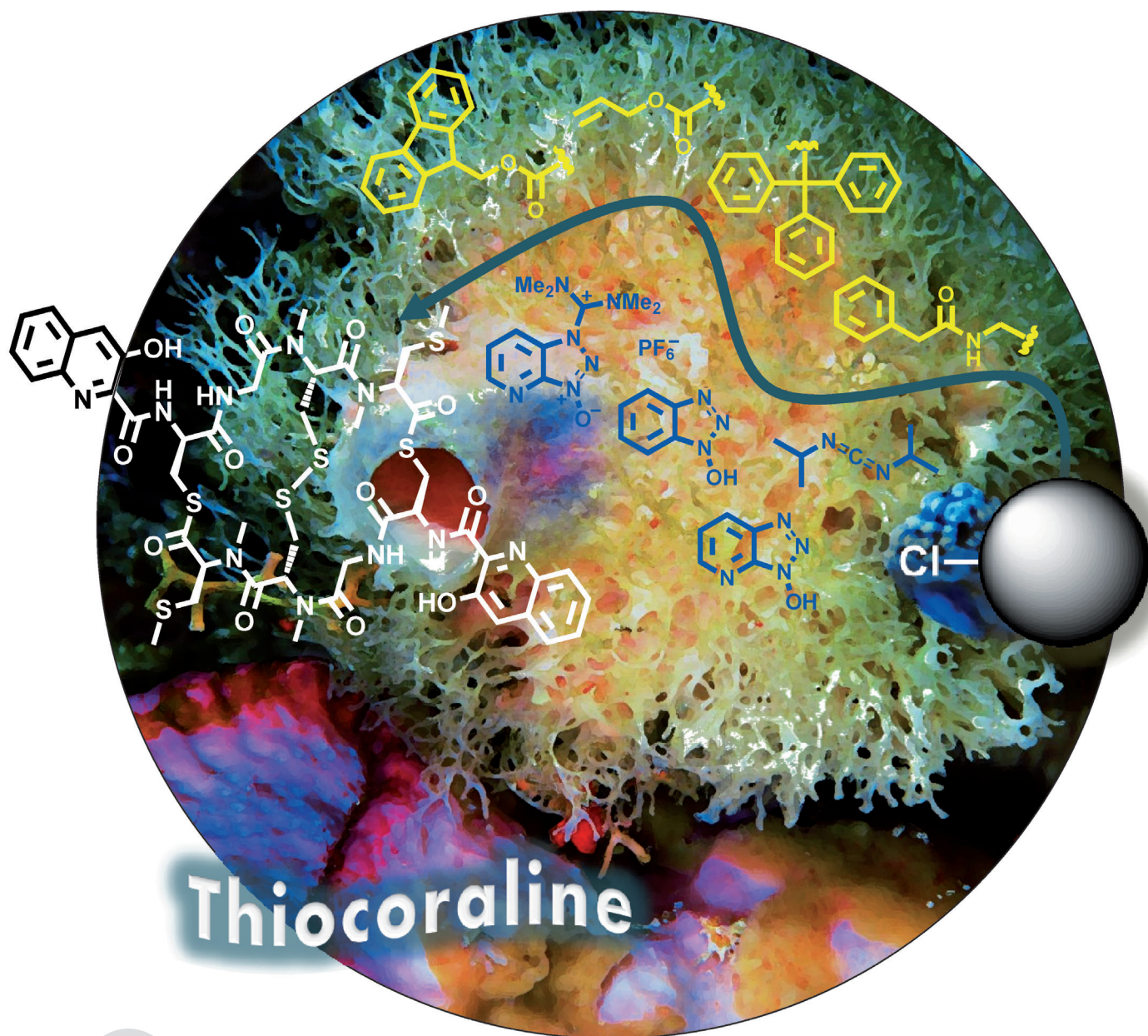


Enzyme-Labile Protecting Groups for the Synthesis of Natural Products: Solid-Phase Synthesis of Thiocoraline**

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Nature creates extremely complex molecules which commonly present pharmaceutical properties of interest.^[1] A particularly intriguing class of these molecules are cyclic peptides isolated from marine species.^[2] The development of these peptides as drug candidates is hampered by the difficulty in isolating sufficient amounts of material from the natural sources. Despite the huge development of chemical methods during the past decade, the synthesis of this kind of compound remains a challenge, with numerous reaction and purification steps. In the case of peptides, many of these steps correspond to protection/deprotection steps, and limitations in a synthetic strategy often arise as a result of the incompatibility of protecting groups. Protecting groups should preferably be orthogonal,^[3] meaning that they can be removed in any order and in the presence of the other protecting groups. Such orthogonal removal is required in the case of cyclic peptides, where an intramolecular reaction takes place once the peptide chain has been constructed. It is best to make these kinds of molecules using solid-phase synthesis, although very often it is necessary to carry out a few solution reactions at the end of the synthesis. Enzyme-labile protecting groups add a new orthogonal level to the synthesis of complex molecules for which strategies based only on chemical methods have shown limitations. This is exemplified herein by the first solid-phase synthesis of the complex cyclotriodepsipeptide thiocoraline^[4,5] (Figure 1). Isolated in 1997 off the coast of Mozambique, this unique and potent antitumor agent has several features that make its structure extremely complex, namely a sequence rich in Cys, the presence of consecutive *N*-methylamino acids, and a bicyclic structure formed by a disulfide bridge flanked by two thioester moieties.

In addition to protection of the α -amino group, the presence of six Cys residues (four of them *N*-methylated and the remaining two in the *D* configuration, which mask a DNA bisintercalating chromophore) requires different protecting

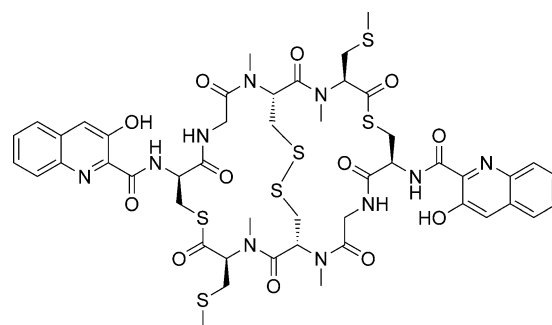


Figure 1. Chemical structure of thiocoraline.

groups for the thiol groups and mild removal conditions for all of them. In this regard, the phenylacetamidomethyl^[6] (Phacm) group is suitable, because it can be cleaved by the enzyme penicillin G acylase (PGA). Therefore, an orchestrated scheme of protecting groups becomes the cornerstone for the synthesis of thiocoraline.^[7]

Although attempts were made to apply three distinct strategies developed by our group to other analogues of thiocoraline that do not have thioester moieties, our efforts were unsuccessful.^[8] The formation of these extremely delicate functional groups needs to be postponed until the final steps of the synthesis, and usually thioester formation is incompatible with the formation of the disulfide bridge. As a result, the *N*-Me-Cys(Me) residue, which is the *C*-carboxyl component of the thioester, was chosen as a starting point for the synthesis. One drawback of this approach was the β -elimination side reaction that this residue undergoes when placed at the anchoring position and piperidine is used to remove the 9-fluorenylmethoxycarbonyl (Fmoc) group. This problem was overcome using the milder allyl-based chemistry during most of the elongation of the peptide chain. Synthesis of the allyloxycarbonyl (Alloc)-protected *N*-methylated Cys was accomplished starting from Boc-Cys(Me)-OH and Boc-Cys(trityl,Trt)-OH, by carrying out an *N*-methylation reaction with NaH and MeI, then introducing the Phacm moiety in the next step, and finally incorporating the Alloc protecting group.^[9] Following this strategy, Alloc-*N*-Me-Cys(Me)-OH and Alloc-*N*-Me-Cys(Phacm)-OH were obtained in good purities (> 95 %) and were used without further purification.

The use of 2-chlorotriethyl chloride (2-CTC) resin^[10] as solid support was compulsory, because the two first residues are *N*-Me-amino acids, which are extremely prone to producing diketopiperazine (DKP).^[11] Therefore, the synthesis began by anchoring Alloc-*N*-Me-Cys(Me)-OH onto the 2-CTC resin (Scheme 1).

Following removal of the Alloc group by treatment with [Pd(PPh₃)₄] and PhSiH₃, Alloc-*N*-Me-Cys(Phacm)-OH was coupled using 1-[bis(dimethylamino)-methylene]-1*H*-1,2,3-triazolo-[4,5-*b*]pyridinium hexafluorophosphate 3-oxide (HATU)/1-hydroxy-7-azabenzotriazole (HOAt)/diisopropylethylamine (DIEA) for one hour. The coupling was repeated to ensure complete reaction of the amino acid. Although 2-CTC had been used, removal of the protecting group was accompanied by DKP formation. We therefore optimized the method to minimize this side reaction, which consisted of

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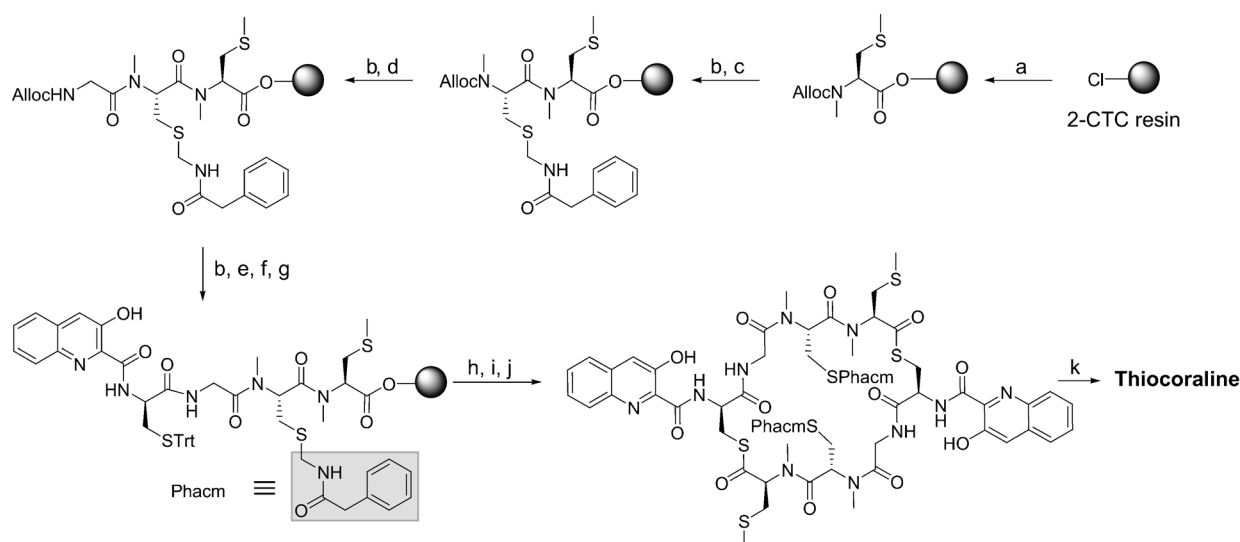
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Scheme 1. Synthetic strategy for the synthesis of thiocoraline; a) Alloc-NMe-Cys(Me)-OH, DIEA, CH_2Cl_2 ; MeOH; b) $[\text{Pd}(\text{PPh}_3)_4]$, PhSiH_3 , CH_2Cl_2 ; c) Alloc-NMe-Cys(Phacm)-OH, HATU, HOAt, DIEA, DMF; d) Alloc-Gly-OH, HATU, HOAt, DIEA, DMF; e) Fmoc-D-Cys(Trt)-OH, DIPCDI, HOBT, DMF; f) piperidine-DMF (1:4); g) 3-hydroxyquinolinaldic acid, DIPCDI, HOBT, CH_2Cl_2 ; h) TFA/ Me_2S /TIS/ CH_2Cl_2 (2:0.5:0.5:97); i) TFA/TIS/ CH_2Cl_2 (10:2.5:87.5); j) DIPCDI, HOAt, DMF/ CH_2Cl_2 ; k) immobilized PGA enzyme, H_2O /DMSO (9:1), pH 6.7.

performing the coupling under almost neutral conditions by adding fewer equivalents of base (4.9 equiv) with respect to the incoming amino acid and coupling reagents (5.0 equiv). At this point, the purity (89%) and the absorbance spectra of the protected tripeptide showed no indication of DKP formation.^[12] To introduce the next residue (D-Cys), which has a 3-hydroxyquinolinaldic unit, either Boc or Fmoc could be used as the protecting group for the α -amino group of the Cys residue to later introduce the heterocycle. There is an advantage in the use of the Fmoc group in that the heterocycle can be introduced during the solid-phase synthesis, where coupling proceeds faster than in solution^[13] and gives better yields, even when using few equivalents of the precious chromophore. A Trt group is suitable to protect the thiol, because it can be removed under mild conditions and allows subsequent formation of the thioester. Therefore, after removing the Alloc group of Gly, Fmoc-D-Cys(Trt)-OH was easily coupled using DIPCDI/HOBT in DMF for one hour. To minimize dehydration of the NMe-Cys(Me) residue, the Fmoc group was removed with two treatments of piperidine/*N,N*-dimethylformamide (DMF) (1:4), each lasting two minutes. Coupling of 3-hydroxyquinolinaldic acid was achieved under mild conditions [*N,N'*-diisopropylcarbodiimide (DIPCDI)/1-hydroxybenzotriazole (HOBT)] and few equivalents (1.1 equiv) to prevent overacylation at the free hydroxy group. After one hour, a ninhydrin test showed completion of the coupling. With the tetrapeptide of thiocoraline fully assembled, we detached it from the solid support. Owing to a large amount of oxidation on the Cys residues, especially NMe-Cys(Me), alternative methods to the standard cleavage conditions for 2-CTC resin [trifluoroacetic acid (TFA)/ CH_2Cl_2 , 1:99], were examined. In this regard, cleavage of the tetrapeptide under mild reductive conditions [TFA/ Me_2S /triisopropylsilane (TIS)/ CH_2Cl_2 , 2:0.5:0.5:97] afforded the

protected tetrapeptide in 91% purity as shown by analytical HPLC (see the Supporting Information).

Next, two possible methods were devised (Figure 2). The first consisted of forming an intermolecular disulfide dimer, which led to synthesis of the analogue oxathiocoraline.^[8b] However, although the formation of the dimer was complete, as indicated by HPLC and HPLC-MS, removal of the Trt groups to perform the double cyclization destabilized the dimer because of the presence of free thiol groups. This strategy was thus abandoned.

The second option, which a priori was more difficult to handle, involved removing the Trt groups and then performing the double thioesterification in a concentrated (18 mM) solution. To this end, the Trt groups were removed with a TFA/TIS/ CH_2Cl_2 (10:2.5:87.5) solution at 4°C for ten minutes, and then co-evaporated with TBME at low temperature to remove the remaining acid. The unprotected tetrapeptide was dissolved in CH_2Cl_2 and the solution was cooled to 4°C. DIEA was added until the pH was neutral. The addition of DIPCDI and HOAt started the cyclization reaction,^[14] which was monitored by HPLC. After two hours, HPLC showed that the reaction had gone to completion, and no monomeric thioesterification was detected. The crude solution was then washed twice with H_2O and pre-purified with an ISCO instrument equipped with a reversed-phase C_{18} column to remove coupling reagents and other impurities. The cyclic thiodipeptide was obtained in 85% purity. To remove the Phacm protecting groups and form the disulfide bond, a portion of this crude product (5 mg) was dissolved in dimethylsulfoxide (DMSO; 1.5 mL), and H_2O was added to a final volume of 15 mL. The immobilized PGA enzyme was then added, resulting in a final pH of 6.7, and the suspension was incubated at 37°C and monitored by HPLC. After 56 hours, the immobilized enzyme was filtered and the

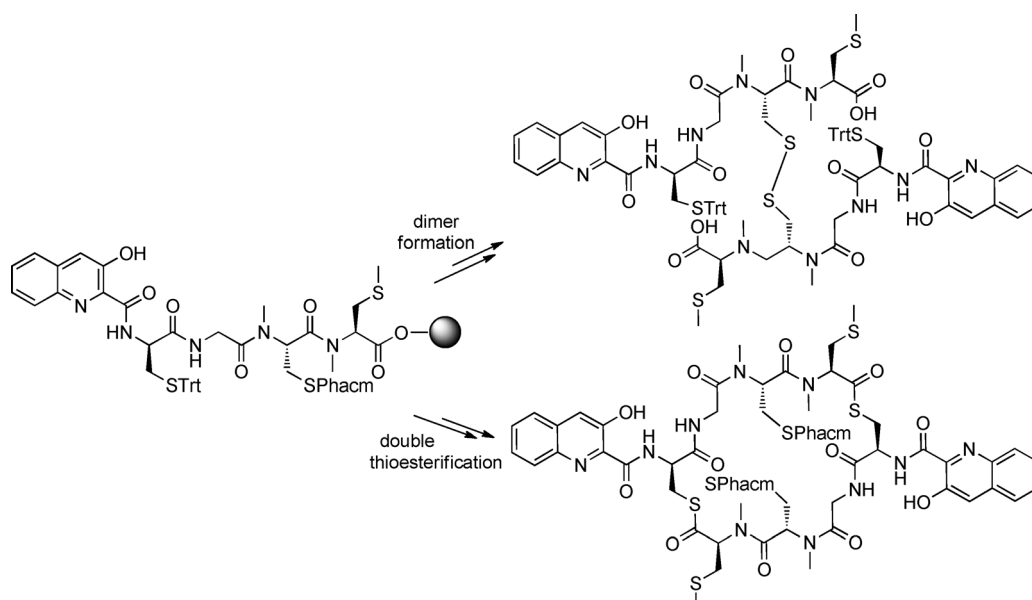


Figure 2. Possible routes from the tetrapeptide: dimer formation and double thioesterification.

reaction solution was lyophilized.^[15] Final purification of thiocoraline was performed using semipreparative HPLC. Co-elution with the natural product using a smooth analytical HPLC gradient (Figure 3), HR-ESMS, and NMR confirmed the identity of the synthetic thiocoraline (Supporting Information). Finally, the in vitro activity of the synthetic compound in four human tumor cell lines showed very similar activity to thiocoraline isolated from its natural source (Table 1).

In summary, the enzyme-labile Phacm protecting group has proven to be key in synthesizing the complex antitumor agent, thiocoraline. Additionally, all synthetic steps were

carried out using mild conditions to remove the protecting groups. The elongation of the monomer was done on a solid-phase support using 2-CTC resin and Alloc as the protecting group for the α -amino group of the first three residues, which prevented two side-reactions: β -elimination to form a dehydroAla residue and DKP formation. Macrocyclization was carried out successfully through the thioester without racemization, taking advantage of the high reactivity of the thiols, in a double

Table 1: In vitro results for natural and synthetic thiocoraline.

Cell line		Breast MDA-MB-231	NSCLC ^[a] A549	Pancreas PSN1	Colon HT-29
Natural thiocoraline	GI ₅₀ ^[b]	2.07E-9	6.22E-9	1.47E-9	4.15E-8
	TGI ^[c]	9.50E-9	2.42E-8	4.23E-9	2.68E-8
	LC ₅₀ ^[d]	3.46E-8	9.50E-8	1.30E-8	1.38E-7
Synthetic thiocoraline	GI ₅₀	1.04E-9	4.29E-9	1.56E-9	1.90E-9
	TGI	4.75E-9	1.90E-8	3.63E-9	1.73E-8
	LC ₅₀	1.73E-8	9.50E-8	9.50E-9	4.06E-7

[a] NSCLC = non-small-cell lung cancer. [b] GI₅₀ = growth inhibition 50%.

[c] TGI = total growth inhibition. [d] LC₅₀ = lethal concentration 50%.

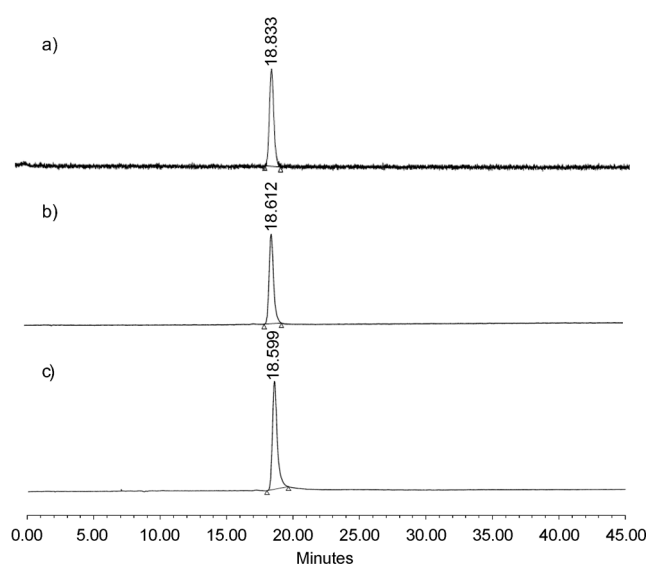


Figure 3. Analytical HPLC of a) natural thiocoraline; b) synthetic thiocoraline; and c) co-elution of natural and synthetic thiocoraline. HPLC conditions: linear gradient of ACN (0.036% TFA)/H₂O (0.045% TFA) 62:38 to 65:35 over 45 min at a flow rate of 1 mL min⁻¹.

reaction. This unprecedented reaction could be favored by the presence of the two *N*-methyl residues, which tend to favor the *cis*-conformation of the peptide bond. Finally, the Phacm groups were removed with concomitant formation of the disulfide bridge to give the synthetically difficult thiocoraline in just a few steps and with only two purification steps.

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- [12] The same strategy carried out with the less hindered acetamidomethyl (Acm) group showed some diketopiperazine formation.
- [13] Coupling of the heterocycle in solution may take up to four days.
- [14] The low temperature and DIPCDI in the presence of HOAt in a rather apolar solvent such as CH₂Cl₂ accompanied by high efficiency of the double macrothiolactamization assured the absence of racemization.
- [15] The use of the Acm instead of Phacm in the diBoc-cyclic analogue was tested, but the I₂ treatment led to total destruction of the compound. Interestingly, similar results were found by Boger et al.^[7] in their synthesis trials.