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N-to-C peptide elongation by ammonia-Ugi reaction: synthesis of potent self-assembling elastin-like short peptides

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The ammonia-Ugi reaction employing ammonium carboxylates of *N*-protected amino acids (or peptides), ketones, and α-isocyano esters enabled N-to-C peptide elongation, together with *in situ* construction of α,α-disubstituted amino acid residues. This method offered an effective synthetic method of novel elastin-like short peptides, which exhibited highly potent self-assembling properties.

Peptides possess considerable potential both as drug delivery vehicles and therapeutic agents against pharmacologically diverse and otherwise intractable biological targets.[1] Incorporation of unnatural α,α-disubstituted amino acid residues into peptides can significantly impact their metabolic resistance, hydrophobicity, membrane permeability, biological activity and selectivity, and immunogenicity, ultimately enhancing the druggability of peptide-based therapeutics.[2]

Peptide synthesis is typically performed *via* stepwise coupling of *N*-protected amino acids to a growing peptide chain anchored on a solid support using condensation agents.[3] Although such a solid-phase peptide synthesis (SPPS) works well with proteinogenic and other α-monosubstituted amino acids, it often results in poor yields with sterically hindered α,α-disubstituted amino acids, requiring excessive amounts of coupling agents under harsh conditions such as heating or microwave irradiation.[4] Moreover, preparation of *N*-protected α,α-disubstituted amino acids generally requires multi-step and tedious processes. Alternatively, highly reactive condensation agents[5] and catalytic reaction systems[6] have offered efficient methods for unnatural peptide synthesis; however, these still use expensive unnatural α,α-disubstituted amino acids as substrates. These synthetic challenges have long posed significant barriers to the discovery and development of bioactive peptides.

The ammonia-Ugi reaction, a variant of the Ugi reaction,[7,8] is a four-component coupling reaction that involves ammonia, an aldehyde or a ketone, a carboxylic acid, and an isocyanide, enabling a straightforward synthesis of peptides.[9] Although the ammonia-Ugi reaction had long been considered impractical and unsuccessful,[10] we recently reported an efficient synthetic protocol of unnatural dipeptides using the ammonia-Ugi reaction: by stirring ammonium carboxylates derived from *N*-protected amino acids **1**, ketones, and isocyanides in trifluoroethanol (TFE) at ambient temperature, a variety of dipeptides **2** were obtained in good yields (Scheme 1a).[11] Of note, these dipeptides **2** contained unnatural α,α-disubstituted amino acids, which were constructed *in situ* during the ammonia-Ugi reaction from readily available ketones as building blocks. Mechanistically, ammonium (NH_4^+) dissociates into NH_3 and H^+, which in turn facilitates the thermodynamically unfavourable *N*-unsubstituted imine formation (Scheme 1a).[12] With its success, however, the products **2** were obtained as amides at their C-termini, rendering them unsuitable for further N-to-C peptide elongation. To the best of our knowledge, neither the ammonia-Ugi reaction nor the Ugi reaction has ever been applied for N-to-C peptide chain elongation.[13,14] Here, this study proposes a novel strategy for N-to-C elongation of unnatural peptides by the ammonia-Ugi reaction employing α-isocyano ester **3** as an elongation unit (Scheme 1b). The expected ammonia-Ugi adducts **4** possess ester moieties at their C-termini, providing a versatile platform for subsequent peptide chain elongation.

Using a commercially available ethyl isocyanoacetate (**3**, CN-Gly-OEt), a series of unnatural tripeptides **4** were synthesized (Scheme 2). The key ammonium carboxylates of *N*-protected amino acids **1** were prepared by stirring *N*-protected amino acids with aqueous ammonia in acetonitrile or THF at 0 °C (Table S1).[11] Then, the ammonia-Ugi reaction using Boc-Phe-ONH_4, cyclopentanone, and CN-Gly-OEt (**3**) afforded the tripeptide Boc-Phe-Ac_5c-Gly-OEt (**4a**) in

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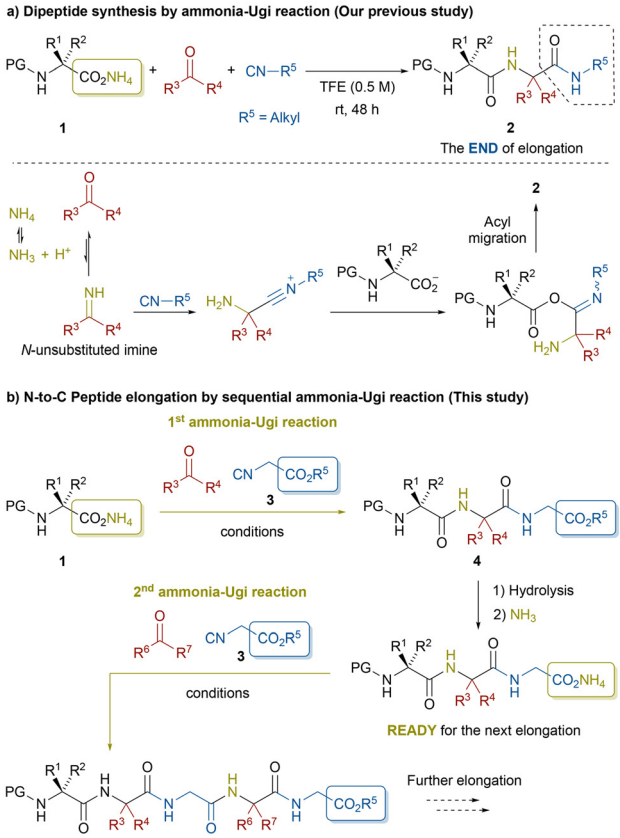
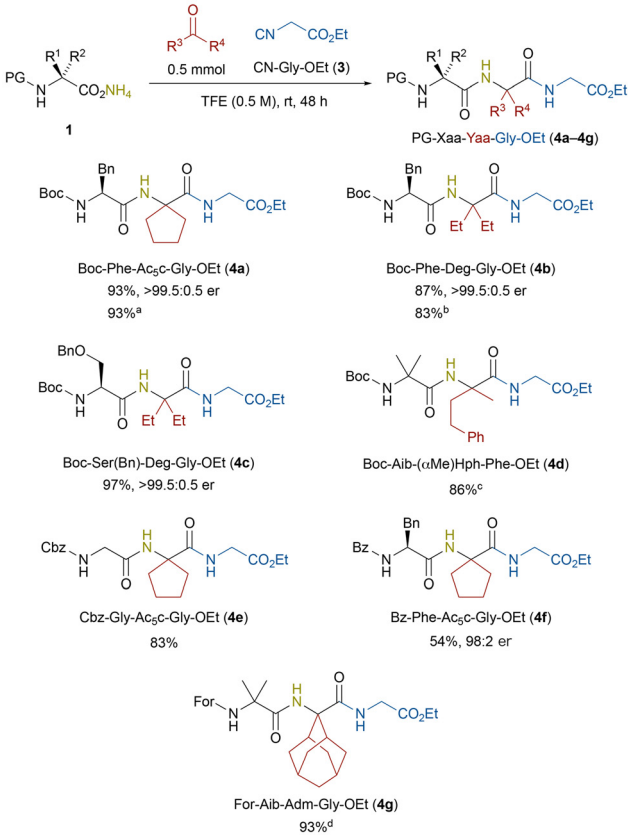


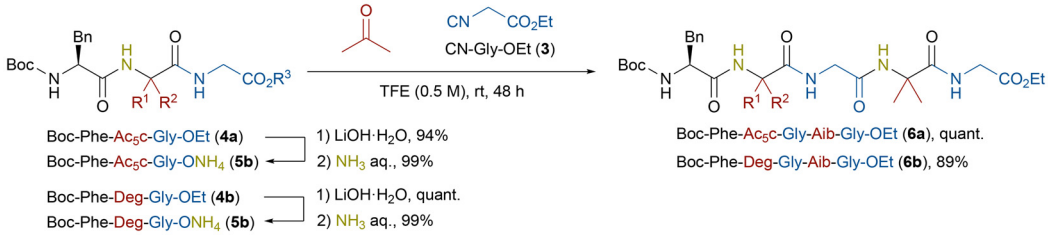
Scheme 1 (a) Dipeptide synthesis by ammonia-Ugi reaction, (b) N-to-C peptide elongation by sequential ammonia-Ugi reaction (this study).



Scheme 2 Synthesis of tripeptides **4a–4g** by ammonia-Ugi reaction using ammonium carboxylates of *N*-protected amino acids. [a] 5.4 mmol, [b] 3.5 mmol, [c] 1 mmol, [d] 4.5 mmol.

93% yield, with no detectable racemization of the chiral α-carbon of phenylalanine (>99.5 : 0.5 er). Herein, the unnatural 1-aminocyclopentane-1-carboxylic acid (Ac_5c) residue in **4a** was constructed *in situ* from cyclopentanone as a substrate. In general, diethylglycine (Deg) is a challenging substrate to be incorporated into peptides under conventional SPPS conditions because of the steric hindrance,[15] whereas the present ammonia-Ugi reaction successfully delivered Boc-Phe-Deg-Gly-OEt (**4b**) in 87% yield. Again, no racemization was observed during this process (>99.5 : 0.5 er). The chiral α-carbon of serine is known to be susceptible to racemization during peptide synthesis;[16] however, the present reaction conditions afforded **4c** in an excellent yield (97%) with a perfect stereochemical integrity (>99.5 : 0.5 er). Even the sterically demanding Boc-Aib was compatible with the present reaction conditions, affording the sterically congested tripeptide **4d**, composed of contiguous α,α-disubstituted amino acids {α-aminoisobutyric acid (Aib) and α-methylhomophenylalanine [(αMe)Hph]}, in 78% yield. In addition to Boc, various *N*-protecting groups, including Cbz, Bz, and formyl (For), were well tolerated, giving the tripeptides **4e**, **4f**, and **4g** in 83%–99% yields. Unfortunately, the stereochemical integrity of Bz-Phe was slightly lost (98 : 2 er), whereas that of Ac-Phe remained intact under the same conditions.[11] It is worth noting that the *N*-formyl group in **4g** can serve as a precursor of an isocyano group, potentially enabling inverse C-to-N peptide elongation.[14] Scale-up experiments (up to 5.4 mmol) proceeded smoothly without any detrimental effects on the reaction system, providing the corresponding products **4a**, **4b**, and **4g** in excellent yields (83%–93%). Overall, the ammonia-Ugi reaction using α-isocyano ester and *N*-protected amino acids enabled the efficient synthesis of unnatural tripeptides containing α,α-disubstituted amino acids. These tripeptides possess ester groups at their C-termini, offering a platform for subsequent N-to-C peptide chain elongation.

Peptides containing glycine are frequently found in biomaterials[17] such as elastin,[18] collagen,[19] and silk fibroin.[20] Owing to glycine's small size and conformational flexibility, it plays a crucial role in modulating peptide structure and function. The development of efficient synthetic strategies for unnatural analogues of glycine-rich peptides is therefore of significant interest in both synthetic and biomedical research. In this study, we developed an efficient N-to-C peptide elongation method for synthesizing glycine-containing unnatural peptides by the ammonia-Ugi reaction employing CN-Gly-OEt (**3**) (Scheme 3). The C-terminal ester moieties of tripeptides **4a** and **4b** were hydrolyzed under basic conditions and subsequently treated with aqueous ammonia to give the corresponding ammonium carboxylates **5a** and **5b** in excellent yields. Under the present



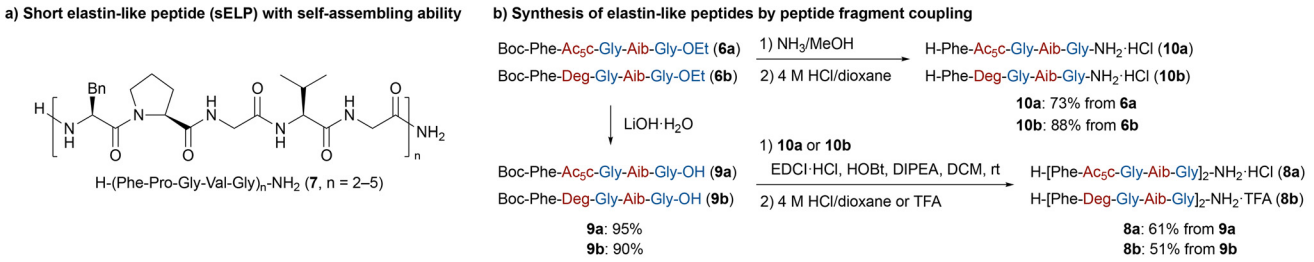
Scheme 3 Synthesis of pentapeptides **6a** and **6b** by ammonia-Ugi reaction starting from ammonium carboxylates of *N*-protected tripeptides **4a** and **4b**.

ammonia-Ugi reaction conditions, both tripeptides were successfully elongated into the pentapeptides Boc-Phe-Xaa-Gly-Aib-Gly-OEt **6a** and **6b** in good yields, together with *in situ* construction of Aib residue from acetone. The resulting peptides again possess ester moieties at C-termini, potentially providing a versatile platform for further N-to-C elongation or other chemical modifications. Totally, starting from *N*-protected amino acids **1**, the first ammonia-Ugi reaction furnished tripeptides **4** (Scheme 2), and the second ammonia-Ugi reaction extended them to pentapeptides **6** (Scheme 3). Each step elongated peptides by two amino acid residues at a time while constructing α,α-disubstituted amino acids *in situ*. This streamlined approach requires no condensation agents, thus providing an environmentally friendly synthetic method of glycine-containing unnatural peptides.

The obtained pentapeptides **6a** and **6b** share the repeating amino acid sequence of a short elastin-like peptide (sELP) H-(Phe-Pro-Gly-Val-Gly)$_n$-NH$_2$ (**7**, Scheme 4a).[21] sELP exhibits reversible lower critical solution temperature (LCST)-type behaviour, being soluble at low temperatures and insoluble at high temperatures.[22] Such reversible temperature-responsive and self-assembling properties make sELP a promising candidate for drug delivery applications. The development of unnatural analogs with enhanced self-assembling properties is therefore of considerable interest. Herein, we designed a novel unnatural analogue, H-(Phe-Ac$_5$c-Gly-Aib-Gly)$_2$-NH$_2$ (**8a**), by modifying the original sELP sequence (Scheme 4b). Specifically, the Pro-2 in **7** was replaced with Ac$_5$c, a noncanonical amino acid structurally related to Pro, and the Val-4, located at a guest position in the original sequence,[23] was substituted with Aib, a noncanonical amino acid analogous to Val.

The decapeptide **8a** was synthesized in a good yield *via* segment coupling between Boc-Phe-Ac$_5$c-Gly-Aib-Gly-OH (**9a**) and H-Phe-Ac$_5$c-Gly-Aib-Gly-NH$_2$ (**10a**) under standard condensation conditions, followed by Boc deprotection under acidic conditions. We also designed and synthesized a structurally related analogue, H-(Phe-Deg-Gly-Val-Gly)$_2$-NH$_2$ (**8b**), in which Ac$_5$c residue in **8a** was replaced with Deg, a noncyclic analogue of Ac$_5$c. Both **8a** and **8b** were obtained as TFA salts in pure form after purification by reversed-phase (RP)-HPLC (Fig. S1). Additionally, we designed and synthesized H-(Phe-Pro-Gly-Aib-Gly)$_2$-NH$_2$ (**11**) as an Aib analogue of the original sELP **7** *via* a standard SPPS protocol (see, SI).

The self-assembling properties of peptides **8a**, **8b**, and **11** were then investigated under buffered aqueous conditions. Each peptide was dissolved in phosphate buffer containing NaCl (pH 7.4; 27.4 mM Na_2HPO_4, 17.8 mM NaH_2PO_4, and 3M NaCl), and their turbidities at 400 nm were recorded upon increasing and decreasing temperatures (Fig. 1a, b and Table S2). The results revealed that these synthetic peptides **8a** and **8b** exhibited reversible LCST behaviour at concentrations of approximately 1–3.5 mM. The control peptide **11** showed the similar behaviour; however, it required significantly higher concentrations to initiate aggregation compared to the peptides **8a** and **8b** (Fig. 1c). Herein, the transition temperature (T_t) was defined as the temperature at which turbidity reached half of its maximum value during heating. The relationship between T_t and peptide concentration of **8a** and **8b** fitted well to a power function ($T_t = aC^b$), while that of **11** followed a conventional logarithmic function ($T_t = a\log(C) + b$) as previously demonstrated for ELPs, where C is peptide concentration and a and b are constants (Fig. 1d).[24] A clear correlation between



Scheme 4 (a) Chemical structure of short elastin-like peptide (sELP) **7**, (b) synthesis of unnatural sELP analogues **8a** and **8b** by conventional peptide segment coupling.

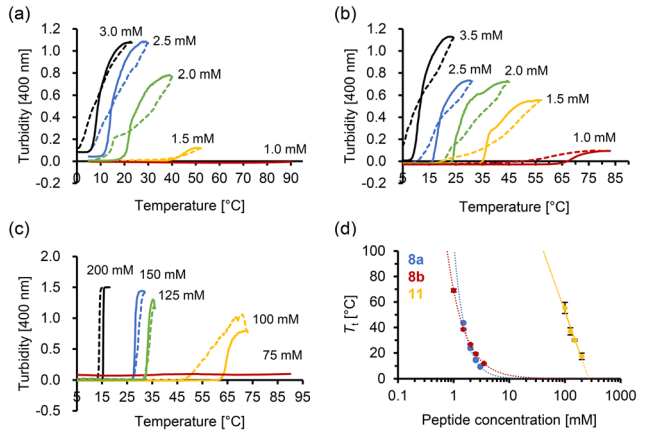


Fig. 1 Turbidity measurements of peptides **8a** (a), **8b** (b), and **11** (c), and the correlation between T_t and concentration (d). In (a)–(c), the solid and dashed lines represent the turbidity profiles upon heating and cooling, respectively. Measured T_t values of peptides **8a** and **8b** were fitted with power functions, while that of **11** was fitted with conventional logarithmic functions. T_t values are shown with standard error.

peptide concentration and T_t demonstrated that the self-assembling capabilities of unnatural analogues **8a** and **8b** were approximately 100-fold stronger than that of reference peptide **11** (Fig. 1d). The reversibility of structural changes in **8a** and **8b** was roughly investigated by circular dichroism measurements (Fig. S2 and S3). Furthermore, the self-assembling behaviours were confirmed by bright-field microscopy (Fig. S4) and dynamic light scattering measurements (Fig. S5). Taken together, both peptides **8a** and **8b** were found to form aggregates above their respective T_t values. Ultra performance liquid chromatography (UPLC)-MS analysis showed peptides **8a** and **8b** were more hydrophobic than peptide **11** (Fig. S1), suggesting that the increased hydrophobicity of **8a** and **8b** may contribute to their enhanced self-assembling properties.

Conclusions

This study, although preliminary, developed a streamlined N-to-C peptide elongation method for synthesizing unnatural peptides using the ammonia-Ugi reaction. Starting from readily available *N*-protected amino acids, ketones, and α-isocyano ester as building blocks, a series of tripeptides **4a–4g** were synthesized in high yields and with excellent stereochemical integrity. Notably, the sterically demanding residues such as Aib, Ac_5c, (αMe)Hph, and Deg were constructed *in situ* from simple ketones, and successfully incorporated into peptides, overcoming limitations of conventional peptide synthesis. The tripeptides **4** were further elongated into pentapeptides **6** *via* the second ammonia-Ugi reaction, demonstrating the method's versatility. Interestingly, both **8a** and **8b** exhibited reversible LCST behaviour at approximately 100-fold lower concentrations than **11**, due probably to the increased hydrophobicity. Future work will focus on synthesis of longer peptides and more sterically congested peptides using α-isocyano α,α-disubstituted amino acids. Extensions in these directions will be reported from our laboratory in due course.

Author contributions

KT, conceptualization, investigation, methodology, and writing – original draft; KT, NT, YK, MU, MA, HK, investigation; HN and TN, supervision and writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: experimental procedures, supplementary figures and tables, NMR spectra of all new compounds, and HPLC charts. See DOI: https://doi.org/10.1039/d5ob01834j.

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