



syn-Elimination of glutamylated threonine in lanthipeptide biosynthesis†

 Raymond Sarksian, ^a Lingyang Zhu ^b and Wilfred A. van der Donk ^{*ac}

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Methyllanthionine (MeLan) containing macrocycles are key structural features of lanthipeptides. They are formed typically by *anti*-elimination of L-Thr residues followed by cyclization of L-Cys residues onto the (Z)-dehydrobutyrine (Dhb) intermediates. In this report we demonstrate that the biosynthesis of lanthipeptides containing the D-*allo*-L-MeLan macrocycle such as the morphogenetic lanthipeptide SapT proceeds through (E)-Dhb intermediates formed by net *syn*-elimination of L-Thr.

Lanthipeptides are peptidic natural products defined by the presence of lanthionine (Lan) and/or methyllanthionine (MeLan) residues and represent a large class of ribosomally synthesized and post-translationally modified peptides (RiPPs).¹ One of the most common posttranslational modifications (PTMs) in RiPPs is macrocyclization.^{2–7} Macrocytic peptides often increase stability towards proteolytic degradation and display more potent bioactivities compared to their linear counterparts.⁸

Macrocyclization for lanthipeptides occurs by thiol-Michael addition of L-Cys to electrophilic dehydroalanine (Dha)/dehydrobutyrine (Dhb) intermediates that are formed by net dehydration of Ser/Thr residues.^{1,5,9} In class I lanthipeptide biosynthesis the dehydration reaction is catalyzed by a LanB enzyme that first activates the side chain of Ser/Thr residues through a transesterification reaction using Glu-tRNA^{Glu} (Fig. 1A).^{10–13} Glutamate elimination by the LanB enzyme in a separate active site then generates Dha/Dhb residues (Fig. 1A). Split LanB enzymes have been reported where the glutamyl

transferase and glutamyl lyase (GL) domains are separate polypeptides.^{14–18} The cyclization process for lanthipeptides can generate up to two Lan and four MeLan diastereomers.^{1,18,19} The cyclization reaction is catalyzed by a LanC cyclase for class I lanthipeptides (Fig. 1A).^{1,20} The (2*S*,6*R*)- and (2*R*,6*R*)-Lan diastereomers, hereafter referred to as DL- and LL-Lan, have been detected in lanthipeptides, and three out of four possible MeLan stereoisomers have been observed, (2*S*,3*S*,6*R*)-, (2*R*,3*R*,6*R*)-, and (2*S*,3*R*,6*R*)-MeLan, hereafter denoted as DL-, LL-, and D-*allo*-L-MeLan (Fig. 1B).^{18,19,21–25}

Dehydration of L-Thr residues yields (Z)-Dhb in all characterized lanthipeptides (Fig. 1C). DL- and LL-MeLan diastereomers are believed to form by *anti*-addition of L-Cys across (Z)-Dhb intermediates; addition across the *Si* face results in DL-MeLan, whereas addition across the *Re* face gives LL-MeLan.^{1,21,23} DL-MeLan has been historically observed for most lanthipeptides including nisin,²⁶ whereas LL-MeLan has been detected only in the past decade, particularly in substrate-controlled cyclizations.^{23,27} D-*allo*-L-MeLan macrocycles were recently discovered in the morphogenetic lanthipeptide SapT (Fig. 2A).¹⁸ D-*allo*-L-MeLan could be formed through *anti*-elimination of L-Thr residues to yield a (Z)-Dhb intermediate followed by *syn*-addition of L-Cys across the *Re* face of the (Z)-Dhb intermediate.¹⁸ Alternatively, D-*allo*-L-MeLan can be generated through net *syn*-elimination of L-Thr residues to generate an (E)-Dhb intermediate followed by *anti*-addition of L-Cys across the *Si* face of the (E)-Dhb intermediate.¹⁸ A lanthipeptide cyclase has yet to be characterized that catalyzes *syn*-addition and (E)-Dhb residues have yet to be observed for a RiPP. In this report we differentiate between these two mechanistic possibilities by characterization of a model biosynthetic intermediate containing a Dhb residue generated by the SapT biosynthetic machinery.

The class I lanthipeptide SapT is produced from the *spt* biosynthetic gene cluster (BGC) that encodes the SptA precursor peptide, a split dehydratase consisting of SptB_a and SptB_b, and the SptC cyclase (Fig. 2A).¹⁸ SptB_a is a glutamyl transferase and SptB_b functions as a GL that catalyzes glutamate elimination

^a Department of Chemistry and Howard Hughes Medical Institute, University of Illinois at Urbana-Champaign, Urbana, IL, 61822, USA.

E-mail: vddonk@illinois.edu; Tel: +1 217 244 5360

^b School of Chemical Sciences NMR Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL, 61822, USA

^c Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana-Champaign, Urbana, IL, 61822, USA

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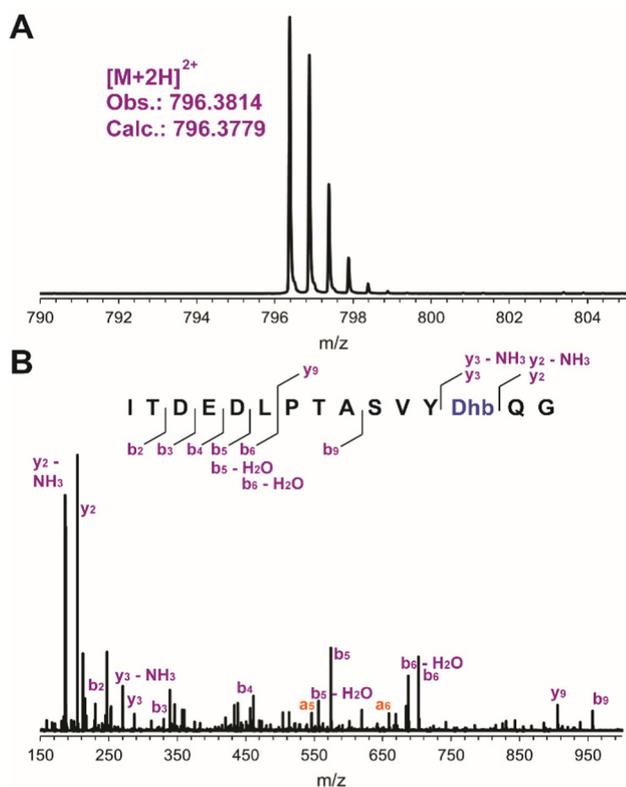


Fig. 4 LC-MS analysis of the C-terminal trypsin digestion fragment from $mSptA_{(1-37)}$ containing a single Dhb residue. (A) High-resolution electrospray ionization MS (ESI-MS) analysis. (B) Tandem ESI-MS analysis, observed ions are shown in orange but not labeled on the peptide.

Ser/Thr residues are part of the SptA leader peptide and are not modified during the biosynthesis of SapT (Fig. 2B).

Next, $mSptA_{(1-37)trypsin}$ was produced on a larger scale for characterization of the alkene geometry by nuclear magnetic resonance (NMR) spectroscopy. One dimensional 1H NMR spectra and two-dimensional homonuclear 1H - 1H TOCSY (total correlation spectroscopy) and NOESY (nuclear Overhauser effect spectroscopy) data were acquired for chemical shift assignment of all resonances (Table S3 and Fig. S1–S4, ESI †). The 1H NMR spectrum of $mSptA_{(1-37)trypsin}$ in 70% acetonitrile- d_3 /30% H_2O revealed distinct resonance frequencies for the Dhb residue (Fig. S1 and Table S3, ESI †). The most downfield singlet at 8.90 ppm was identified as the Dhb amide proton, and a distinct quartet was observed at 5.75 ppm for the vinylic proton of the Dhb residue. Only a single set of Dhb-derived signals was detected, consistent with the MS-MS data suggesting that only Thr35 was dehydrated in $mSptA_{(1-37)}$. The vinylic proton is coupled to the allylic methyl group of the Dhb residue at 1.85 ppm that is present as the expected doublet. An NOE signal was observed between the vinylic proton and methyl protons of the Dhb residue, as well as a distinct NOE signal between the vinylic proton of the Dhb residue and the amide proton of the same residue (Fig. 5 and Fig. S4, ESI †), revealing the spatial vicinity of the vinylic and the amide protons of the Dhb residue. An NOE signal was not observed between the

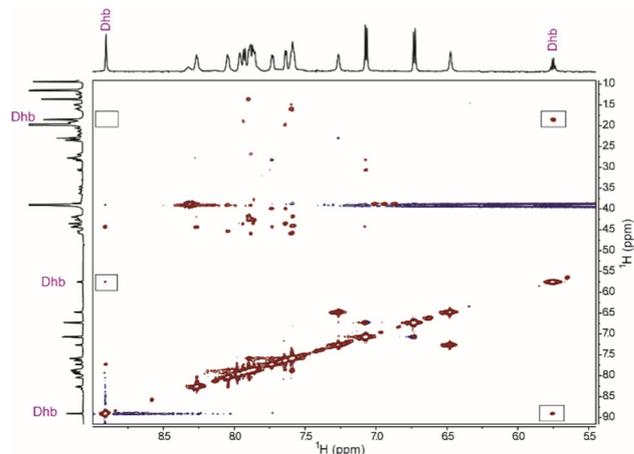


Fig. 5 Characteristic region of the 1H - 1H NOESY spectrum of $mSptA_{(1-37)trypsin}$. Boxes are used to highlight presence and absence of key NOE signals for determining the Dhb geometry.

methyl group and amide proton of the Dhb residue (Fig. 5 and Fig. S4, ESI †). The observed NOEs differ significantly from what is observed for (*Z*)-Dhb residues in previously characterized lanthipeptides^{30,31} (Fig. S5 and S6, ESI †) and linaridins.^{32,33} Although we cannot rule out that during purification minor products may have been removed that could contain (*Z*)-Dhb, these results clearly demonstrate that the predominant product of $mSptA_{(1-37)trypsin}$ contains an (*E*)-Dhb and not a (*Z*)-Dhb residue. To our knowledge, this represents the first example of detection of a peptide containing an (*E*)-Dhb with ribosomal origin. Cypemycin had been proposed to contain an (*E*)-Dhb, but that proposal was recently shown to be incorrect.³² Therefore, the GL SptB_b in SapT biosynthesis catalyzes net *syn*-elimination of glutamylated Thr residues to form (*E*)-Dhb residues. Subsequent *anti*-addition of *L*-Cys across the *Si* face of the (*E*)-Dhb residue by SptC then forms *D-allo-L*-MeLan macrocycles found in SapT. Whether the formation involves a concerted *syn*-elimination reaction or potentially an $E1_{cb}$ mechanism is currently not known. It is intriguing, however, that neither sequence alignments nor a homology model of SptB_b identified a residue that may stabilize the enolate intermediate that would be formed in an $E1_{cb}$ mechanism.¹⁹ We cannot rule out however that amide backbone hydrogens might stabilize the build-up of negative charge on the oxygen of the enolate through hydrogen bonding interactions as often seen in proteases.³⁴

The characterization of a model biosynthetic intermediate containing an (*E*)-Dhb generated by SptB_b provides a direct link between the stereochemistry of the Dhb intermediate and bioinformatic signatures that are observed for *syn*-GLs that differ from *anti*-GLs.^{18,19} For the gene clusters that have been investigated thus far that contain a *syn*-GL (*spt* and *coi*), it is intriguing to note that the products contain *D-allo-L*-MeLan cross-links, but not (*E*)-Dhb residues.^{18,19} Whether this will hold true for other lanthipeptides containing *D-allo-L*-MeLan cross-links with *syn*-GLs in the corresponding BGCs, which



constitute nearly one-fifth of all class I lanthipeptide BGCs, remains to be determined.

This study was designed by R. S and W. A. V. Experiments were performed by R. S. L. Z. assisted in NMR experiment setup. All authors contributed to data analysis and interpretation. R. S. and W. A. V. wrote the paper. All authors have given approval to the final version of the manuscript.

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Conflicts of interest

There are no conflicts to declare.

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