Design and Combinatorial Development of Shield-1 Peptide Mimetics Binding to Destabilized FKBP12

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ABSTRACT: On the basis of computational design, a focused one-bead one-compound library has been prepared on microparticle-encoded PEGA1900 beads consisting of small tripeptides with a triazole-capped N-terminal. The library was screened towards a double point-mutated version of the human FKBP12 protein, known as the destabilizing domain (DD). Inspired by the decoded library hits, unnatural peptide structures were screened in a novel on-bead assay, which was useful for a rapid structure evaluation prior to off-bead resynthesis. Subsequently, a series of 19 compounds were prepared and tested using a competitive fluorescence polarization assay, which led to the discovery of peptide ligands with low micromolar binding affinity towards the DD. The methodology represents a rapid approach for identification of a novel structure scaffold, where the screening and initial structure refinement was accomplished using small quantities of library building blocks.

KEYWORDS: destabilizing domain, one-bead one-compound library, encoded beads, solid-phase synthesis

INTRODUCTION

The engineered and double point-mutated version of the human FK506-binding protein, F36V-L106P-FKBP12, is known as the destabilizing domain (DD).1 This domain can confer its instability to proteins-of-interests (POIs) when fused to it.2,3 When expressed in cells, the DD and the fusion protein will rapidly be degraded by the proteasome, resulting in low levels of the POI.1 Upon stabilization of the DD by addition of a small ligand, the degradation is reduced, which induces a dose-dependent accumulation of the POI within the cell. Hereby, the level of gene product can be chemically controlled, creating a powerful tool for interrogating biological systems. The compound Shield-1 (Shld1, Figure 1) is a small molecule derived from the natural ligand FK506 and has been shown to interact selectively with the DD.4,5 The Shld1–DD system has proven its vast utility in several biological systems, including living mice,6 plants,7,8 parasites,9–11 mammalian cells,1 and yeast.12 Previous studies have reported Kᵢ values of 7.5 nM from in vitro experiments between Shld1 and the DD.13 However, in plant systems genetically modified to express DD-POI fusion proteins, high concentrations of Shld1 were required to induce accumulation of the destabilized complex.7 In studies with rice and wheat, treatment with 3–10 μM Shld1 solutions was required to achieve sufficient diffusion of the small Shld1 molecule through the plant cuticle and subsequent stabilization of DD-POI.8 A recent study highlighted the challenges of improving the plant cell penetrating properties of Shld1 derivatives, while preserving sufficient potency of the modified compounds.13 In connection to this project, alternative and novel stabilizing compounds with a less demanding synthetic route were envisioned. We describe, in this study, a method for using computational design, combined with a series of encoded combinatorial synthesis and screening
using only 10 mg of resin per compound, thus enabling a rapid hit structure elucidation prior to off-bead resynthesis. The scaffold allowed synthesis of one-bead-one-compound (OBOC) libraries and comprised two strategies with different points of attachment to the support (1 and 2, Figure 1). The compound SLP* (Figure 1), which is closely related to Shld1, has a carboxylic acid handle for attachment to the solid support and was selected as a reference for studying the on-bead target interaction.

The screening of a focused combinatorial library, synthesized on optically encoded beads containing fluorescent microparticles, facilitated rapid identification of hit compounds through simple optical decoding. This library encoding approach is suitable for synthesis and screening of small- to medium-sized libraries (500–50 000 beads) and permits, as do other bead-based encoding technologies, the identification of library members binding to the fluorescent target. The method relies on the fact that each bead in the library carries a unique distribution of microparticles as a code obtained by recording the microparticle coordinates that distinguish it from all other beads in the library. The encoded library technology is particularly useful for bead-based libraries of compounds for which conventional mass-spectrometry methods are complicated and inefficient, as was the case in the presented study.26

The structural insight gained from the on-bead assay assisted the design of 19 unnatural peptides which were screened in a competitive fluorescence polarization assay, and our findings has led to the discovery of novel and small unnatural peptides with low micromolar binding affinity towards the DD.

RESULTS AND DISCUSSION

With the aim of developing a core structure with modifiable moieties for combinatorial library development, a tripeptide with a triazole capped N-terminal was designed by computer modeling to adopt a similar binding pose to that of Shld1 in the DD binding site.5 The reference compound SLP* and an example of the computational designed ligand 1 is depicted in Figure 2. Modeling was performed with Molecular Operating

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Figure 1. Illustration of the development process for small molecule peptide mimetics and their respective attachment strategies. Prior to this study, DD-ligands, such as SLP* and Shield-1 (Shld1), were derived by structure-based design originating from the natural product FK506. Strategy 1 of the peptide mimetics involves standard solid-phase synthesis in the C- to N-direction, whereas in strategy 2, the ligand is anchored via a carboxylic linker attached to a tyrosine side-chain.

Figure 2. Comparison of the binding modes of SLP* (A) and an example of peptide mimetic 1 (B) to the crystal structure of the SLP*-stabilized F36V–FKBP12 complex. In the modeling of the complex between F36V–FKBP12 and the peptide mimetic, key features of the ligand were maintained while building the structure. The water-soaked complexes of F36V–FKBP12 with the peptide mimetic were subjected to several rounds simulated annealing (MOE, Amber 10, ETH; T = 430 K, 1 ns, 430–230 K, 1 ns, 230 K, 3 ns). In the first round, the coordinates of F36V–FKBP12 were fixed, and in the subsequent rounds, the contact residues in F36V–FKBP12 were relaxed to allow an induced fit of F36V–FKBP12 and the ligand.
Environment (MOE, CCG) using the crystal structure of SLF<sup>*</sup> bound to F36V–FKBP12 (PDB 1BL4) as a starting point.<sup>5</sup> Upon fixing the coordinates of the protein, the SLF<sup>*</sup> compound was replaced with peptide mimetics, soaked in a water droplet, and relaxed by energy minimization as described in detail in the Supporting Information. Modifications were explored on key features of the peptides during structural development. The peptidic moiety is located in a groove on the active site of the protein and has in several studies been investigated and selected to explore its capacity. Those alkyl groups providing favorable interactions in the pocket during modeling were included in subsequent library synthesis. For the remaining residues, interaction over the entire binding site was evaluated and structural components displaying appropriate contact with the protein were selected for combinatorial library synthesis.

The design of the peptide mimetic scaffold allowed usage of the large pool of natural and unnatural amino acid building blocks in combination with the orthogonal CuAAC click chemistry to survey the pharmacophore interactions. To screen for optimal interaction with the protein for the immobilized substrates in the library, two different linker strategies were employed. As presented in Scheme 1, strategy 1 involve standard solid-phase peptide synthesis (SPPS) in the C- to N-direction. Whereas, strategy 2 is anchored via a linker piece from the tyrosine side chain, protruding from the other end of the compound and resembling the part of the SLF<sup>*</sup> from the tyrosine side chain, protruding from the other end of the pocket. Originating from an α-aminoabutryic acid, the ethyl part adjacent to the triazole is designed to dock into the hydrophobic cavity formed after the F36V mutation,<sup>5</sup> and various lengths of alkyl groups were investigated and selected to explore its capacity.

**Strategy 1:**

Reagents and conditions: (a) Fmoc-4-Amb-OH, TBTU, NEM, DMF, 2 h; (b) piperidine/DMF (1:4), 20 min; (c) Fmoc-L-Phe-OH, TBTU, NEM, DMF, 2 h; (d) Fmoc-L-Pip-OH, TBTU, NEM, DMF, 2 h; (e) Fmoc-D-Abu-OH, TBTU, NEM, DMF, 2 h, then piperidine/DMF (1:4), 20 min; (f) 2-(3,4,5-trimethoxyphenyl)butanoic acid, TBTU, NEM, DMF, 2 h; (g) phenylacetylene, CuSO<sub>4</sub>, ascorbic acid, t-BuOH/H<sub>2</sub>O (3:1), 16 h; (h) Ac<sub>2</sub>O/pyridine/DMF (1:1:8), 30 min; (i) 2-(3,4,5-trimethoxyphenyl)butanoic acid, TBTU, NEM, DMF, 2 h; (j) benzylamine, PyBOP, NEM, DMF, 2 h, 99%; (k) ethyl-2-bromoacetate, Cs<sub>2</sub>CO<sub>3</sub>, DMF, 3 h, 86%; (l) TFA/CH<sub>2</sub>Cl<sub>2</sub> (1:1), 0 °C to rt, 1.5 h, 93% (2 steps); (m) MgI<sub>2</sub>, THF, mw 120 °C, 15 min, quant; (o) TBTU, NEM, DMF, 2 h.

**Reference:**

Reagents and conditions: (a) Fmoc-4-Amb-OH, TBTU, NEM, DMF, 2 h; (b) piperidine/DMF (1:4), 20 min; (c) Fmoc-L-Phe-OH, TBTU, NEM, DMF, 2 h; (d) Fmoc-L-Pip-OH, TBTU, NEM, DMF, 2 h; (e) Fmoc-L-Abu-OH, TBTU, NEM, DMF, 2 h, then piperidine/DMF (1:4), 20 min; (f) 2-(3,4,5-trimethoxyphenyl)butanoic acid, TBTU, NEM, DMF, 2 h; (g) phenylacetylene, CuSO<sub>4</sub>, ascorbic acid, t-BuOH/H<sub>2</sub>O (3:1), 16 h; (h) Ac<sub>2</sub>O/pyridine/DMF (1:1:8), 30 min; (i) 2-(3,4,5-trimethoxyphenyl) butanoic acid, TBTU, NEM, DMF, 2 h; (j) benzylamine, PyBOP, NEM, DMF, 1 h, 99%; (k) ethyl-2-bromoacetate, Cs<sub>2</sub>CO<sub>3</sub>, DMF, 3 h, 86%; (l) TFA/CH<sub>2</sub>Cl<sub>2</sub> (1:1), 0 °C to rt, 60 min; (m) Fmoc-Cl, Na<sub>2</sub>CO<sub>3</sub>, dioxane/H<sub>2</sub>O (2:1), 0 °C to rt, 1.5 h, 93% (2 steps); (n) MgI<sub>2</sub>, THF, mw 120 °C, 15 min, quant. 

Scheme 1<sup>1a</sup>
immobilization of 18. Presumably, attachment from this part of the peptide would exhibit a smaller degree of steric interaction with the DD. To initially verify the scaffold design and test the two linking strategies, 2–3 examples of the scaffold linked by each of the methods were synthesized on solid support (Scheme 1). The building block for the strategy 2 linker was synthesized by coupling of 9 with benzylamine, followed by a substitution of ethyl 2-bromoacetate to give 10. A Boc to Fmoc protection group exchange of 10 was performed, and after ester hydrolysis orthogonal to the Fmoc protection group,10 a 11 was formed in five steps with an overall yield of 79%, starting from Boc-protected L-tyrosine. A set of solid-supported compounds were then synthesized on a PEGA1900 resin (500–550 μm)28 and subjected to a maltose binding protein (MBP) fused DD, which had been fluorescently labeled with the rhodamine-X fluorophore (MBP-DD-(ROX)). The MBP was fused to the DD to prevent aggregation of the destabilized protein and to increase the overall polarity of the protein, hence reducing the nonspecific binding. The unique swelling properties of the porous PEGA1900 resin in aqueous media enabled the large fusion protein to gain access to the bead interior.30 As a reference compound for the initial test screen, a solid-supported version of the SLF* compound was synthesized by adapting known procedures (see Supporting Information).18

The carboxylic acid part of the SLF* has been shown to have minor influence on the binding to the DD protein and has previously been used as an anchor for solid-support while retaining its interaction with the protein.31 To estimate any level of nonspecific binding, three different control tripeptides presenting negative, positive, and neutral charge (19–21, see Figure 3) were tested in the on-bead binding assay. As presented in Figure 3, compounds from both attachment strategies containing the 2-trimethoxyphenylbutyric acid building block showed significant binding, albeit with lower affinity than the reference solid-supported SLF* (18) in the single concentration on-bead screen. The acetylated compound 7 bound poorly to the protein, while the derivatives 6 and 15, containing a phenyltriazole, presented good binding, as measured by the fluorescence due to the resin-bound MBP-DD-(ROX). With a relatively high effective ligand concentration of approximately 3.4 mM, a situation of on-bead binding saturation is presumably observed for strong binding ligands. Indeed, compound 6 provided the same if not more fluorescence intensity than resin bound SLF*. However, these results indicated that the triazole-based mimetics of the 2-trimethoxyphenylbutyric acid would be a good starting point for development of a combinatorial library.

The main advantage of this approach was that the azido acid could be generated on bead from amino acid building blocks, hereby removing the need for introducing a stereocenter through enantioselective alkylation of a range of phenylacetic acid derivatives.39,40 Because of the anticipation of slightly better interaction and the ease of synthesis, strategy 1 was selected for the development of the combinatorial library.

**Library Screening.** Using the split-and-mix approach, a library of in total 896 different compounds were synthesized on PEGA1900 beads (500–550 μm) that were optically encoded by MicroParticleMatrix (MPM)-encoding (Figure 4).32 Encoding of the immobilized peptides was performed by recording three orthogonal images of every bead in each portion of the split process, to generate a microparticle coordinate matrix used as a barcode for the individual beads. The images were recorded using a custom-made MPM decoding instrument comprising a solid state laser, three CCD-cameras with telecentric optics and a carousel for individual bead handling.21 Subsequently, the isolated hit-
beads were recorded and the 3-dimensional matrix represented by their microparticle coordinates were determined, allowing tracking through the synthetic history of the immobilized compound.\textsuperscript{21} Pipeolic acid and 4-(aminomethyl) benzoic acid were maintained as structural features during the library development. The remaining amino acid building blocks were varied and coupled using either coupling reagents TBTU or HATU. Subsequently, a solid-phase diazotransfer to the N-terminal amine was carried out to form the corresponding azide,\textsuperscript{33} which in turn was reacted by the CuAAC click reaction using various alkynes (see Table S1 for the full list of library building blocks).

The selection of structure variations of R, R\textsubscript{1}, and R\textsubscript{2} were guided by computational design as described above. The moieties on the R-position were primarily aliphatic and aromatic cyclic structures, whereas the R\textsubscript{2}-position consisted of small linear and branched alkyl groups. Presumably, the enlargement of the hydrophobic cavity formed upon F36V mutation of FKBP12 could allow binding of longer alkyl groups, particularly in combination with the less bulky triazole moiety, as compared to the reference trimethoxy phenylbutyric acid residue of SLF\textsuperscript{*}. To induce the correct folding of the protein, the MBP-DD-(ROX) was preincubated for 30 min with a stoichiometric amount of Shld1 prior to the incubation of the library beads. A final concentration of 1 μM MBP-DD-(ROX) was used, and the beads were incubated for 48 h to establish equilibrium between the individual compounds in a binding-competition assay. As presented in Figure 4, a clear difference in interaction with the protein among the solid-supported ligands was observed, which was visualized by recording the fluorescence intensity of the bead collections. The binding was quite selective and provided a number of bright beads on a background of many inactive beads. The identified hit-beads were manually sorted based on their apparent fluorescence intensity. The structures attached to the isolated encoded hit-beads were decoded giving a total of 16 different hit-structures out of 17 isolated beads (see Supporting Information for all the hit structures).\textsuperscript{21} Nine of the hit compounds contained a 4-trifluoromethyl phenylalanine derivative as the second amino acid. In addition, 12 compounds contained an ethyl group on the R\textsubscript{1}-position and primarily either a 4-methoxy phenyl or a cyclopropyl on the R\textsubscript{2}-position.

**On-Bead Assay and Structure Evaluation.** To distinguish and verify the potency among the structures of the solid-supported hit compounds, a well-based on-bead binding assay was employed.\textsuperscript{34} Guided by the results from the library screen, a set of immobilized substrates were resynthesized on PEGA\textsubscript{100} beads (125–200 μm). The beads were singly sorted into a 96-well plate using a COMPAS bead sorter (Union Biometrica) and subjected to a dilution series of MBP-DD-(ROX). After 16 h of incubation, the fluorescence intensity was measured on wide-field fluorescence microscope. The individual binding profiles of the resynthesized peptide mimetics was compared to the solid-supported SLF\textsuperscript{*} and their potency was graded in a scale from 1 to 4. Nine of the hit compounds contained a 4-trifluoromethyl phenylalanine derivative as the second amino acid. In addition, 12 compounds contained an ethyl group on the R\textsubscript{1}-position and primarily either a 4-methoxy phenyl or a cyclopropyl on the R\textsubscript{2}-position.

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**Table 1. On-Bead Screening of Compounds Derived from the Hits Identified through Optically Encoded Split-and-Mix Library Technology**

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<th>Cmp.</th>
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<th>R\textsubscript{1}</th>
<th>R\textsubscript{2}</th>
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*Binding profile of the peptide mimetics was compared to the solid-supported SLF*\textsuperscript{*} and their potency was graded in a scale from 1 to 4.

**Immobile SLF* (see Scheme 1).**

selected for comparison with the binding of 25. These two compounds displayed a comparable binding profile to the anisole of 25, which indicated that aromatic moieties on this position was preferred. Resynthesis of the peptide mimetics in the solid-supported screening format was realized on a low micromolar scale, requiring a minimal amount of the unnatural amino acid building-blocks, which in combination with the library screening gave an efficient and rapid structure evaluation.
Off-Bead Peptide Resynthesis and Screening. The next step was to survey the nonlinked scaffold for binding to the MBP-DD in solution. On the basis of the results obtained from the well-based on-bead assay, a set of 19 unnatural peptides were synthesized in solution or from solid-support (see Supporting Information). Using the same synthetic approach as presented in Scheme 1, the compounds containing a primary amide or a benzoic acid on the C-terminal of the peptides were synthesized from the Rink-amide linker and the 2-chloro trityl linker, respectively. The solid-supported peptides were synthesized from the Rink-amide linker and the approach as presented in Scheme 1, the compounds containing (see Supporting Information). Using the same synthetic peptides were synthesized in solution or from solid-support from the well-based on-bead assay, a set of 19 unnatural the MBP-DD in solution. On the basis of the results obtained (36) revealed that changing to an aliphatic amide substituent (40), some activity could be achieved and that this was lost when switching to a lipophilic substituent (49). However, the effect appeared not only to be enhanced solubility, since benzoic acid derivatives (45–47) or shorter aliphatic amide substituent (42–44) in the R1-position only led to inactive derivatives. Compound 40 exhibited a Kᵢ of 33.9 μM and has a primary amide positioned in a similar distance from the pipecolic core as compound 37, suggesting that a hydrogen bond donor in this position may be advantageous to the binding of the protein. Testing rather small moieties on the R1-position in combination with or without changing the R- and R₂-substituents (50–54) interestingly revealed the two most potent compounds in the series (51 and 53) with Kᵢ-values of 5.13 and 11.2 μM, respectively. Both compounds are among the most hydrophilic, but again, this effect is not the only determining factor, as introducing the aliphatic amide substituent found the active derivative 40 in the R1-position of 51 led to loss of activity (41). This underlines that further optimization of the scaffold has to be multidimensional, which exactly is the strength of combinatorial screening. However, the presented data demonstrates that the combination of computational design and combinatorial synthesis and screening is a powerful concept for developing new active scaffolds towards a given biological target.

Binding Evaluation of Peptide Ligands. The mode of interaction of the two ligands, 37 and 51 was analyzed in detail. The interactions between ligand 37 and F36V–FKBP12 involve two hydrophobic pockets (see Figure 5A). One for the
The alternate binding mode presented by compound and ligand FKBP12. (C) The overlay of SLF network of interacting residues between the complex interaction between presented by computational modeling. (A) Contact residues of crystal structure of F36V− Tyr-26, and Leu-97 of F36V ethyl group, which interact with Ile-91, Gly-28, Val-36, Phe-99, Tyr-26, and Leu-97 of F36V−FKBP12, and one for the pipercolic acid, which is lined by Phe-46, Phe-99, Tyr-82 and the triazole binds perpendicularly to the NH of the Phe(CF3) residue. Overall the fit of 37 is not as tight as that of SLF. The optimized interaction of the three peripheral aromatic rings seem to lift the core pipercolic amide and α-aminobutyric acid residue slightly from their binding pockets, since it cannot reach over the rim of the binding pocket. Hereby, interaction with the protein is compromised, and as visualized in Figure 5C, the SLF* is in significant closer contact with the protein in the deep hydrophobic binding pocket. The complex of F36V−FKBP12 with compound 51 presents an alternative binding mode in which the cyclopropane ring interacts with Ile-90, His-97, and Tyr-82 and the triazole binds perpendicularly to the NH of the Phe(CF3). This redirects Tyr-82 to form a hydrogen bond to the carbonyl of Phe(CF3), allowing optimal interaction of the morpholine residue with Ile-56. Surprisingly, the smaller compound 37 showed the highest binding affinity. However, since all peripheral residues of 51 are relatively small, they may allow optimal interaction of the core pipercolic amide and α-aminobutyric acid residues with the F36V−FKBP12. These observations suggest that the scaffold could be even further improved by extending the core framework to position the peripheral aromatic residues at more favorable regions of the interaction interface, thus providing a better match of binding to the active site of the DD.

In summary, an 896-member one-bead one-compound library was synthesized on microparticle encoded PEGA1900 beads using the split-and-mix approach. The library was screened towards a fluorescently labeled version of the DD-protein and the screen resulted in 16 different structures, which were identified as hits and deconvoluted using in-house developed decoder equipment. General trends among the hits included the presence of a 4-trifluoromethyl-1-phenylalanine as the second amino acid and an ethyl-group on the R2-position (Figure 4) originating from an α-α-aminobutyric acid. Guided by the library hits, solid supported peptide mimetics were resynthesized on small scale and screened in a novel on-bead binding format to confirm and distinguish the potency among the library hits. The structure information was then used for the synthesis of 19 peptide mimetics. By exploiting the fixed stereochemistry of the unnatural amino acids, the small peptide-like compounds were synthesized in few steps using either solution- or solid-phase synthesis. The peptide mimetics were tested in a competition fluorescence polarization assay and one compound with a low micromolar binding affinity towards the DD was identified. Analysis of the identified low potency ligand (37) indicates that binding may be partly compromised by the small displacement of the pipercolic and butyric acids caused by rim interaction of the peripheral residues. This may also add to the explanation, why a small compound like 51 bind better than 37, while displaying less interaction. Our high-throughput screening approach to identify a novel peptide-like structure scaffold for the DD has involved the combination of computational modeling.
combinatorial library screening, and on-bead structure evaluation.

With a focus on improving the solubility of the peptide mimetics, the identified ligand S1 could serve as a starting point for development of unnatural peptides that mimic the ShldI–DD interaction. We envision that the present methodology can be applied to the synthesis and screening of larger peptide and nonpeptide libraries, where the screening and initial structure refinement can be accomplished routinely and rapidly using small quantities of library building blocks in a high throughput manner using the MPM-encoding technology.

**ASSOCIATED CONTENT**

1. Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acscombsci.9b00197.

Full description of the materials and methods, including HPLC, NMR, and MS data (PDF)

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Author Contributions
The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes
The authors declare no competing financial interest.

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**ABBREVIATIONS**

Ac, acetyl; Abu, α-aminobutyric acid; Amb, aminomethylbenzoic acid; Boc, tert-butoxycarbonyl; Comp, compound; DD, destabilizing domain; DMF, N,N-dimethylformamide; FKBP, FK506-binding protein; Fmoc, 9-fluorenlymethylxoycarbonyl; HATU, 1-[(dimethylamino)methylene]-1H-1,2,3-triazolo[4,5-b]pyridinium 3-oxide hexafluorophosphate; HMBA, hexafluoroacetone; MBP, maltose-binding protein; NEM, N-ethylmaleimide; NSB, nonspecific binding; PEGA, polyethylene glycol dimethyl acrylamide; Pip, pipelic acid; POI, protein of interest; PyBOP, benzotriazole-1-yl-1,3,2-oxazaphospholidine; PEG, polyethylene glycol dimethyl acrylamide; rt, room temperature; ShldI, Shld-I; SPPS, solid-phase peptide synthesis; SPS, solid-phase synthesis; TBTU, N-(1H-benzotriazol-1-yl)(dimethylamino)methylene)-N-methyl methanaminium tetrafluoroborate; TFA, trifluoroacetic acid; THF, tetrahydrofuran

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