoxyphenylthio (S-Dmp) and 2,4,6-trimethoxyphenylthio (S-Tmp) have since been reported as replacements for the StBu protecting group.¹⁶³

5.10.9 *N*-Methyl-phenacyloxycarbamidomethyl (Pocam). The *N*-methyl-phenacyloxycarbamidomethyl (Pocam) Cys protecting group (Fig. 40a) is both reducing agent- and acid-labile, removable by Zn/AcOH (aq.) or TFA (1 h, 50 °C). At lower temperatures, Pocam is relatively resistant to TFA treatment (4 h, 4 °C). If Pocam is used for the thioester method of protein ligation it can be removed at the same time as *N*-azido groups protecting amino functionalities. Pocam has been used as an orthogonal protecting group in the synthesis of disulfide containing peptides, such as growth-blocking peptide (GBP) and α -conotoxin SI.¹⁶⁰ However, Pocam still has limited applicability due to its lack of acid-stability and has since been effectively replaced by the introduction of Pac.⁶

5.10.10 Phenacyl (Pac). Introduced in 2008 for Boc solution phase synthesis,²⁷⁷ and in 2013 for Fmoc SPPS,¹⁶¹ the phenacyl (Pac) Cys protecting group (Fig. 40b) has effectively replaced the Pocam group.⁶ Pac may be removed using Zn in acid (AcOH (aq.), MPS in 6 M Gdn·HCl).^{161,162} The group is slightly labile to

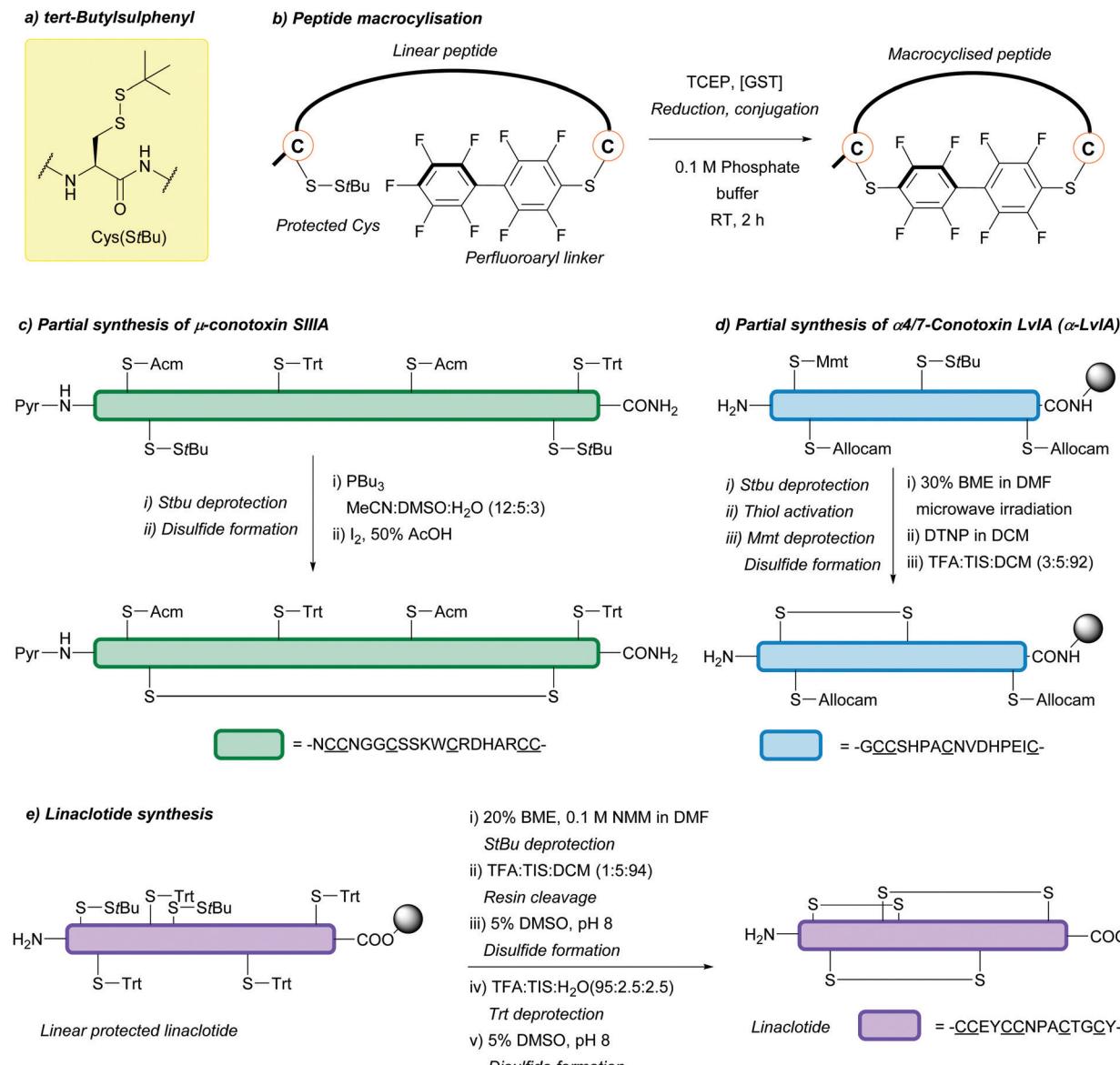
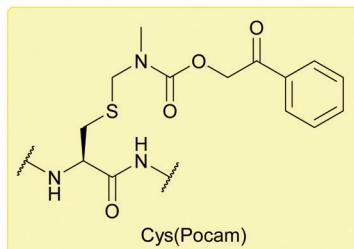


Fig. 39 (a) Cys thiol protection with the *tert*-butylsulphenyl (StBu) protecting group. (b) Reduction of Cys(StBu) and perfluoroaryl linker-containing peptide with TCEP in the presence of glutathione *S*-transferase (GST). Deprotection of Cys(StBu) yields the free thiol, which can then undergo macrocyclisation with the perfluoroaryl linker facilitated by GST. (c) Partial synthesis of μ -conotoxin SIIIA using Cys(StBu). (d) Partial synthesis of α -LvIA using Cys(StBu). (e) Synthesis of Linactolide using Cys(StBu).

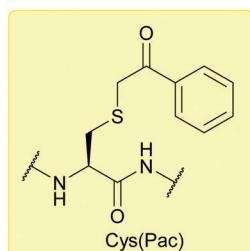
strongly acidic conditions (1 M TMFSA in TFA) and when AgNO_3 is used; these conditions are used to deprotect Cys(Mob) and Cys(Acm) respectively, and thus (in a given case) deprotection of Cys(Pac) prior to these two groups has been recommended.⁶ As with Pocam, the group can be removed at the same time as an *N*-azido group with Zn/AcOH for use in the thioester method of protein ligation.¹⁶¹ Peptides including the antimicrobial peptide tachyplesin could be synthesised using Cys(Pac) in standard Fmoc SPPS (Fig. 40c).¹⁶¹

The Pac protecting group has been employed in the semi-synthesis of histone H3 bearing an N^{e} trimethylated Lys residue ($[\text{Lys}(\text{Me}_3)^3]\text{H3.1}$, Fig. 40d).²⁷⁸ First, the C-terminal fragment of the peptide containing an N-terminal Cys and two internal Cys

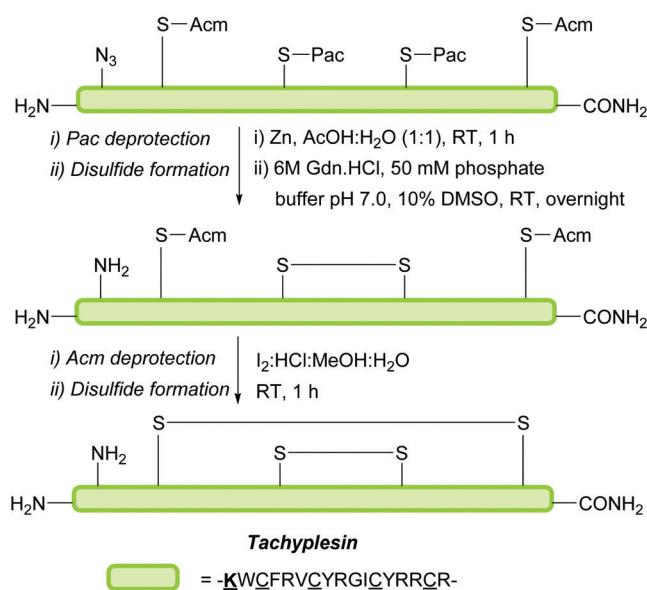
residues (H3.1(26-135)) was recombinantly produced by gene expression and subsequent peptide production in *E. coli*. The N-terminal Cys residue was then orthogonally protected with Thz, whereas both the internal Cys were protected with Pac. Conditions for deprotection of N-terminal Cys(Thz) using methoxyamine also lead to oxime ether formation at the ketone position of Pac, converting Pac to “PacN”; this, however, does not impact on downstream deprotection as PacN also shows lability to Zn/AcOH similar to Pac. Deprotection of the N-terminal Cys(Thz), followed by CPE ligation with a suitable H3 N-terminal fragment and subsequent desulfurisation gave the dual Cys(PacN) protected peptide. Critically, the Cys(PacN) groups remained resistant to desulfurisation. Deprotection with Zn powder and

a) *N*-Methyl-phenacyloxycarbamidomethyl

b) Phenacyl



c) Synthesis of tachyplesin



d) Synthesis of histone H3.1

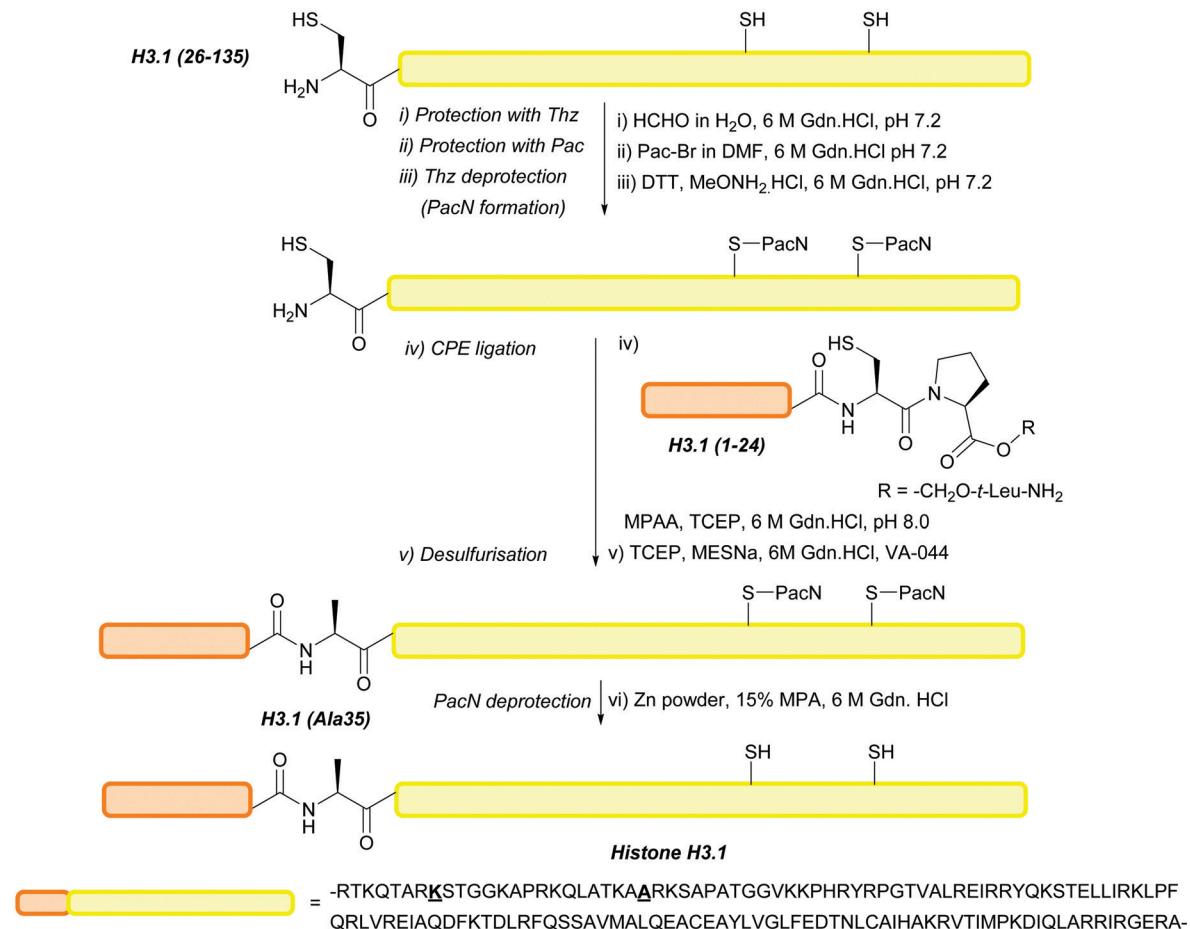


Fig. 40 (a) Cys thiol protection with the *N*-methyl-phenacyloxycarbamidomethyl (Pocam) protecting group. (b) Cys thiol protection with the phenacyl (Pac) protecting group. (c) Synthesis of tachyplesin using Cys(Pac). (d) Semi-synthesis of histone H3.1 using Cys(Pac).



15% 3-mercaptopropionic acid (MPA) in H_2O with 6 M Gdn yielded the product $[\text{Lys}(\text{Me}_3)^9]\text{H3.1}$ histone.²⁷⁸ Similarly, it has been shown that Cys(Pac) can be used in conjunction with recombinantly generated protein segments for the traceless semisynthesis of human small heat shock protein (Hsp27) and a lipidated variant of murine prion protein (Prp).¹⁶² Pac proved compatible both with installation into thioester-containing peptides, and in radical desulfurisation steps. Cys(Trt) was also investigated; however, in this case, desulfurisation of Cys(Trt) containing Hsp27 proved lead to a mixture of products.¹⁶²

5.10.11 S-Iso-propyl (SiPr). The *S*-iso-propyl (SiPr) Cys protecting group (Fig. 41a) has been used in the Boc solution phase synthesis of disulfide containing peptides.²⁷⁹ More recently, the group has been featured in one of the first examples of using orthogonal Cys protecting groups for construction of multi-drug containing ADCs.¹¹⁴ In this example, a dual protected Cys-based carrier containing Cys(SiPr) and Cys(Acm) was constructed using Fmoc SPPS, and furnished with a “self stabilising” maleimide linker. The carrier could then be used to site specifically modify free Cys (generated from reduction of interchain disulfides) of an immunoglobulin G (IgG), specifically CD30-directed antibody cAC10 (Fig. 41b). Orthogonal deprotection of Cys(SiPr) with TCEP accompanied by sequential conjugation of maleimide-linked monomethyl auristatin F (MMAF) give rise to the installation of one drug molecule per carrier. This was then followed by Cys(Acm)

deprotection with $\text{HgO}(\text{Ac})_2$ and addition of monomethyl auristatin E (MMAE), allowing for the installation of two different drug moieties per conjugated carrier, resulting in an average of 16 drugs per antibody (8 MMAF + 8 MMAE, Fig. 41c). The *in vitro* and *in vivo* activities of the dual-auristatin ADC were then compared to cAC10 loaded with only MMAF or cAC10 loaded with only MMAE. The dual-auristatin ADC displayed both resistance to drug exportation *via* multi drug resistance (MDR) exporters due to MMAF, and cell permeability due to MMAE, combining the advantageous properties of both drugs onto a single ADC.¹¹⁴

5.10.12 Dimethoxyphenylthio (S-Dmp) and 2,4,6-trimethoxyphenylthio (S-Tmp). The dimethoxyphenylthio (S-Dmp, Fig. 42a) and 2,4,6-trimethoxyphenylthio (S-Tmp, Fig. 42b) groups were synthesised in 2012 as highly-labile replacements for the *S*tBu group in Fmoc SPPS.¹⁶³ Both groups can be removed using NMM (0.1 M) with either 20% BME in DMF or 5% DTT in DMF in 5 min. In contrast, removal of the *S*tBu protecting group using the aforementioned conditions required 3 h of incubation with BME, whereas little to no deprotection of *S*tBu was observed when using DTT. Both the S-Dmp and S-Tmp groups were noted to be compatible to Fmoc removal conditions (20% piperidine in DMF, 4 h). Model tripeptides containing either group displayed stability towards conditions for resin cleavage (95% TFA, 1 h, RT); however, partial instability (8–13% deprotection) was observed following treatment with TFA/TIS/ H_2O (95 : 2.5 : 2.5) at RT when

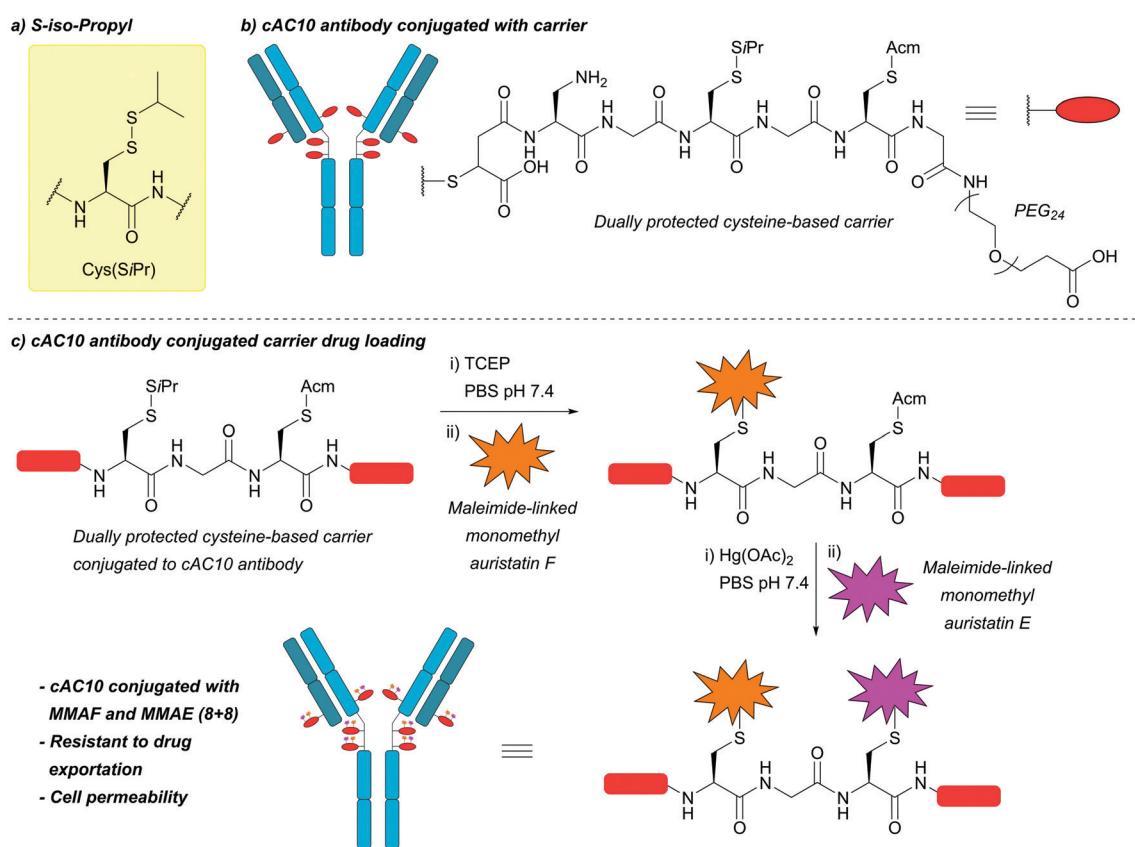


Fig. 41 (a) Cys thiol protection with the *S*-iso-propyl (SiPr) protecting group. (b) CD30-directed antibody cAC10 bearing a dual protected cysteine-based carrier containing Cys(SiPr) and Cys(Acm). (c) Construction of cAC10 conjugated with MMAF and MMAE (8 + 8) using Cys(SiPr).

applied to oxytocin synthesis. This could be avoided by using a more acid-labile resin, avoiding the requirement for high TFA concentrations. As with StBu, *S*-Dmp and *S*-Tmp should be deprotected first in orthogonal protecting group strategies (which usually results in deprotection prior to TFA cleavage from the resin). The use of *S*-Dmp and *S*-Tmp has been demonstrated practically, with sample syntheses of oxytocin on-resin, and T22 carried out.¹⁶³ Both groups produced better yields than the corresponding peptides synthesised using StBu. Out of the two groups, *S*-Tmp showed higher stability and produced purer peptides, and is therefore recommended for use.¹⁶³ In addition to using DTT, deprotection of the *S*-Dmp group has also been demonstrated using a novel reducing agent 2-(dibenzylamino)-butane-1,4-dithiol (DABDT).¹⁶⁴ The *S*-Tmp protecting group has since been used in conjunction with *N*-chlorosuccinimide in the on-resin, regioselective synthesis of α -conotoxin SI (Fig. 42c),²⁸⁰ and very recently in the synthesis of a disulfide containing, truncated neuropeptide Y (NPY) analogue.²⁸¹

5.10.13 Sec-isoamyl mercaptan (SIT) and 2-methyloxolane-3-thiol (MOT). 3-Methyl-2-butanethiol/sec-isoamyl mercaptan (SIT, Fig. 42d) and 2-methyloxolane-3-thiol (MOT, Fig. 42e) have very recently been described as disulfide-based protecting groups for Cys.¹⁶⁵ In contrast to other disulfide-based protecting groups, SIT and MOT show greater thiol lability compared to StBu (and are therefore easier to remove), but display greater stability towards 20% piperidine than *S*-Dmp. Deprotection of both SIT and MOT could be achieved with BME in DMF (1 : 4) and 0.1 M DIEA. Alternatively, 20 equiv. DTT in MeCN with 5% DIEA could also be used to remove both groups; the rate of

deprotection was further enhanced by addition of 5% H₂O, with SIT and MOT fully removed within 40 and 20 min respectively. Treatments of 5 equiv. DTT in DMF : DIEA : H₂O (95 : 2.5 : 2.5, three treatments, 10 min) was also sufficient for deprotection of Cys(SIT) and Cys(MOT) located within Asn(Trt)-Cys(SIT/MOT)-Asn(Trt) tripeptides. Both of these groups have been successfully used in the synthesis of vasopressin *via* Fmoc SPPS, although minor thiol deprotection (*ca.* 2%) of protected vasopressin during SPPS was noted for the more labile MOT group. Furthermore, the SIT protecting group could be used in microwave-assisted synthesis of vasopressin.¹⁶⁵

5.10.14 2-Pyridinesulfenyl (S-Pyr). The 2-pyridinesulfenyl (S-Pyr) group is a thiol-labile protecting group (Fig. 43).²⁸² It is suitable for use in Boc SPPS²⁸³ and is stable to acidic conditions, *e.g.* 1 M TFMSA in TFA-anisole (10 : 1, 2 h, 0 °C).⁴ S-Pyr can also act as an activating group; free thiols can attack the activated sulfur atom, displacing S-Pyr to generate disulfide containing peptides.^{142,284} This has recently been shown in the synthesis of sialic acid-containing insulin analogues, referred to as "Sialic-Ins".²⁸⁵

5.11 Safety-catch protecting groups

5.11.1 4,4-Bis(dimethylsulfinyl)benzhydryl (Msbh). The 4,4-bis(dimethylsulfinyl)benzhydryl (Msbh) protecting group is an example of a 'safety-catch' protecting group – that is, it is stable to a particular set of conditions until the group undergoes a specific reaction. In the case of Msbh, it is stable to acidic (TFA, HF), oxidative and reductive conditions until its electron-withdrawing sulfoxide groups are reduced. It is both reduced and removed by a cocktail of NH₄I/DMS/TFA. Iodine/iodosulfonium ions are produced as a

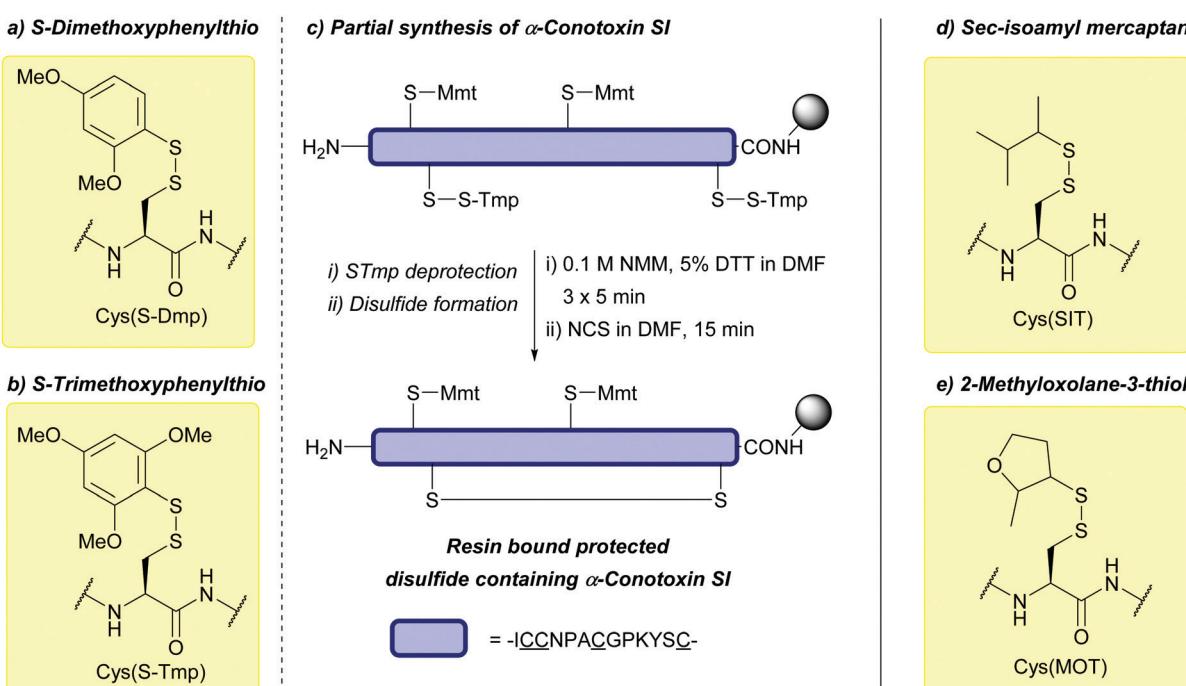


Fig. 42 (a) Cys thiol protection with the dimethoxyphenylthio (S-Dmp) protecting group. (b) Cys thiol protection with the 2,4,6-trimethoxyphenylthio (S-Tmp) protecting group. (c) Partial synthesis of synthesis of α -conotoxin SI using Cys(S-Tmp). (d) Cys thiol protection with the sec-isoamyl mercaptan (SIT) protecting group. (e) Cys thiol protection with the 2-methyloxolane-3-thiol (MOT) protecting group.



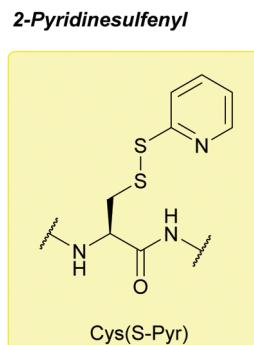


Fig. 43 Cys thiol protection with the 2-pyridinesulfenyl (S-Pyr) protecting group.

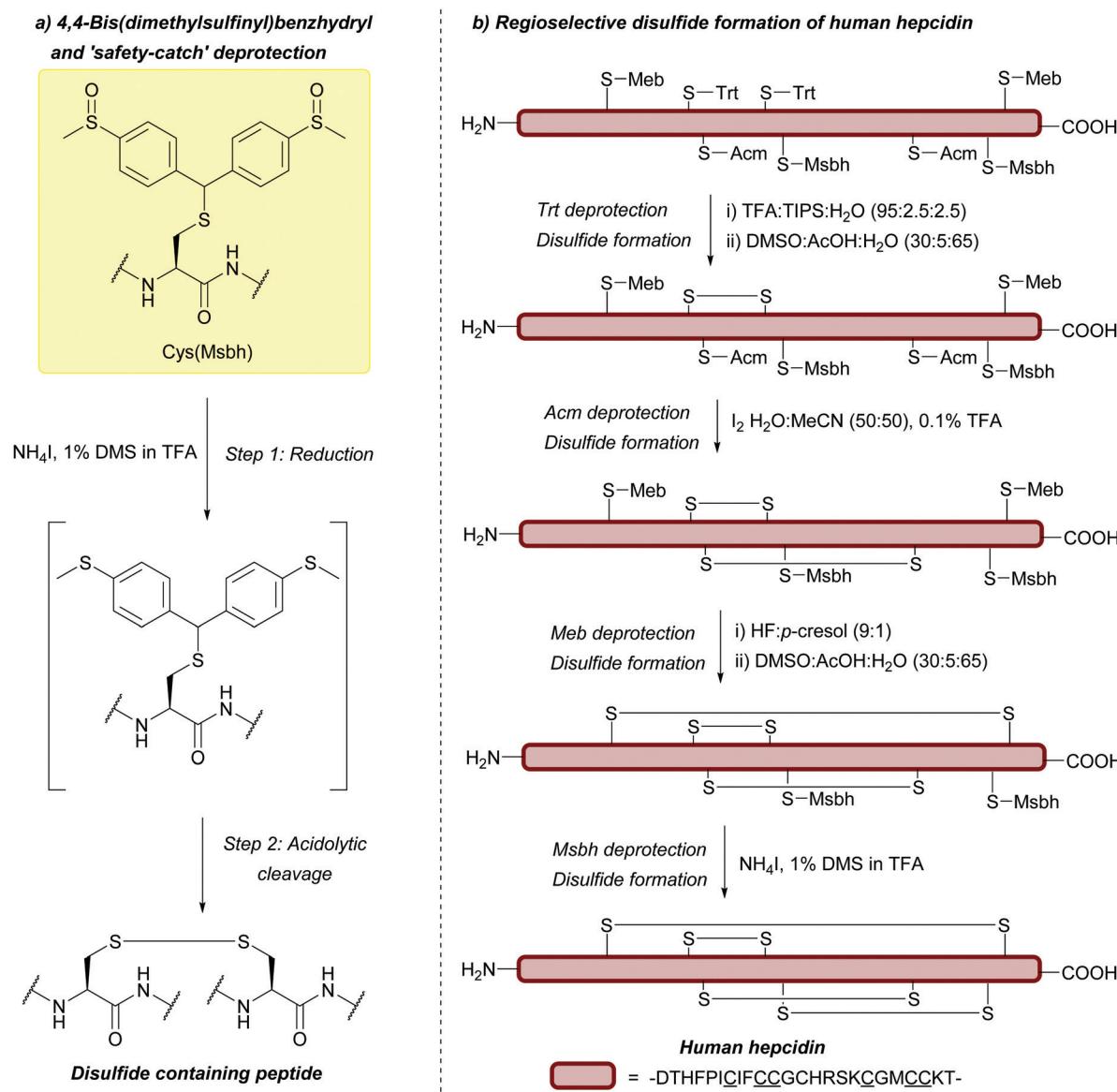


Fig. 44 (a) Cys thiol protection with the 4,4-bis(dimethylsulfinyl)benzhydryl (Msbh) protecting group. Treatment with a cocktail of NH_4I /DMS/TFA results in initial reduction of the Msbh protecting group, followed by acid-mediated cleavage and subsequent iodine-mediated oxidation to yield disulfide containing peptides. (b) Partial synthesis and regioselective disulfide formation of human hepcidin using Cys(Msbh).

side product of the reaction and thus oxidise the liberated thiols directly to the disulfide (Fig. 44a). Msbh is fully compatible with a range of other protecting groups, such as Trt, Acm, Meb and Mob.¹⁶⁶

$\text{NH}_4\text{I}/\text{TFA}$ treatment is incompatible with Trp-containing peptides, as Trp undergoes a number of side reactions (due to the presence of I_2) unless the indole nitrogen is protected with a formyl group. This is standard in Boc SPPS and thus should not present a significant issue in this case. The formyl group is, however, removed by piperidine treatment so if Fmoc SPPS is being used alternative sulfoxide reduction methods or Trp protecting groups are needed.¹⁶⁶ Msbh has been used in the regioselective synthesis of human hepcidin (Fig. 44b), providing an orthogonal strategy for the synthesise of peptides containing four disulfide bonds.¹⁶⁶ It has also been theorised to

be key to the regiospecific construction of peptides containing five or more disulfide bonds, a feat that is yet to be accomplished.⁵

6. Conclusions

Methods for the protection, and subsequent deprotection, of the thiol side chain of Cys has enabled a vast array of peptide and protein chemistry over the last 70 years. The development of protecting groups that are orthogonal to one another in particular has proved critical to facilitating the synthesis of complex products such as disulfide rich peptides. Although there are now numerous protecting strategies that have been reported for Cys, it is likely that research and development on the subject will continue over the course of the coming years. This will undoubtedly involve taking well-established Cys protecting groups, and developing new deprotection conditions that offer advantages over established methods. For example, protecting groups originally reported decades ago for use in Boc peptide synthesis such as Dpm, Thp, and SiPr, have greatly benefitted from being revisited for use in Fmoc peptide synthesis, both from the perspective of developing new deprotection protocols, and the application of such groups. Transition metal chemistry applied to Cys protecting group chemistry in recent years has also yielded new, milder conditions to deprotect protecting groups such as Trt, *t*Bu, Acm, and Thz, or improved deprotection protocols in the case of Allocam. Alternatively, the development of new protecting groups with their own set of deprotection conditions will also likely prove paramount to furthering Cys-based peptide and protein chemistry. Protecting groups such as Mbom and Ddm offer C-terminal Cys-containing peptides with reduced racemisation side-reactions. Redesigning previously reported protecting group scaffolds has also led to the development of new protecting groups that are significantly easier to deprotect, as seen with *S*-Dmp/*S*-Tmp and SIT/MOT. Furthermore, newer protecting groups with unique “turn on/off” deprotection conditions, such as Hmb^{off/on} and Msbh, will likely see further development in challenging peptide synthesis. For example, regioselective synthesis of peptides with greater than four disulfide bonds has not yet been reported; novel protecting groups will likely prove critical to achieving this.

Finally, there is an increasing desire to make the process of SPPS more “green”, which currently uses toxic and environmentally unfriendly reagents such as piperidine, DMF, and DCM.²⁸⁶ This will require protecting group chemistry that is compatible with greener reagents, such as water/aqueous-based solvent systems. Enzymatically labile protecting groups such as Phacm, or photo-labile groups such as NDBF, have already been successfully utilised in this context; future protecting groups with similar properties will likely prove important in the “greening” of SPPS. We additionally anticipate the field of peptide chemistry and growing field of protein bioconjugation will likely benefit each other in the coming years. In contrast to conventional peptide synthesis, protein bioconjugation/deconjugation is, by design, carried out in benign/environmentally friendly aqueous systems in a site-specific manner. Additionally, there is a continuing search for new methodology

for use in bioconjugation; although these must yield stable conjugates, strategies whereby the bioconjugate can be released in a controlled manner offers huge potential in applications such as controlled drug release. This interplay has already been demonstrated with Cys protecting groups that have since been applied to bioconjugation, such as Acm, Scm, Thz, and SiPr. Similarly, Suc, which is routinely used in bioconjugation, has very recently been demonstrated as a Cys protecting group in peptide synthesis. It is likely other bioconjugation strategies will also be applied to peptide synthesis in the coming years.

We have reviewed, analysed, and discussed over 60 individual protecting groups for the thiol group of Cys. We hope that this review provides a useful resource for peptide and protein chemists research, and encourages further research into both old and new Cys protecting groups.

Abbreviations

2-Moxan	2-methoxy-9 <i>H</i> -xanthen-9-yl
2,6-diMeOBn	2,6-dimethoxybenzyl
4MeO-2MeBn	4-methoxy-2-methylbenzyl
5-Npys	5-nitro-2-pyridinesulfenyl
7,8BCMCMOC	[7,8-bis(carboxymethoxy)coumarin-4-yl]-methoxycarbonyl
Acm	acetamidomethyl
AcOH	acetic acid
Ad/1-Ada	1-adamantyl
ADC	antibody drug conjugate
Alloc	allyloxycarbonyl
Allocam	allyloxycarbonylaminomethyl
AgOAc	silver acetate
AgOTf	silver trifluoromethanesulfonate
Arg	arginine
Bam	benzamidomethyl
BCMACMOC	[7-bis(carboxymethyl)-amino-coumarin-4-yl]methoxycarbonyl
Bhc	6-bromo-7-hydroxycoumarin
BME	2-mercaptoethanol
Boc	<i>tert</i> -butyloxycarbonyl
Bom	benzyloxymethyl
BSA	bovine serum albumin
Bu ₃ SnH	tributyltin hydride
Bzl/Bn	benzyl
C4MNB	α-carboxy-4-methoxy-2-nitrobenzyl
CAN	ceric ammonium nitrate
CDMNB	α-carboxy-4-methoxy-2-nitrobenzyl
CuAAC	copper(i)-catalysed alkyne-azide cyclo-addition
CPE	cysteinylprolyl ester
CPI	cysteinylprolyl imide
Cys	cysteine
Dbs/Sub	5-dibenzosuberyl
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DCC	dicyclohexylcarbodiimide
DCM	dichloromethane

Ddm/4,4'-diMeODpm	4,4'-dimethoxydiphenylmethyl	Mob/MBzl	4-methoxybenzyl
DIEA	<i>N,N</i> -diisopropylethylamine	MOT	2-methyloxolane-3-thiol
DMB	3,4-dimethylbenzyl	MPAA	4-mercaptophenylacetic acid
Dmbm	(4,6-dimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-yl)methanol	MPS	mercaptopropiosulfonic acid
DMF	dimethylformamide	Mpt	dimethylphosphinothiyl
DMS	dimethyl sulfide	Msbh	4,4-bis(dimethylsulfinyl)benzhydryl
DMSO	dimethylsulfoxide	Mtt	4-methyltrityl
Dnpe	2-(2,4-dinitrophenyl)ethyl	NCL	native chemical ligation
DPDS	2,2'-dipyridyl disulfide	NDBF	nitrodibenzofuran
Dpm	diphenylmethyl	Nin	1,3-dimethylbarbituric acid
DSF	disulfiram	NMM	ninhydrin
DTC	diethyldithiocarbamate	NpsCl	<i>N</i> -methylmorpholine
DTNB	5,5'-dithiobis-(2-nitrobenzoic acid)	Npys	2-nitrophenylsulfenyl chloride
DTNP	2,2'-dithiobis(5-nitropyridine)	OMe-NDBF	3-nitro-2-pyridinesulfenyl
DTP	2,2'-dithiodipyridine	<i>o</i> NB	methoxy-nitrodibenzofuran
DTT	dithiothreitol	<i>o</i> NV	2-nitrobenzyl
EDT	ethane-1,2-dithiol	<i>p</i> AB	2-nitroveratryl
EDTA	ethylenediaminetetraacetic acid	Pac	<i>para</i> -aminobenzyl
EETI-II	<i>Ecballium elaterium</i> trypsin inhibitor II	PAL	phenacyl
EGFP	enhanced green fluorescent protein	PB	peptide-amide-linker
EtOH	ethanol	Pbfm/Pmbf	phosphate buffer
Fm	9-fluorenylmethyl	pBNP	2,2,4,6,7-pentamethyl-2,3-dihydrobenzofuran-5-methyl
Fmoc	9-fluorenylmethoxycarbonyl	PBS	porcine brain natriuretic peptide
Fnam	[<i>N</i> -[2,3,5,6-tetrafluoro-4-(<i>N'</i> -piperidino)phenyl], <i>N</i> -allyloxycarbonyl]aminomethyl	[Pd(allyl)Cl] ₂	phosphate-buffered saline
Fsam	<i>S</i> -[<i>N</i> -[2,3,5,6-tetrafluoro-4-(phenylthio)phenyl], <i>N</i> -allyloxycarbonyl]aminomethyl	PdCl ₂ (PPh ₃) ₂	allylpalladium(II) chloride dimer
GBP	growth-blocking peptide	Pd(OAc) ₂	bis(triphenylphosphine)palladium(II) dichloride
Gdn·HCl	guanidinium chloride	Pd(PPh ₃) ₄	palladium(II) acetate
GFP	green fluorescent protein	PFTase	tetrakis(triphenylphosphine)palladium(0)
GSH	glutathione	PGA	protein farnesyltransferase
H ₂ O	water	Phacm	penicillin G acylase
HEPES	(4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid)	PhSiH ₃	phenylacetamidomethyl
HEPPS	4-(2-hydroxyethyl)-1-piperazinepropanesulfonic acid	Pmem	phenylsilane
HFIP	hexafluoro-2-propanol	<i>p</i> NB	2,2,5,7,8-pentamethylchroman-6-methyl
Hgm	hydroxyglycine-Acm	Pocam	<i>para</i> -nitrobenzyl
Hg(OAc) ₂	mercury(II) acetate	PTM	<i>N</i> -methyl-phenacyloxy carbamidomethyl
His	histidine	Pym	post-translational modification
Hmb	2-hydroxy-4-methoxy benzyl	RP-HPLC	2-oxo-1-pyrrolidinyl)methyl
hNP2	defensin human neutrophil peptide-2	Sac	reversed phase high-performance liquid chromatography
HOBt	1-hydroxybenzotriazole	Scm	<i>S</i> -allyl cysteine
Hqm	hydroxyquinoline-Acm	S-Dmp	carbomethoxysulfenyl
Lys	lysine	SIT	dimethoxyphenylthio
MAA	3-mercaptopropanoic acid		<i>sec</i> -isoamyl mercaptan/3-methyl-2-butanethiol
mBhc	6-bromo-7-hydroxy-3-methylcoumarin	SiPr	<i>S</i> -iso-propyl
Mbom	4-methoxybenzyloxymethyl	Snm	(<i>N</i> '-methyl- <i>N</i> '-phenylcarbamoyl)sulfenyl
Meb/4-MeBn/4-MeBzl	4-methylbenzyl	SO ₂ R	sulfonyl
MeCN	acetonitrile	SO ₃ H	sulfonic acid
MeOH	methanol	SPPS	solid phase peptide synthesis
MeONH ₂ ·HCl	<i>O</i> -methylhydroxylamine	SprC	<i>S</i> -propargyl-cysteine
MESNA	sodium 2-mercaptopethanesulfonate	S-Pyr	2-pyridinesulfenyl
Met	methionine	StBu	<i>tert</i> -butylsulphenyl
Mmt	4-methoxytrityl	S-Tmp	2,4,6-trimethoxyphenylthio



Suc	succinimide
Tacm	trimethylacetamidomethyl
TBAF	tetrabutylammonium fluoride
tBu	tert-butyl
TCEP	tris(2-carboxyethyl)phosphine
TES	triethylsilane
TFA	trifluoroacetic acid
TFE	tetrafluoroethylene
TFMSA	trifluoromethanesulfonic acid
THF	tetrahydrofuran
Thp	tetrahydropyranyl
Thz	thiazolidine
TIS	triisopropylsilane
Tmbm	4,5,6-trimethoxy-2,2-dimethyl-2,3-dihydrobenzofuran-7-methyl
Tmob	2,4,6-trimethoxybenzyl
TMSBr	bromotrimethylsilane
TMSOTf	trimethylsilyl trifluoromethanesulfonate
TMTr	4,4',4''-trimethoxytriphenylmethyl
Tppts	3,3',3''-phosphanetriyltris(benzene-sulfonic acid) trisodium salt
Trp	tryptophan
Trt	trityl
Trx	thioredoxin
Tyr	tyrosine
VA-044	2,2'-azobis[2-(2-imidazolin-2-yl)propane]-dihydrochloride
UBL5	ubiquitin-like protein 5
Xan	9H-xanthen-9-yl
ΨPro	pseudoproline
μ-SIIA	μ-conotoxin SIIIA

Author contributions

R. J. S., C. M. and V. C. co-wrote the review and co-analysed the literature with R. J. S. and V. C. leading in writing and analysing.

Conflicts of interest

V. C. is a co-founder and director of the company ThioLogics.

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References

- 1 G. Sartori, R. Ballini, F. Bigi, G. Bosica, R. Maggi and P. Righi, *Chem. Rev.*, 2004, **104**, 199–250.
- 2 B. Ghosh and S. S. Kulkarni, *Chem. – Asian J.*, 2020, **15**, 450–462.
- 3 M. Schelhaas and H. Waldmann, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2056–2083.
- 4 A. Isidro-Llobet, M. Álvarez and F. Albericio, *Chem. Rev.*, 2009, **109**, 2455–2504.
- 5 R. He, J. Pan, J. P. Mayer and F. Liu, *ChemBioChem*, 2020, **21**, 1101–1111.
- 6 T. M. Postma and F. Albericio, *Eur. J. Org. Chem.*, 2014, 3519–3530.
- 7 B. J. Tombling, C. K. Wang and D. J. Craik, *Angew. Chem., Int. Ed.*, 2020, **59**, 11218–11232.
- 8 M. Góngora-Benítez, J. Tulla-Puche and F. Albericio, *Chem. Rev.*, 2014, **114**, 901–926.
- 9 D. Imhof, D. Roy and F. Albericio, *Front. Chem.*, 2020, **8**, 841.
- 10 V. du Vigneaud, C. Ressler, J. M. Swan, C. W. Roberts and P. G. Katsoyannis, *J. Am. Chem. Soc.*, 1954, **76**, 3115–3121.
- 11 V. du Vigneaud, C. Ressler, C. J. M. Swan, C. W. Roberts, P. G. Katsoyannis and S. Gordon, *J. Am. Chem. Soc.*, 1953, **75**, 4879–4880.
- 12 I. Vecchio, C. Tornali, N. L. Bragazzi and M. Martini, *Front. Endocrinol.*, 2018, **9**, 613.
- 13 J. G. McGivern, *Neuropsychiatr. Dis. Treat.*, 2007, **3**, 69–85.
- 14 M. Corsetti and J. Tack, *United Eur. Gastroenterol. J.*, 2013, **1**, 7–20.
- 15 U. Hennrich and M. Benešová, *Pharmaceuticals*, 2020, **13**(3), 38.
- 16 A. Fra, E. D. Yoboue and R. Sitia, *Front. Mol. Neurosci.*, 2017, **10**, 167.
- 17 S. Verma, R. Dixit and K. C. Pandey, *Front. Pharmacol.*, 2016, **7**, 107.
- 18 C. D. Spicer and B. G. Davis, *Nat. Commun.*, 2014, **5**, 4740.
- 19 V. Chudasama, A. Maruani and S. Caddick, *Nat. Chem.*, 2016, **8**, 114–119.
- 20 N. Joubert, A. Beck, C. Dumontet and C. Deneault-Sabourin, *Pharmaceuticals*, 2020, **13**, 245.
- 21 P. Stathopoulos, S. Papas, C. Pappas, V. Mousis, N. Sayyad, V. Theodorou, A. G. Tzakos and V. Tsikaris, *Amino Acids*, 2013, **44**, 1357–1363.
- 22 Y. Fujiwara, K. Akaji and Y. Kiso, *Chem. Pharm. Bull.*, 1994, **42**, 724–726.
- 23 D. Lelièvre, V. P. Terrier, A. F. Delmas and V. Aucagne, *Org. Lett.*, 2016, **18**, 920–923.
- 24 J. Lukszo, D. Patterson, F. Albericio and S. A. Kates, *Lett. Pept. Sci.*, 1996, **3**, 157–166.
- 25 S. Laps, G. Satish and A. Brik, *Chem. Soc. Rev.*, 2021, **50**, 2367–2387.
- 26 E. Fischer and E. Fourneau, *Ber. Dtsch. Chem. Ges.*, 1901, **34**, 2868–2877.
- 27 J. C. Sheehan and G. P. Hess, *J. Am. Chem. Soc.*, 1955, **77**, 1067–1068.
- 28 L. A. Carpino, *J. Am. Chem. Soc.*, 1957, **79**, 4427–4431.
- 29 F. C. McKay and N. F. Albertson, *J. Am. Chem. Soc.*, 1957, **79**, 4686–4690.
- 30 R. B. Merrifield, *J. Am. Chem. Soc.*, 1963, **85**, 2149–2154.
- 31 J. M. Palomo, *RSC Adv.*, 2014, **4**, 32658–32672.
- 32 L. A. Carpino and G. Y. Han, *J. Am. Chem. Soc.*, 1970, **92**, 5748–5749.
- 33 D. M. M. Jaradat, *Amino Acids*, 2018, **50**, 39–68.



34 M. Ahangarpour, I. Kavianinia, P. W. R. Harris and M. A. Brimble, *Chem. Soc. Rev.*, 2021, **50**, 898–944.

35 P. R. Hansen and A. Oddo, in *Fmoc Solid-Phase Peptide Synthesis*, ed. G. Houen, Springer New York, New York, NY, 2015, pp. 33–50.

36 V. Agouridas, O. El Mahdi, M. Cargoët and O. Melnyk, *Bioorg. Med. Chem.*, 2017, **25**, 4938–4945.

37 P. E. Dawson, T. W. Muir, I. Clark-Lewis and S. B. Kent, *Science*, 1994, **266**, 776–779.

38 P. E. Dawson and S. B. H. Kent, *Annu. Rev. Biochem.*, 2000, **69**, 923–960.

39 D. Bang and S. B. H. Kent, *Angew. Chem., Int. Ed.*, 2004, **43**, 2534–2538.

40 T. C. Evans Jr., J. Benner and M.-Q. Xu, *Protein Sci.*, 1998, **7**, 2256–2264.

41 T. W. Muir, D. Sondhi and P. A. Cole, *Proc. Natl. Acad. Sci. U. S. A.*, 1998, **95**, LP6705–LP6710.

42 L. Z. Yan and P. E. Dawson, *J. Am. Chem. Soc.*, 2001, **123**, 526–533.

43 Q. Wan and S. J. Danishefsky, *Angew. Chem., Int. Ed.*, 2007, **46**, 9248–9252.

44 T. Kawakami and S. Aimoto, *Chem. Lett.*, 2006, 76–77.

45 M. Yanase, K. Nakatsu, C. J. Cardos, Y. Konda, G. Hayashi and A. Okamoto, *Chem. Sci.*, 2019, **10**, 5967–5975.

46 G.-M. Fang, Y.-M. Li, F. Shen, Y.-C. Huang, J.-B. Li, Y. Lin, H.-K. Cui and L. Liu, *Angew. Chem., Int. Ed.*, 2011, **50**, 7645–7649.

47 G.-M. Fang, J.-X. Wang and L. Liu, *Angew. Chem., Int. Ed.*, 2012, **51**, 10347–10350.

48 J.-S. Zheng, S. Tang, Y.-K. Qi, Z.-P. Wang and L. Liu, *Nat. Protoc.*, 2013, **8**, 2483–2495.

49 Y. Qiao, G. Yu, K. C. Kratch, X. A. Wang, W. W. Wang, S. Z. Leeuwon, S. Xu, J. S. Morse and W. R. Liu, *J. Am. Chem. Soc.*, 2020, **142**, 7047–7054.

50 H. Hojo and S. Aimoto, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 111–117.

51 H. Hojo, Y. Murasawa, H. Katayama, T. Ohira, Y. Nakahara and Y. Nakahara, *Org. Biomol. Chem.*, 2008, **6**, 1808–1813.

52 H. Katayama, H. Hojo, T. Ohira and Y. Nakahara, *Tetrahedron Lett.*, 2008, **49**, 5492–5494.

53 H. Hojo, *Org. Biomol. Chem.*, 2016, **14**, 6368–6374.

54 W. Hou, X. Zhang and C.-F. Liu, *Trans. Tianjin Univ.*, 2017, **23**, 401–419.

55 A. C. Conibear, E. E. Watson, R. J. Payne and C. F. W. Becker, *Chem. Soc. Rev.*, 2018, **47**, 9046–9068.

56 S. S. Kulkarni, J. Sayers, B. Premdjee and R. J. Payne, *Nat. Rev. Chem.*, 2018, **2**, 122.

57 V. Agouridas, O. El Mahdi, V. Diemer, M. Cargoët, J.-C. M. Monbaliu and O. Melnyk, *Chem. Rev.*, 2019, **119**, 7328–7443.

58 G. Barany and R. B. Merrifield, *J. Am. Chem. Soc.*, 1977, **99**, 7363–7365.

59 H. C. Hang, C. Yu, D. L. Kato and C. R. Bertozzi, *Proc. Natl. Acad. Sci. U. S. A.*, 2003, **100**, LP14846–LP14851.

60 S. S. Nguyen and J. A. Prescher, *Nat. Rev. Chem.*, 2020, **4**, 476–489.

61 E. M. Sletten and C. R. Bertozzi, *Acc. Chem. Res.*, 2011, **44**, 666–676.

62 P. Agarwal, B. J. Beahm, P. Shieh and C. R. Bertozzi, *Angew. Chem., Int. Ed.*, 2015, **54**, 11504–11510.

63 S. T. Laughlin, J. M. Baskin, S. L. Amacher and C. R. Bertozzi, *Science*, 2008, **320**, 664–667.

64 R. Brabham and M. A. Fascione, *ChemBioChem*, 2017, **18**, 1973–1983.

65 C. H. Kim, M. Kang, H. J. Kim, A. Chatterjee and P. G. Schultz, *Angew. Chem., Int. Ed.*, 2012, **51**, 7246–7249.

66 A. Deiters, D. Groff, Y. Ryu, J. Xie and P. G. Schultz, *Angew. Chem., Int. Ed.*, 2006, **45**, 2728–2731.

67 V. du Vigneaud, L. F. Audrieth and H. S. Loring, *J. Am. Chem. Soc.*, 1930, **52**, 4500–4504.

68 D. Andreu, F. Albericio, N. A. Solé, M. C. Munson and G. Barany, in *Methods in Molecular Biology, Peptide Synthesis Protocols*, ed. M. W. Pennington and B. M. Dunn, Human Press Inc., Totowa, NJ, 1994, vol. 35, pp. 91–169.

69 H. Yajima, N. Fujii, S. Funakoshi, T. Watanabe, E. Murayama and A. Otaka, *Tetrahedron*, 1988, **44**, 805–819.

70 L. Zervas and I. Photaki, *J. Am. Chem. Soc.*, 1962, **84**, 3887–3897.

71 K. Barlos, D. Gatos, O. Hatzi, N. Koch and S. Koutsogianni, *Int. J. Pept. Protein Res.*, 1996, **47**, 148–153.

72 K. Akaji, K. Fujino, T. Tatsumi and Y. Kiso, *J. Am. Chem. Soc.*, 1993, **115**, 11384–11392.

73 D. Kobayashi, N. Naruse, M. Denda, A. Shigenaga and A. Otaka, *Org. Biomol. Chem.*, 2020, **18**, 8638–8645.

74 M. Mochizuki, S. Tsuda, K. Tanimura and Y. Nishiuchi, *Org. Lett.*, 2015, **17**, 2202–2205.

75 M. Góngora-Benítez, L. Mendive-Tapia, I. Ramos-Tomillero, A. C. Breman, J. Tulla-Puche and F. Albericio, *Org. Lett.*, 2012, **14**, 5472–5475.

76 G. F. Holland and L. A. Cohen, *J. Am. Chem. Soc.*, 1958, **80**, 3765–3769.

77 I. Ramos-Tomillero, H. Rodriguez and F. Albericio, *Org. Lett.*, 2015, **17**, 1680–1683.

78 J. J. Pastuszak and A. Chimiak, *J. Org. Chem.*, 1981, **46**, 1868–1873.

79 S. Sakakibara, Y. Shimonishi, Y. Kishida, M. Okada and H. Sugihara, *Bull. Chem. Soc. Jpn.*, 1967, **40**, 2164–2167.

80 A. L. Schroll, R. J. Hondal and S. Flemer, *J. Pept. Sci.*, 2012, **18**, 1–9.

81 O. Nishimura, C. Kitada and M. Fujino, *Chem. Pharm. Bull.*, 1978, **26**, 1576–1585.

82 K. Akaji, T. Tatsumi, M. Yoshida, T. Kimura, Y. Fujiwara and Y. Kiso, *J. Chem. Soc., Chem. Commun.*, 1991, 167–168.

83 N. Fujii, A. Otaka, S. Funakoshi, K. Bessho, T. Watanabe, K. Akaji and H. Yajima, *Chem. Pharm. Bull.*, 1987, **35**, 2339–2347.

84 F. Wu, J. P. Mayer, V. M. Gelfanov, F. Liu and R. D. Dimarchi, *J. Org. Chem.*, 2017, **82**, 3506–3512.

85 M. Jbara, S. Laps, M. Morgan, G. Kamnesky, G. Mann, C. Wolberger and A. Brik, *Nat. Commun.*, 2018, **9**, 3154.

86 E. J. Ste Marie and R. J. Hondal, *J. Pept. Sci.*, 2018, **24**, e3130.

87 N. Fujii, A. Otaka, T. Watanabe, A. Okamachi, H. Tamamura, H. Yajima, Y. Inagaki, M. Nomizu and K. Asano, *J. Chem. Soc., Chem. Commun.*, 1989, 283.

88 A. Cuthbertson and B. Indrevoll, *Org. Lett.*, 2003, **5**, 2955–2957.



89 S. Akabori, S. Sakakibara, Y. Shimonishi and Y. Nobuhara, *Bull. Chem. Soc. Jpn.*, 1964, **37**, 433–434.

90 K. M. Harris, S. Flemer and R. J. Hondal, *J. Pept. Sci.*, 2007, **13**, 81–93.

91 B. W. Erickson and R. B. Merrifield, *J. Am. Chem. Soc.*, 1973, **95**, 3750–3756.

92 D. Yamashiro, R. L. Noble and C. H. Li, *J. Org. Chem.*, 1973, **38**, 3561–3565.

93 N. Fujii, A. Otaka, S. Funakoshi, H. Yajima, O. Nishimura and M. Fujino, *Chem. Pharm. Bull.*, 1986, **34**, 869–872.

94 A. Otaka, H. Morimoto, N. Fujii, T. Koide, S. Funakoshi and H. Yajima, *Chem. Pharm. Bull.*, 1989, **37**, 526–528.

95 M. C. Munson, C. Garcia-Echeverria, F. Albericio and G. Barany, *J. Org. Chem.*, 1992, **57**, 3013–3018.

96 M. C. Munson, C. Garcia-Echeverria, F. Albericio and G. Barany, in *Peptides Chemistry and Biology (Proceedings of the Twelfth American Peptide Symposium)*, ed. J. A. Smith and J. E. Rivier, Leiden, 1992, pp. 605–606.

97 T. Wöhr, F. Wahl, A. Nefzi, B. Rohwedder, T. Sato, X. Sun and M. Mutter, *J. Am. Chem. Soc.*, 1996, **118**, 9218–9227.

98 M. S. Y. Wong and K. A. Jolliffe, *Aust. J. Chem.*, 2010, **63**, 797–801.

99 T. M. Postma and F. Albericio, *Org. Lett.*, 2014, **16**, 1772–1775.

100 S. Tsuda, S. Masuda and T. Yoshiya, *J. Org. Chem.*, 2020, **85**, 1674–1679.

101 M. Pelay-Gimeno, A. Meli, J. Tulla-Puche and F. Albericio, *J. Med. Chem.*, 2013, **56**, 9780–9788.

102 Y. Han and G. Barany, *J. Org. Chem.*, 1997, **62**, 3841–3848.

103 O. Garcia, J. M. Bofill, E. Nicolas and F. Albericio, *Eur. J. Org. Chem.*, 2010, 3631–3640.

104 H. Hibino and Y. Nishiuchi, *Org. Lett.*, 2012, **14**, 1926–1929.

105 I. Ramos-Tomillero, L. Mendive-Tapia, M. Góngora-Benítez, E. Nicolás, J. Tulla-Puche and F. Albericio, *Molecules*, 2013, **18**, 5155–5162.

106 H. Hibino, Y. Miki and Y. Nishiuchi, *J. Pept. Sci.*, 2014, **20**, 30–35.

107 Y.-K. Qi, S. Tang, Y.-C. Huang, M. Pan, J.-S. Zheng and L. Liu, *Org. Biomol. Chem.*, 2016, **14**, 4194–4198.

108 D. F. Veber, J. D. Milkowski, R. G. Denkewalter and R. Hirschmann, *Tetrahedron Lett.*, 1968, **9**, 3057–3058.

109 S. Laps, H. Sun, G. Kamnesky and A. Brik, *Angew. Chem., Int. Ed.*, 2019, **58**, 5729–5733.

110 D. F. Veber, J. D. Milkowski, S. L. Varga, R. G. Denkewalter and R. Hirschmann, *J. Am. Chem. Soc.*, 1972, **94**, 5456–5461.

111 M. Muttenthaler, Y. G. Ramos, D. Feytens, A. D. de Araujo and P. F. Alewood, *Biopolymers*, 2010, **94**, 423–432.

112 S. K. Maity, M. Jbara, S. Laps and A. Brik, *Angew. Chem., Int. Ed.*, 2016, **55**, 8108–8112.

113 N. Kamo, G. Hayashi and A. Okamoto, *Org. Lett.*, 2019, **21**, 8378–8382.

114 M. R. Levengood, X. Zhang, J. H. Hunter, K. K. Emmerton, J. B. Miyamoto, T. S. Lewis and P. D. Senter, *Angew. Chem., Int. Ed.*, 2017, **56**, 733–737.

115 J. Pless, *Helv. Chim. Acta*, 1976, **59**, 499–512.

116 P. K. Chakravarty and R. K. Olsen, *J. Org. Chem.*, 1978, **43**, 1270–1271.

117 Y. Kiso, M. Yoshida, Y. Fujiwara, T. Koimura, M. Shimokura and K. Akaji, *Chem. Pharm. Bull.*, 1990, **38**, 673–675.

118 M. Ueki and K. Shinozaki, *Bull. Chem. Soc. Jpn.*, 1983, **56**, 1187–1191.

119 M. Ueki, T. Ikeo, K. Hokari, K. Nakamura, A. Saeki and H. Komatsu, *Bull. Chem. Soc. Jpn.*, 1999, **72**, 829–838.

120 Y. Kiso, M. Yoshida, T. Kimura, Y. Fujiwara and M. Shimokura, *Tetrahedron Lett.*, 1989, **30**, 1979–1982.

121 M. Yoshida, T. Tatsumi, Y. Fujiwara, S. Iinuma, T. Kimura, K. Akaji and Y. Kiso, *Chem. Pharm. Bull.*, 1990, **38**, 1551–1557.

122 M. Bodanszky and M. A. Bednarek, *Int. J. Pept. Protein Res.*, 1982, **20**, 434–437.

123 M. Ruiz-Gayo, F. Albericio, E. Pedroso and E. Giralt, *J. Chem. Soc., Chem. Commun.*, 1986, 1501.

124 M. Royo, C. García-Echeverría, E. Giralt, R. Eritja and F. Albericio, *Tetrahedron Lett.*, 1992, **33**, 2391–2394.

125 C. W. West, M. A. Estiarte and D. H. Rich, *Org. Lett.*, 2001, **3**, 1205–1208.

126 M. Royo, J. Alsina, E. Giralt, U. Slomczynska and F. Albericio, *J. Chem. Soc., Perkin Trans. 1*, 1995, 1095–1102.

127 M. Góngora-Benítez, A. Basso, T. Bruckdorfer, M. Royo, J. Tulla-Puche and F. Albericio, *Chem. – Eur. J.*, 2012, **18**, 16166–16176.

128 F. Shen, Z. P. Zhang, J. Bin Li, Y. Lin and L. Liu, *Org. Lett.*, 2011, **13**, 568–571.

129 A. Loffet and H. X. Zhang, *Int. J. Pept. Protein Res.*, 1993, **42**, 346–351.

130 A. M. Kimbonguila, A. Merzouk, F. Guibé and A. Loffet, *Tetrahedron Lett.*, 1994, **35**, 9035–9038.

131 T. D. Kondasinghe, H. Y. Saraha, S. B. Odeesho and J. L. Stockdill, *Org. Biomol. Chem.*, 2017, **15**, 2914–2918.

132 P. Gomez-Martinez, A. Malanda Kimbonguila and F. Guibé, *Tetrahedron*, 1999, **55**, 6945–6960.

133 P. Gomez-Martinez, F. Guibé and F. Albericio, *Lett. Pept. Sci.*, 2000, **7**, 187–194.

134 M. P. Exner, T. Kuenzl, T. M. T. To, Z. Ouyang, S. Schwagerus, M. G. Hoesl, C. P. R. Hackenberger, M. C. Lensen, S. Panke and N. Budisa, *ChemBioChem*, 2017, **18**, 85–90.

135 J. Liu, R. Cheng, H. Wu, S. Li, P. G. Wang, W. F. DeGrado, S. Rozovsky and L. Wang, *Angew. Chem., Int. Ed.*, 2018, **57**, 12702–12706.

136 G. B. Vamisetti, G. Satish, P. Sulkshane, G. Mann, M. H. Glickman and A. Brik, *J. Am. Chem. Soc.*, 2020, **142**, 19558–19569.

137 S. Rather and H. T. Clarke, *J. Am. Chem. Soc.*, 1937, **59**, 200–206.

138 M. Jbara, S. K. Maity, M. Seenaiah and A. Brik, *J. Am. Chem. Soc.*, 2016, **138**, 5069–5075.

139 N. Naruse, D. Kobayashi, K. Ohkawachi, A. Shigenaga and A. Otaka, *J. Org. Chem.*, 2020, **85**, 1425–1433.

140 H. Katayama and S. Morisue, *Tetrahedron*, 2017, **73**, 3541–3547.

141 C. T. Pool, J. G. Boyd and J. P. Tam, *J. Pept. Res.*, 2004, **63**, 223–234.

142 J. A. Karas, D. B. Scanlon, B. E. Forbes, I. Vetter, R. J. Lewis, J. Gardiner, F. Separovic, J. D. Wade and M. A. Hossain, *Chem. – Eur. J.*, 2014, **20**, 9549–9552.

143 A. B. Smith, S. N. Savinov, U. V. Manjappara and I. M. Chaiken, *Org. Lett.*, 2002, **4**, 4041–4044.



144 N. Kotzur, B. Briand, M. Beyermann and V. Hagen, *J. Am. Chem. Soc.*, 2009, **131**, 16927–16931.

145 M. M. Mahmoodi, D. Abate-Pella, T. J. Pundsack, C. C. Palsuledesai, P. C. Goff, D. A. Blank and M. D. Distefano, *J. Am. Chem. Soc.*, 2016, **138**, 5848–5859.

146 M. M. Mahmoodi, S. A. Fisher, R. Y. Tam, P. C. Goff, R. B. Anderson, J. E. Wissinger, D. A. Blank, M. S. Shoichet and M. D. Distefano, *Org. Biomol. Chem.*, 2016, **14**, 8289–8300.

147 T. K. Bader, F. Xu, M. H. Hodny, D. A. Blank and M. D. Distefano, *J. Org. Chem.*, 2020, **85**, 1614–1625.

148 S. B. Gunnoo, A. Iyer, W. Vannecke, K. W. Decoene, T. Hebbrecht, J. Gettemans, M. Laga, S. Loverix, I. Lasters and A. Madder, *Chem. Commun.*, 2018, **54**, 11929–11932.

149 A. L. Schroll and G. Barany, *J. Org. Chem.*, 1989, **54**, 244–247.

150 W. Chan and P. White, *Fmoc Solid Phase Peptide Synthesis: A Practical Approach*, Oxford University Press, Oxford, 2000, p. 87.

151 A. Gosden, D. Stevenson and G. T. Young, *J. Chem. Soc., Chem. Commun.*, 1972, 1123.

152 R. B. Merrifield, *The Chemistry of Polypeptides*, Springer US, Boston, MA, 1973.

153 I. Maugras, J. Gosteli, E. Rapp and R. Nyfeler, *Int. J. Pept. Protein Res.*, 1995, **45**, 152–156.

154 C. Rentier, K. Fukumoto, A. Taguchi and Y. Hayashi, *J. Pept. Sci.*, 2017, **23**, 496–504.

155 R. Matsueda, T. Kimura, E. T. Kaiser and G. R. Matsueda, *Chem. Lett.*, 1981, 737–740.

156 R. J. Ridge, G. R. Matsueda, E. Haber and R. Matsueda, *Int. J. Pept. Protein Res.*, 1982, **19**, 490–498.

157 F. Albericio, D. Andreu, E. Giralt, C. Navalpotro, E. Pedroso, B. Ponsati and M. Rue-Gayo, *Int. J. Pept. Protein Res.*, 1989, **34**, 124–128.

158 F. Rabanal, W. F. DeGrado and P. L. Dutton, *Tetrahedron Lett.*, 1996, **37**, 1347–1350.

159 R. Eritja, J. P. Ziehler-Martin, P. A. Walker, T. D. Lee, K. Legesse, F. Albericio and B. E. Kaplan, *Tetrahedron*, 1987, **43**, 2675–2680.

160 H. Katayama, Y. Nakahara and H. Hojo, *Org. Biomol. Chem.*, 2011, **9**, 4653.

161 H. Katayama and H. Hojo, *Org. Biomol. Chem.*, 2013, **11**, 4405–4413.

162 M. Matveenko, S. Hackl and C. F. W. Becker, *ChemistryOpen*, 2018, **7**, 106–110.

163 T. M. Postma, M. Giraud and F. Albericio, *Org. Lett.*, 2012, **14**, 5468–5471.

164 S. N. Mthembu, A. Sharma, F. Albericio and B. G. de la Torre, *Org. Lett.*, 2019, **21**, 10111–10114.

165 A. Chakraborty, A. Sharma, F. Albericio and B. G. de la Torre, *Org. Lett.*, 2020, **22**, 9644–9647.

166 Z. Dekan, M. Mobli, M. W. Pennington, E. Fung, E. Nemeth and P. F. Alewood, *Angew. Chem., Int. Ed.*, 2014, **53**, 2931–2934.

167 R. Deslauriers, R. Walter and I. C. P. Smith, *Biochem. Biophys. Res. Commun.*, 1972, **48**, 854–859.

168 G. Flouret, W. Brieher, K. Mahan and L. Wilson, *J. Med. Chem.*, 1991, **34**, 642–646.

169 B. Banerji, M. Chatterjee, C. Prodhan and K. Chaudhuri, *RSC Adv.*, 2016, **6**, 112667–112676.

170 M. Amblard, J.-A. Fehrentz, J. Martinez and G. Subra, *Mol. Biotechnol.*, 2006, **33**, 239–254.

171 B. Kamber, A. Hartmann, K. Eisler, B. Riniker, H. Rink, P. Sieber and W. Rittel, *Helv. Chim. Acta*, 1980, **63**, 899–915.

172 D. A. Pearson, M. Blanchette, M. Lou Baker and C. A. Guindon, *Tetrahedron Lett.*, 1989, **30**, 2739–2742.

173 E. E. Büllsbach and C. Schwabe, *J. Biol. Chem.*, 1991, **266**, 10754–10761.

174 J. Ying, X. Gu, M. Cai, M. Dedek, J. Vagner, D. B. Trivedi and V. J. Hruby, *J. Med. Chem.*, 2006, **49**, 6888–6896.

175 C. Fagundez, D. Sellanes and G. Serra, *ACS Comb. Sci.*, 2018, **20**, 212–219.

176 G. P. Schwartz and P. G. Katsoyannis, *J. Chem. Soc., Perkin Trans.*, 1973, **1**, 2894.

177 R. G. Hiskey and J. B. Adams, *J. Org. Chem.*, 1966, **31**, 2178–2183.

178 S. A. Khan and K. M. Sivanandaiah, *Int. J. Pept. Protein Res.*, 1978, **12**, 164–169.

179 A. Sharma, I. Ramos-Tomillero, A. El-Faham, E. Nicolas, H. Rodriguez, B. G. de la Torre and F. Albericio, *Chemistry-Open*, 2017, **6**, 168–177.

180 A. Chimiak, in *Proceedings of 5th European Peptide Symposium*, 1962, p. 37.

181 X. Zhang, Y. Yang, M. Zhao, L. Liu, M. Zheng, Y. Wang, J. Wu and S. Peng, *Eur. J. Med. Chem.*, 2011, **46**, 3410–3419.

182 N. Zheng, P. Karra, M. A. Vandenberg, J. H. Kim, M. J. Webber, W. L. Holland and D. H. C. Chou, *J. Med. Chem.*, 2019, **62**, 11437–11443.

183 J. Tytgat, K. G. Chandy, M. L. Garcia, G. A. Gutman, M.-F. Martin-Eauclaire, J. J. van der Walt and L. D. Possani, *Trends Pharmacol. Sci.*, 1999, **20**, 444–447.

184 H. Juichi, R. Ando, T. Ishido, M. Miyashita, Y. Nakagawa and H. Miyagawa, *J. Pept. Sci.*, 2018, **24**, e3133.

185 H. Yajima, S. Funakoshi, N. Fujii, K. Akaji and H. Irie, *Chem. Pharm. Bull.*, 1979, **27**, 1060–1061.

186 A. R. Urmey and N. J. Zondlo, *Pept. Sci.*, 2020, **112**, e24137.

187 N. Fujii, A. Otaka, T. Watanabe, H. Arai, S. Funakoshi, K. Bessho and H. Yajima, *J. Chem. Soc., Chem. Commun.*, 1987, 1676–1678.

188 F. Wu, J. P. Mayer, A. N. Zaykov, F. Zhang, F. Liu and R. D. DiMarchi, *Chem. – Eur. J.*, 2016, **22**, 9777–9783.

189 N. Fujii, A. Otaka, S. Funakoshi, T. Watanabe, H. Arai, K. Bessho and H. Yajima, *J. Protein Chem.*, 1988, **7**, 151–156.

190 N. Fujii, T. Watanabe, T. Aotake, A. Otaka, I. Yamamoto, J. Konishe and H. Yajima, *Chem. Pharm. Bull.*, 1988, **36**, 3304–3311.

191 V. J. Hruby, D. A. Upson and N. S. Agarwal, *J. Org. Chem.*, 1977, **42**, 3552–3556.

192 J. J. Knittel, T. K. Sawyer, V. J. Hruby and M. E. Hadley, *J. Med. Chem.*, 1983, **26**, 125–129.

193 S. Tsuda, T. Yoshiya, M. Mochizuki and Y. Nishiuchi, *Org. Lett.*, 2015, **17**, 1806–1809.

194 N. Fujii, H. Yajima, A. Otaka, S. Funakoshi, M. Nomizu, K. Akaji, I. Yamamoto, K. Torizuka, K. Kitagawa, T. Akita, K. Ando, T. Kawamoto, Y. Shimonishi and T. Takao, *J. Chem. Soc., Chem. Commun.*, 1985, 602–603.



195 S. Futaki, M. Aoki, T. Ishikawa, F. Kondo, T. Asahara, M. Niwa, Y. Nakaya, T. Yagami and K. Kitagawa, *Bioorg. Med. Chem.*, 1999, **7**, 187–192.

196 T. Brown, J. H. Jones and J. D. Richards, *J. Chem. Soc., Perkin Trans. 1*, 1982, 1553–1561.

197 T. Haack and M. Mutter, *Tetrahedron Lett.*, 1992, **33**, 1589–1592.

198 A. Krežel, J. Wójcik, M. Maciejczyk and W. Bal, *Inorg. Chem.*, 2011, **50**, 72–85.

199 A. Krežel and W. Bal, *Org. Biomol. Chem.*, 2003, **1**, 3885–3890.

200 V. Martos, P. Castreño, M. Royo, F. Albericio and J. de Mendoza, *J. Comb. Chem.*, 2009, **11**, 410–421.

201 J. D. Smith, L. N. Cardwell, D. Porciani, A. Nolla, B. T. Cornelison, M. C. Schulte, F. Gallazzi, D. H. Burke, M. A. Daniels and B. D. Ulery, *Mol. Syst. Des. Eng.*, 2020, **5**, 269–283.

202 A. Aletras, K. Barlos, D. Gatos, S. Koutsogianni and P. Mamos, *Int. J. Pept. Protein Res.*, 1995, **45**, 488–496.

203 A. S. Galanis, F. Albericio and M. Grøtli, *Pept. Sci.*, 2009, **92**, 23–34.

204 A. Graziadio, M. Zanda, S. Frau, I. N. Fleming, M. Musolino, S. Dall'Angelo, M. Baldassarre and M. Piras, *Bioconjugate Chem.*, 2016, **27**, 1332–1340.

205 T. D. Kondasinghe, H. Y. Saraha, S. T. Jackowski and J. L. Stockdill, *Tetrahedron Lett.*, 2019, **60**, 23–28.

206 D.-L. Huang, C. Montigny, Y. Zheng, V. Beswick, Y. Li, X.-X. Cao, T. Barbot, C. Jaxel, J. Liang, M. Xue, C.-L. Tian, N. Jamin and J.-S. Zheng, *Angew. Chem., Int. Ed.*, 2020, **59**, 5178–5184.

207 D.-L. Huang, Y. Li, J. Liang, L. Yu, M. Xue, X.-X. Cao, B. Xiao, C.-L. Tian, L. Liu and J.-S. Zheng, *J. Am. Chem. Soc.*, 2020, **142**, 8790–8799.

208 J. Halstrøm, K. Brunfeldt and K. Kovács, *Acta Chem. Scand.*, 1979, **33b**, 685–689.

209 J. Tulla-Puche and G. Barany, *J. Org. Chem.*, 2004, **69**, 4101–4107.

210 S. Liu, B. L. Pentelute and S. B. H. Kent, *Angew. Chem., Int. Ed.*, 2012, **51**, 993–999.

211 H. Lamthanh, C. Roumestand, C. Deprun and A. Ménez, *Int. J. Pept. Protein Res.*, 1993, **41**, 85–95.

212 M. A. Y. Engebretsen, E. Agner, J. Sandosham and P. M. Fischer, *J. Pept. Res.*, 1997, **49**, 341–346.

213 Y. Wang, L. Han, N. Yuan, H. Wang, H. Li, J. Liu, H. Chen, Q. Zhang and S. Dong, *Chem. Sci.*, 2018, **9**, 1940–1946.

214 H. Chen, Y. Xiao, N. Yuan, J. Weng, P. Gao, L. Breindel, A. Shekhtman and Q. Zhang, *Chem. Sci.*, 2018, **9**, 1982–1988.

215 S. Laps, F. Atamleh, G. Kamnesky, H. Sun and A. Brik, *Nat. Commun.*, 2021, **12**, 870.

216 N. Fujii, A. Otaka, S. Funakoshi, K. Bessho and H. Yajima, *J. Chem. Soc., Chem. Commun.*, 1987, 163–164.

217 M. Noda and M. Kiffe, *J. Pept. Res.*, 1997, **50**, 329–335.

218 A. K. Ivanov, E. É. Grigor'eva, A. A. Antonov and I. A. Donetskii, *Chem. Nat. Compd.*, 1993, **29**, 97–103.

219 M. Ueki, T. Inazu and S. Ikeda, *Bull. Chem. Soc. Jpn.*, 1979, **52**, 2424–2427.

220 K. Akaji, T. Tatsumi, M. Yoshida, T. Kimura, Y. Fujiwara and Y. Kiso, *J. Am. Chem. Soc.*, 1992, **114**, 4137–4143.

221 G. Greiner and P. Hermann, in *Peptides 1990, Proceedings of the Twenty-First European Peptide Symposium*, ed. E. Giralt and D. Andreu, ESCOM Science Publishers B.V., Leiden, 1991, pp. 227–278.

222 S. K. Maity, G. Mann, M. Jbara, S. Laps, G. Kamnesky and A. Brik, *Org. Lett.*, 2016, **18**, 3026–3029.

223 F. Liu, Q. Liu and A. R. Mezo, *Org. Lett.*, 2014, **16**, 3126–3129.

224 X. Yang, V. Gelfanov, F. Liu and R. DiMarchi, *Org. Lett.*, 2016, **18**, 5516–5519.

225 O. Dangles, F. Guibe, G. Balavoine, S. Lavielle and A. Marquet, *J. Org. Chem.*, 1987, **52**, 4984–4993.

226 F. Guibé, *Tetrahedron*, 1998, **54**, 2967–3042.

227 A. Malanda Kimbonguila, A. Merzouk, F. Guibé and A. Loffet, *Tetrahedron*, 1999, **55**, 6931–6944.

228 J. Borlinghaus, F. Albrecht, M. C. H. Gruhlke, I. D. Nwachukwu and A. J. Slusarenko, *Molecules*, 2014, **19**, 12591–12618.

229 N. D. J. Yates, M. A. Fascione and A. Parkin, *Chem. – Eur. J.*, 2018, **24**, 12164–12182.

230 J. M. J. M. Ravasco, H. Faustino, A. Trindade and P. M. P. Gois, *Chem. – Eur. J.*, 2019, **25**, 43–59.

231 K. Renault, J. W. Fredy, P.-Y. Renard and C. Sabot, *Bioconjugate Chem.*, 2018, **29**, 2497–2513.

232 H. P. Hemantha, S. N. Bavikar, Y. Herman-Bachinsky, N. Haj-Yahya, S. Bondalapati, A. Ciechanover and A. Brik, *J. Am. Chem. Soc.*, 2014, **136**, 2665–2673.

233 M. Seenaiah, M. Jbara, S. M. Mali and A. Brik, *Angew. Chem., Int. Ed.*, 2015, **54**, 12374–12378.

234 V. Y. Torbeev and S. B. H. Kent, *Angew. Chem., Int. Ed.*, 2007, **46**, 1667–1670.

235 M. Jbara, S. K. Maity and A. Brik, *Angew. Chem., Int. Ed.*, 2017, **56**, 10644–10655.

236 G. Mann, G. Satish, R. Meledin, G. B. Vamisetti and A. Brik, *Angew. Chem., Int. Ed.*, 2019, **58**, 13540–13549.

237 R. L. Brabham, R. J. Spears, J. Walton, S. Tyagi, E. A. Lemke and M. A. Fascione, *Chem. Commun.*, 2018, **54**, 1501–1504.

238 X. Bi, K. K. Pasunooti, J. Lescar and C.-F. Liu, *Bioconjugate Chem.*, 2017, **28**, 325–329.

239 R. J. Spears, R. L. Brabham, D. Budhadev, T. Keenan, S. McKenna, J. Walton, J. A. Brannigan, A. M. Brzozowski, A. J. Wilkinson, M. Plevin and M. A. Fascione, *Chem. Sci.*, 2018, **9**, 5585–5593.

240 K. Ohkawachi, D. Kobayashi, K. Morimoto, A. Shigenaga, M. Denda, K. Yamatsugu, M. Kanai and A. Otaka, *Org. Lett.*, 2020, **22**, 5289–5293.

241 H. Katayama and K. Nagata, *J. Pept. Sci.*, 2021, **27**, e3290.

242 G. Prota and E. Ponsiglione, *Tetrahedron*, 1973, **29**, 4271–4274.

243 G. J. Hoogerheide, in *Peptides 1980 (Proceedings of the sixteenth European peptide symposium)*, ed. K. Brunfeldt, Copenhagen, 1981.

244 J. O. Campeciño, L. W. Dudycz, D. Tumelty, V. Berg, D. E. Cabelli and M. J. Maroney, *J. Am. Chem. Soc.*, 2015, **137**, 9044–9052.

245 D. P. Nguyen, M. Mahesh, S. J. Elsässer, S. M. Hancock, C. Uttamapinant and J. W. Chin, *J. Am. Chem. Soc.*, 2014, **136**, 2240–2243.

246 N. Wu, A. Deiters, T. A. Cropp, D. King and P. G. Schultz, *J. Am. Chem. Soc.*, 2004, **126**, 14306–14307.



247 K. D. Philipson, J. P. Gallivan, G. S. Brandt, D. A. Dougherty and H. A. Lester, *Am. J. Physiol. – Cell Physiol.*, 2001, **281**, C195–C206.

248 G. Marriott and M. Heidecker, *Biochemistry*, 1996, **35**, 3170–3174.

249 A. G. Russell, M.-E. Ragoussi, R. Ramalho, C. W. Wharton, D. Carteau, D. M. Bassani and J. S. Snaith, *J. Org. Chem.*, 2010, **75**, 4648–4651.

250 S. P. Fodor, J. L. Read, M. C. Pirrung, L. Stryer, A. T. Lu and D. Solas, *Science*, 1991, **251**, LP767–LP773.

251 A. Patchornik, B. Amit and R. B. Woodward, *J. Am. Chem. Soc.*, 1970, **92**, 6333–6335.

252 R. Miyajima, Y. Tsuda, T. Inokuma, A. Shigenaga, M. Imanishi, S. Futaki and A. Otaka, *Biopolymers*, 2016, 531–546.

253 R. Rakauskaitė, G. Urbanavičiūtė, A. Rukšėnaitė, Z. Liutkevičiūtė, R. Juškėnas, V. Masevičius and S. Klimašauskas, *Chem. Commun.*, 2015, **51**, 8245–8248.

254 J. Pan and K. S. Carroll, *Org. Lett.*, 2015, **17**, 6014–6017.

255 J. H. Wosnick and M. S. Shoichet, *Chem. Mater.*, 2008, **20**, 55–60.

256 C. Berse, R. Boucher and L. Piché, *J. Org. Chem.*, 1957, **22**, 805–808.

257 M. D. Bachi and K. J. Ross-Petersen, *J. Org. Chem.*, 1972, **37**, 3550–3551.

258 S. J. Brois, J. F. Pilot and H. W. Barnum, *J. Am. Chem. Soc.*, 1970, **92**, 7629–7631.

259 L. Chen, I. Zoulíková, J. Slaninová and G. Barany, *J. Med. Chem.*, 1997, **40**, 864–876.

260 S. J. Mear and T. F. Jamison, *J. Org. Chem.*, 2019, **84**, 15001–15007.

261 R. Matsueda and K. Aiba, *Chem. Lett.*, 1978, 951–952.

262 A. Taguchi, K. Fukumoto, Y. Asahina, A. Kajiyama, S. Shimura, K. Hamada, K. Takayama, F. Yakushiji, H. Hojo and Y. Hayashi, *Org. Biomol. Chem.*, 2015, **13**, 3186–3189.

263 Y. Cui, A. Taguchi, K. Kobayashi, H. Shida, K. Takayama, A. Taniguchi and Y. Hayashi, *Org. Biomol. Chem.*, 2020, **18**, 7094–7097.

264 E. J. Ste Marie, E. L. Ruggles and R. J. Hondal, *J. Pept. Sci.*, 2016, **22**, 571–576.

265 U. Weber and P. Hartter, *Hoppe. Seylers. Z. Physiol. Chem.*, 1970, **351**, 1384–1388.

266 P. S. Herradura, K. A. Pendola and R. K. Guy, *Org. Lett.*, 2000, **2**, 2019–2022.

267 S. S. More and R. Vince, *Bioorg. Med. Chem. Lett.*, 2006, **16**, 6039–6042.

268 L. Moroder, M. Gemeiner, W. Goehring, E. Jaeger, P. Thamm and E. Wünsch, *Biopolymers*, 1981, **20**, 17–37.

269 S. Wang, D. Gao, K. Li, S. Ye, Q. Liu, Y. Peng, G. Lv, L. Qiu and J. Lin, *Org. Biomol. Chem.*, 2020, **18**, 3512–3521.

270 B. Roubinet, A. Chevalier, P.-Y. Renard and A. Romieu, *Eur. J. Org. Chem.*, 2015, 166–182.

271 N. S. Khan, B. A. Riggle, G. K. Seward, Y. Bai and I. J. Dmochowski, *Bioconjugate Chem.*, 2015, **26**, 101–109.

272 C. Zhang, P. Dai, A. M. Spokoyny and B. L. Pentelute, *Org. Lett.*, 2014, **16**, 3652–3655.

273 J. A. Brailsford, J. L. Stockdill, A. J. Axelrod, M. T. Peterson, P. A. Vadola, E. V. Johnston and S. J. Danishefsky, *Tetrahedron*, 2018, **74**, 1951–1956.

274 B. J. Umlauf, K. A. Mix, V. A. Grosskopf, R. T. Raines and E. V. Shusta, *Bioconjugate Chem.*, 2018, **29**, 1605–1613.

275 X. Zhao, G. Lv, K. Li, Y. Peng, Q. Liu, L. Qiu and J. Lin, *Nucl. Med. Biol.*, 2020, **82–83**, 72–79.

276 M. Góngora-Benítez, J. Tulla-Puche, M. Paradís-Bas, O. Werbitzky, M. Giraud and F. Albericio, *Biopolymers*, 2011, **96**, 69–80.

277 G. Tang, T. Ji, A. F. Hu and Y. F. Zhao, *Synlett*, 2008, 1907–1909.

278 T. Kawakami, R. Yoshikawa, Y. Fujiyoshi, Y. Mishima, H. Hojo, S. Tajima and I. Suetake, *J. Biochem.*, 2015, **158**, 403–411.

279 P. Hartter, *Biol. Chem.*, 1976, **357**, 1683–1694.

280 T. M. Postma and F. Albericio, *Org. Lett.*, 2013, **15**, 616–619.

281 K. Krieger, B. Wängler, R. Schirrmacher and C. Wängler, *ChemMedChem*, 2020, **15**, 1652–1660.

282 M. Ruiz-Gayo, F. Albericio, M. Pons, M. Royo, E. Pedrosa and E. Giralt, *Tetrahedron Lett.*, 1988, **29**, 3845–3848.

283 H. Huang and R. I. Carey, *J. Pept. Res.*, 1998, **51**, 290–296.

284 R. A. D. Bathgate, F. Lin, N. F. Hanson, L. Otvos, A. Guidolin, C. Giannakis, S. Bastiras, S. L. Layfield, T. Ferraro, S. Ma, C. Zhao, A. L. Gundlach, C. S. Samuel, G. W. Tregear and J. D. Wade, *Biochemistry*, 2006, **45**, 1043–1053.

285 D. E. K. Kabotso, D. Smiley, J. P. Mayer, V. M. Gelfanov, D. Perez-Tilve, R. D. DiMarchi, N. L. B. Pohl and F. Liu, *J. Med. Chem.*, 2020, **63**, 6134–6143.

286 O. Al Musaimi, B. G. de la Torre and F. Albericio, *Green Chem.*, 2020, **22**, 996–1018.

