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The Biosynthesis of Rare Homo-Amino Acid Containing Variants of Microcystin by a Benthic Cyanobacterium

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Abstract: Microcystins are a family of chemically diverse hepatotoxins produced by distantly related cyanobacteria and are potent inhibitors of eukaryotic protein phosphatases 1 and 2A. Here we provide evidence for the biosynthesis of rare variants of microcystin that contain a selection of homo-amino acids by the benthic cyanobacterium Phormidium sp. LP904c. This strain produces at least 16 microcystin chemical variants many of which contain homophenylalanine or homotyrosine. We retrieved the complete 54.2 kb microcystin (mcy) gene cluster from a draft genome assembly. Analysis of the substrate specificity of McyB and McyC adenylation domain binding pockets revealed divergent substrate specificity sequences, which could explain the activation of homo-amino acids which were present in 31% of the microcystins detected and included variants such as MC-LHty, MC-HphHty, MC-LHph and MC-HphHph. The mcy gene cluster did not encode enzymes for the synthesis of homo-amino acids but may instead activate homo-amino acids produced during the synthesis of anabaenopeptins. We observed the loss of microcystin during cultivation of a closely related strain, Phormidium sp. DVL1003c. This study increases the knowledge of benthic cyanobacterial strains that produce microcystin variants and broadens the structural diversity of known microcystins.

Keywords: adenylation domain; hepatotoxin; cyanobacteria; nonribosomal peptide synthetase (NRPS); polyketide synthase (PKS); mass spectrometry

1. Introduction

Microcystins are potent hepatotoxins, which inhibit eukaryotic protein phosphatases type 1 and 2A [1]. Microcystins are frequently detected during blooms of cyanobacteria in freshwater environments and are linked to poisoning of humans and animals [2,3]. Microcystins have an unusual chemical structure with more than 240 reported chemical variants [4]. The microcystin chemical structure can be summarized as cyclo-D-Ala1-X2-D-MeAsp3-Z4-Adda5-D-Glu6-Mdha7 where X and Z are variable L-amino acids. The bulk of microcystin chemical variation can be attributed to the amino acids found at positions two (X) and four (Z).

Microcystins are synthesized by large hybrid multifunctional enzymes known as nonribosomal peptide synthetases (NRPS) and polyketide synthases (PKS) [5–8]. The chemical variability of microcystins is mainly attributed to a substrate promiscuity of microcystin biosynthetic enzymes,
which allows the incorporation of a diverse range of proteinogenic/non-proteinogenic amino acids, non-proteinogenic organic acids and different degrees of methylation [9]. This is due to differences in substrate specificity of the NRPS enzymes, the deletion of enzymatic domains or loss/gain of tailoring enzymes [1,8].

Homo-amino acids have an extra methylene (CH$_2$) group in the carbon side chain and are frequently found in cyanobacterial natural products [9–16]. Cyanobacteria have been found to produce microcystins that contain homo-amino acids in positions X and Z, such as homotyrosine (Hty), homophenylalanine (Hph), homoisoleucine (Hil), and homoarginine (Har) [4,10–13]. However, the biosynthetic origins of such microcystins are unclear.

*Phormidium* is a genus of cyanobacteria belonging to Oscillatoriales order that includes unbranched filamentous strains. *Phormidium* is not well defined taxonomically and further studies are needed to improve its separation with other genera of Oscillatoriales [17], which complicates the interpretation of reports about *Phormidium* in the scientific literature. Cyanobacteria belonging to *Phormidium* genus have been isolated from mangrove [18], saline-alkaline lakes [19], thermal springs [20], high altitude lakes [21] and mats/biofilms in Antarctic lakes [22] among others. *Phormidium* spp. isolated from Egypt, USA, Brazil and Spain have been reported to produce microcystins [13,23–25]. Putative *Phormidium* spp. producers of microcystin were reported to be associated to the poisoning of a dog in New Zealand [26]. However, analysis based on 16S rRNA sequences indicates a close similarity of these strains with *Planktothrix* [26]. Microcystin-LR was detected from *Phormidium* strains isolated from benthic environments in USA [24] and here we further analyze selected strains from that study. We describe the microcystin biosynthetic gene cluster from *Phormidium* sp. LP904c and show that this strain produces rare homo-amino acid containing microcystins in addition to microcystin-LR. We also report the loss of the microcystin synthesis by *Phormidium* sp. DVL1003c after 11 years of cultivation in our laboratory.

2. Results

2.1. *Phormidium* Strains Producing Unusual Microcystins (MCs)

*Phormidium* sp. LP904c is a benthic cyanobacterium isolated from the Lake Perris in Riverside County, California (USA) that is reported to produce microcystin-LR. This cyanobacterium was found to produce diverse microcystins varying in the positions X and Z (Figure 1A). Further variations were related to the presence or absence of methylation in the aspartic acid (Aa$^3$) or Adda (Aa$^5$) and for the presence of a methylated serine or dehydroalanine instead of the N-methyldehydroalanine (Aa$^7$) (Figure 2).

MC-LR was the main variant as previously reported [24] and accounted for 55% of the total microcystin produced by this strain. However, the strain produces a range of other microcystins including MC-LHty, MC-HphHty, MC-LHph and MC-HphHph (Figure 2, Table 1). A number of amino acids were found in position X and Z, such as Leu, Arg, Phe, Trp, Tyr, Met and unusual homo-amino acids such as Hph and Hty (Figure 2, Table 1).
Figure 1. Photomicrography of the studied Phormidium strains. (A) LP904c. (B) DVL1003c. (C) LM603d. (D) LS703b.

Figure 2. Structural variation in the 16 microcystins detected in the Phormidium sp. LP904c. The column charts indicate the relative amounts of amino acids (%) detected in the X and Z positions of microcystins. Hty = homotyrosine, Hph = homophenylalanine.
**Table 1.** Protonated ion masses of microcystin (MC) variants from *Phormidium* sp. LP904c and their relative amounts (%) identified from either *Phormidium* sp. LP904c or DVL1003c by HPLC-ESI-ITMS. Peak areas of the extracted ion chromatograms of the protonated microcystins were used in relative amount calculations. Hty = homotyrosine, Hph = homophenylalanine, [M + H]+ (m/z) = mass per charge value of protonated microcystins, Rt (min) = retention time in minutes, RA = relative amount, Aa = amino acid. Additional information presented in Figure S1.

| No. | Microcystin | Aa in Position | [M + H]+ (m/z) | Error (ppm) | RA (%) |
|-----|-------------|----------------|---------------|-------------|--------|
| 1   | MC-YR       | Y R            | 1045.5335     | 1.54         |        |
| 2   | MC-HtyR     | Hty R          | 1059.5510     | 1.58         |        |
| 3   | MC-MR       | M R            | 1013.5125     | 1.58         |        |
| 4   | [DMDada]5MC-LR | L R        | 981.5404      | 1.58         |        |
| 5   | [L-MeSer]7MC-LR | L R        | 1013.5666     | 1.66         |        |
| 6   | [D-Asp]9MC-LR | L R            | 981.5404      | 1.74         |        |
| 7   | MC-LR       | L R            | 995.5560      | 1.74         |        |
| 8   | MC-FR       | F R            | 1029.5404     | 1.74         |        |
| 9   | [Dha]7MC-LR | L R            | 981.5404      | 1.74         |        |
| 10  | MC-HphR     | Hph R          | 1043.5560     | 1.74         |        |
| 11  | MC-LY       | L Y            | 1002.5183     | 2.22         |        |
| 12  | MC-LHty     | L Hty          | 1016.5339     | 2.22         |        |
| 13  | MC-HphHty   | Hph Hty        | 1064.5337     | 2.22         |        |
| 14  | MC-LW       | L W            | 1025.5342     | 2.22         |        |
| 15  | MC-Lhph     | L Hph          | 1000.5390     | 2.22         |        |
| 16  | MC-HphHph   | Hph Hph        | 1048.5390     | 2.22         |        |

*Phormidium* sp. DVL1003c (Figure 1B) was isolated from a freshwater reservoir in Riverside County, California. Strains DVL1003c and LP904c were shown to synthesize similar microcystin variants in 2005 (Table 1, Supplementary Figures S1–S3). Structural characterizations of microcystins produced by *Phormidium* sp. LP904c were done using high-performance liquid chromatography/electrospray ionization ion-trap mass spectrometry (HPLC-ESI-ITMS) and ultra-high performance liquid chromatography-quadrupole time-of-flight mass spectrometry (UPLC-QTOF). MCs identified were divided into two groups, ten arginine (Arg) containing MCs (Numbers 1–10) and six non Arg MCs (Numbers 11–16) (Table 1). All Arg MCs eluted first, followed by the more hydrophobic non Arg MCs (Supplementary Figures S2 and S3). These two MC groups fragment differently as protonated molecules resulting in distinct product ion spectra (Supplementary Figure S4). Both spectral groups were highly similar to spectra recorded in similar ion trap conditions [27]. In Arg containing MC structures fragmentation prefers the formation of ion 4a–6c (relative intensities (RI) from 51 to 100%), Arg4-Adda5-Glu6, Supplementary Figures S4 and S5) which have an m/z 599 when methyl group 2 is present. When the methyl group is absent, e.g., [DMDada]5MC, an m/z 585 is detected. Serine in MC structure generates a base peak of [M + H – H2O]+ which was seen in the spectra of [MeSer]7MC-LR and which lowered the relative intensity of 4a-6c ion (Supplementary Figure S4). Ions 4a-6c – CO (RI 26–94%) and 4a–6c – NH3 (RI 6–28%) were also present (Supplementary Figure S4). The presence of ion 4a–7c (RI 4–20%, Arg4-Adda5-Glu6-Aa7, Supplementary Figure S5) shows the identity of the Aa7. Other diagnostic intense ions were 4a-2c/7a-5c (RI 8–38%) which showed the identity of amino acids 3 and 6, and 7a–4c (RI 45–94%, Aa7-Ala1-Aa2-MeAsp5-Arg5) together with other ions showed the identity of amino acids 4 and 5. Ion 5y-5x-7c was present in all the protonated MC product ion spectra except in the [DMDada]5MC-LR spectra because cleavage at position 5y is not so favorable when there is hydroxyl group instead of the methoxy group vicinal to the 5y bond [28]. In the presence of methyl group 3 the ion mass is m/z 375 or 393 when Aa7 is MeSer and when it is absent the mass is m/z 361, such as in the [Dha]7MC-LR. Ion 5y-5x-7c identifies amino acids 5, 6 and 7. Identification of amino acids 1 and 2 using MS is challenging because the intensities of the diagnostic ions are near the noise level but for example ion 4a–1c (m/z 753) was clearly present in the spectrum of MC-MR showing the presence of methionine in this microcystin (Supplementary Figures S4 and S5).

The base peak is [M + H – C8H10O]+ in the product ion spectra of protonated non Arg microcystins [29]. In the *Phormidium* sp. LP904c microcystins spectra, the most intense peak was [M + H – NH3]+ followed by [M + H – C8H10O]+ (same as 5y), [M + H – (NH3 + C8H10O)]+ (same...
as 5y-5x-4c) and [M + H − H2O]+ (Supplementary Table S1). The ion 5y-5x-7c was present in all protonated MC product ion spectra identifying amino acids 5, 6 and 7 (Supplementary Figure S4). Medium intensity ions 5y-5x-1c (m/z 446) and 5y-5x-2c, which are present in all non-Arg MCs, identify the amino acids 1 and 2. Ions 5y-5x-3c and 5y-5x-4c identify amino acids 3 and 4. The low intensity of ion 5y-5x-3c in some MCs weakened the certainty of amino acids 2 and 4. Product ion spectra of sodiated non-Arg microcystins are presented in Supplementary Figure S6 and product ion assignments are presented in Supplementary Table S2. These data support the assignments of the protonated product ions but do not clearly enhance the identity of amino acids 2 and 4. Additional proof for the MC structures gave the accurate masses measured from the protonated molecules error being lower than ±2.4 ppm (Table 1). The immonium and other diagnostic ions of amino acids 2, 4 measured with UPLC-QTOF were also in agreement with the presented MC structures (Supplementary Table S3).

In addition to the mass spectral behavior, the chromatographic retention behavior was consistent with the structures of microcystins produced by Phormidium spp. DVL1003c and LP904c (Supplementary Figures S2 and S3). Polar surface areas obtained with the topological method from the microcystin 3D molecular structures correlated well ($R^2 = 0.951$) with the measured retention times obtained from reversed phase chromatography (Figure 3 and Supplementary Figure S7). Large macrocyclic structures with many polar groups did not give the best polar surface areas with a topological method. Despite this, Topological Polar Surface Area (TPSA) values of microcystins, which are macrocyclic and polar groups containing molecules correlated well with the retention times. These results show that there is no discrepancy between the derived microcystin structures and their surface polarities.

![Figure 3. Effect of polar surface areas (PSA) to the retention times ($R_t$, min) of Phormidium sp. LP904c microcystins calculated with a topological polar surface area (TPSA) method [30]. High correlation ($R^2 = 0.951$) shows that the proposed microcystin structures fit well to the measured retention times.](image)

Microcystin contents of Phormidium spp. LM603a (5–11b), LM603d (12–29d) (Figure 1C), and LS703b (1–2, Figure 1D) strains were very similar with the Phormidium spp. DVL1003c and LP904c (Supplementary Figure S8). However, recent chemical analysis indicates that microcystin is no longer produced by Phormidium sp. DVL1003c and we decided to choose strain LP904c for further analysis.

### 2.2. Microcystin and Homophenylalanine Biosynthetic Genes from Phormidium

A draft genome sequence from Phormidium sp. LP904c (7.7 Mb, 108 scaffolds, 129,707 N50) was obtained to identify the microcystin biosynthetic gene cluster (mcy). The complete 54.2 kb mcy gene cluster was identified through tBLASTn searches (Figure 4). The microcystin biosynthetic gene cluster from Phormidium sp. LP904c encodes ten genes organized in a bidirectional operon (Figure 4). There are three NRPS genes (mcyA, mcyB and mcyC), one PKS gene (mcyD), two hybrid NRPS-PKS genes (mcyE and mcyG), an aspartate racemase (mcyF), an ABC transporter (mcyH), a dehydrogenase (mcyI), and...
and a methyltransferase (mcyJ) (Figure 4 and Supplementary Table S4). Most of the protein sequences from the microcystin biosynthetic pathway in Phormidium sp. LP904c are similar to sequences from Planktothrix spp. (Supplementary Table S4). The organization of mcy genes is identical to the Planktothrix agardhii CYA126 except for the positions of mcyI and mcyJ (Figure 4). Many of the microcystin variants produced by Phormidium sp. LP904c contain homo-amino acids (Figure 2 and Table 1). However, the mcy biosynthetic gene cluster from Phormidium sp. LP904c lacked obvious enzymes for the biosynthesis of homo-amino acids (Figure 4).

![Figure 4. The 54.2 kb microcystin (mcy) gene cluster from Phormidium sp. LP904c.](image)

**Figure 4.** The 54.2 kb microcystin (mcy) gene cluster from Phormidium sp. LP904c. The respective sequences that will be transcribed to NRPS (nonribosomal peptide synthetase), PKS (polyketides synthase) and tailoring enzymes are indicated in the gene cluster.

### 2.3. McyB1 and McyC from Phormidium sp. LP904c

The adenylation domains of McyB1 and McyC are responsible for the selection and activation of the amino acids in the positions X and Z of the microcystin, respectively. Sequence information based on microcystin biosynthetic genes from Phormidium sp. DVL1003c was obtained using PCR products based on specific primers prior to loss of microcystin biosynthesis by this strain [10]. These DNA sequences were translated to amino acid sequences and the predicted adenylation domain binding pockets of McyB1 and McyC from different cyanobacteria were obtained (Tables 2 and 3). Both McyB1 and McyC adenylation domains binding pockets from Phormidium sp. LP904c and Phormidium sp. DVL1003c differ at the positions 236, 239 and 278 (in addition to position 331 in the McyB1 and exception in position 278 in McyC of DVL1003c) when compared to the same adenylation domains from other strains previously described in the literature (Tables 2 and 3).

Phylogenetic analysis based on the conserved sequences of 16S rRNA genes indicates the relationship of the studied strain to the other cyanobacteria sequences available in the National Center for Biotechnology Information (NCBI) GenBank database (Figure 5). Phormidium spp. DVL1003c and LP904c are grouped with other Phormidium, Oscillatoria and Lyngbya strains in the 16S rRNA gene phylogenetic tree (Figure 5). Other strains producing microcystin belonging to the order Nostocales, Oscillatoriales, Stigonematales and Chroococcales were included in the phylogenetic tree of the 16S rRNA gene and a broad distribution of these strains based on their relativeness to similar strains can be seen (Figure 5).

The concatenated phylogenetic tree based on microcystin biosynthetic enzymes McyD and McyE indicates the relationship of the Phormidium sp. LP904c sequences and other cyanobacteria producers of microcystins (Supplementary Figure S9). The studied strains are grouped with close related Phormidium and Planktothrix strains. However, recombination can be seen analyzing the phylogenetic history based on condensation and adenylation domains from the McyB1 and McyC (Supplementary Figure S10). Condensation domains sequences are divided into two big groups according to each enzyme: McyB1 and McyC (Supplementary Figure S10A). In contrast, the adenylation domain phylogenetic tree shows the recombination events occurred between the gene sequences (Supplementary Figure S10B). Adenylation domains from Phormidium spp. LP904c and DVL1003c McyB1 are grouped with domains from McyB1 and McyC from Dolichospermum and Hapalosiphon (Supplementary Figure S10B), while the adenylation domain from McyC in Phormidium sp. LP904c and DVL1003c is grouped with sequences from the McyB1 domains from Planktothrix spp.
Table 2. Specificity codes inferred from the protein sequence of first adenylation domain of McyB₁ according to [31] or NRPSpredictor2 [32,33]. Conserved amino acids are highlighted in light blue and variable amino acids are highlighted in dark green. Homo-amino acids are highlighted in red.

| Organism                  | Strain         | McyB₁ | P * | %  | Aa  #       |
|---------------------------|----------------|-------|-----|---|-------------|
| **Phormidium sp.**        | L904c          |       | D   | I | C   V       |
|                           | DVL1003c       |       | D   | I | C   V       |
| **Planktothrix agardhii** | CYA 126/8      |       | D   | A | L   F       |
|                           | NIVA-CYA56/3   |       | D   | A | L   F       |
| **Planktothrix rubescens**| NIVA-CYA 407   |       | D   | A | L   F       |
| **Dolichospermum sp.**    | 90             |       | D   | V | W   F       |
|                           | 18B6           |       | D   | V | W   S       |
|                           | 66 A           |       | D   | V | W   S       |
| **Nostoc sp.**            | 152            |       | D   | A | L   F       |
|                           | 102-1          |       | D   | V | L   F       |
| **Fischerella sp.**       | PCC9339        |       | D   | V | L   F       |
| **Hapalosiphon fribonius**| BZ-3-1         |       | D   | V | L   F       |
| **Microcystis aeruginosa**| PCC 9807       |       | D   | A | W   F       |
|                           | PCC 9443       |       | D   | A | W   F       |
| **Microcystis aeruginosa**| DIANCHI905     |       | D   | A | W   F       |
|                           | PCC 9007       |       | D   | A | W   F       |
| **Microcystis aeruginosa**| PCC 7941       |       | D   | A | W   F       |
| **Microcystis aeruginosa**| PCC 9443       |       | D   | A | W   F       |
| **Microcystis aeruginosa**| NIES-843       |       | D   | G | W   T       |
| **Microcystis aeruginosa**| SPC777         |       | D   | G | W   T       |
| **Microcystis viridis**   | NIES 102       |       | D   | G | W   T       |

| Organism                  | Strain         | McyB₁ | P * | %  | Aa  #       |
|---------------------------|----------------|-------|-----|---|-------------|
|                           |                |       | Ser-Thr | 60 | Leu, Hph, Phe, Hty, Tyr, Arg |
|                           |                |       | Ser-Thr | 60 | Leu, Hph, Phe, Hty, Tyr, Arg |
|                           |                |       | Leu    | 100| Arg, Leu    |
|                           |                |       | Leu    | 100| Arg, Leu    |
|                           |                |       | Leu    | 100| Arg, Leu    |
|                           |                |       | Leu    | 100| Arg, Leu    |
|                           |                |       | Leu    | 100| Arg, Leu    |
|                           |                |       | Leu    | 90 | Leu, Arg, Hty |
|                           |                |       | Ser    | 80 | Leu, Arg, Hil |
|                           |                |       | Ser    | 80 | Arg, X      |
|                           |                |       | Ser    | 70 | Hty, X, Hph, Leu, Tyr, Phe |
|                           |                |       | Leu    | 80 | Leu, Hil, X, Val |
|                           |                |       | Gln    | 50 | Leu, X, Phe, Hil, Tyr |
|                           |                |       | Pro    | 70 | Leu         |
|                           |                |       | Ser    | 80 | Leu, Arg    |
|                           |                |       | Leu    | 100| Val         |
|                           |                |       | Arg    | 90 | Leu         |
|                           |                |       | Arg    | 90 | Leu         |
|                           |                |       | Arg    | 100| Arg         |
|                           |                |       | Leu    | 100| Leu         |
|                           |                |       | Leu    | 100| Leu         |
|                           |                |       | Arg    | 90 | Leu         |
|                           |                |       | Leu    | 100| Leu         |
|                           |                |       | Arg    | 90 | Arg, Leu, Tyr |
|                           |                |       | Arg    | 90 | Arg         |
|                           |                |       | Hil    | 90 | Leu, Arg, Tyr, Trp, Phe, Hty, X |

P * prediction by NRPSpredictor2; Aa  # amino acid detected by LC-MS (Supplementary Table S5); X. MC contains an unknown amino acid or the overall amino acid content is not known; Ni. No information.  

Planktonic *Anabaena* have recently been taxonomically assigned to the genus *Dolichospermum*. 

Table 3. Specificity codes inferred from the protein sequence of the adenylation domain of McyC according to [31] or NRPS predictor2 [32,33]. Conserved amino acids are highlighted in light blue and variable amino acids are highlighted in dark green. Homo-amino acids are highlighted in red.

| Organism                    | Strain       | MeCyC       | P * prediction by NRPSpredictor2; Aa # amino acid detected by LC-MS (Supplementary Table S5); X. MC contains an unknown amino acid or the overall amino acid content is not known; Ni. No information.   |
|-----------------------------|--------------|-------------|------------------------------------------------|
| Phormidium sp.              | LP904c       | D 236       | Leu 100 Arg, Hty, Hph, Trp                        |
| Phormidium sp.              | DVL1003c     | D 235 239   | Leu 100 Arg, Hty, Hph, Trp                        |
| Planktothrix agardhii       | CYA 126/8    | D 278       | Gln 70 Arg                                        |
| Planktothrix agardhii       | NIVA-CYA 56/3| D 301       | Arg                                              |
| Planktothrix pedifica       | NIVA-CYA 98  | D 322       | Arg                                              |
| Planktothrix rubescens      | NIVA-CYA 407 | D 330       | Arg                                              |
| Dolichospermum sp.          | 18B6         | D 517       | Arg                                              |
| Planktothrix agardhii       | CYA 126/8    | D 278       | Gln 70 Arg                                        |
| Planktothrix agardhii       | NIVA-CYA 56/3| D 301       | Arg                                              |
| Planktothrix pedifica       | NIVA-CYA 98  | D 322       | Arg                                              |
| Planktothrix rubescens      | NIVA-CYA 407 | D 330       | Arg                                              |
| Dolichospermum sp.          | 18B6         | D 517       | Arg                                              |
| Dolichospermum lemmiermannii| 66 A         | D 278       | Arg                                              |
| Nostoc sp.                  | 152          | D 278       | Arg                                              |
| Fischerella sp.             | PC9039       | D 278       | Arg                                              |
| Hapalosiphon hibernicus     | BZ-3-1       | D 278       | Ala, Leu, Val                                     |
| Microcystis aeruginosa      | PCC 7806     | D 278       | Arg                                              |
| Microcystis aeruginosa      | FCY-28       | D 278       | Arg                                              |
| Microcystis aeruginosa      | FCY-26       | D 278       | Arg                                              |
| Microcystis aeruginosa      | UV027        | D 278       | Arg                                              |
| Microcystis aeruginosa      | K139         | D 278       | Arg                                              |
| Microcystis aeruginosa      | DIANCH1905   | D 278       | Arg                                              |
| Microcystis aeruginosa      | PCC 9807     | D 278       | Arg                                              |
| Microcystis aeruginosa      | PCC 7941     | D 278       | Arg                                              |
| Microcystis aeruginosa      | PCC 9443     | D 278       | Arg                                              |
| Microcystis aeruginosa      | NIES-843     | D 278       | Arg                                              |
| Microcystis aeruginosa      | SPC777       | D 278       | Arg                                              |
| Microcystis viridis         | NIES 102     | D 278       | Arg                                              |
3. Discussion

3.1. Benthic Cyanobacteria Producing Unusual Microcystins

Cyanobacteria are known for the production of toxins implicated in the toxicosis of animals and humans [2]. The hepatotoxin microcystin producing cyanobacteria have been detected mainly from planktonic strains present in freshwater environments distributed worldwide [2]. However, microcystins have been reported from benthic *Fischerella* and *Phormidium* strains [13,23–26,34,35]. *Phormidium* sp. LP904c was previously described to produce a high amount (441 ± 109 µg L⁻¹) of microcystin and the main variant detected was microcystin-LR [24]. The present study shows the benthic *Phormidium* sp. LP904c producing altogether 16 microcystins. Different isolates from diverse genera of cyanobacteria have been related to the hepatotoxin production, such as *Anabaena/Dolichospermum* spp., *Nostoc*, *Plectonema* sp. and *Phormidium* sp. from Egypt [23], *Phormidium* sp. from USA, New Zealand...
and Brazil [13,24,26] and Fischerella sp. from Brazil and Australia [34–36]. Microcystin has been detected in benthic environmental samples from diverse places worldwide, including Switzerland [37], Spain [38,39], Australia [40], Antarctica [41] and the Arctic [42]. These wide distributions of toxic samples and the rise of the number of cyanobacterial isolates from diverse places in the world highlights the need to monitor these benthic communities for toxin production.

3.2. Microcystins Containing Homo-Amino Acids

The results show Phormidium sp. LP904c producing, in addition to the main variant microcystin-LR (55%), a variation of amino acids in position X and Z (Figure 2, Table 1). Leucine, arginine, phenylalanine, tryptophan, tyrosine, methionine and rare homo-amino acids Hph and Hty were detected (Figure 2, Table 1). Microcystins varying in different parts of its chemical structure were also detected, such as D-Asp³, L-MeSer⁷, Dha⁷ and DMAdda⁵ (Figure 2, Table 1). Microcystins are synthesized by nonribosomal peptide synthetases and polyketide synthases [5,9]. These nonribosomal pathways are known for the ability to incorporate proteinogenic and non-proteinogenic amino acids to the growing peptide chain. Phormidium sp. LP904c has been shown in this study to produce diverse variants of microcystins containing Hty and Hph at positions X and Z (Figure 2 and Table 1). Altogether, 31% of the microcystin variants produced contained homo-amino acids. The homo-amino acids are 14 mass units bigger than the proteinogenic amino acid due the presence of a methylene (CH₂) group in the carbon side chain. Phormidium sp. CENA270 isolated from Brazil produces a range of [D-Leu¹] microcystin variants, including Har at the position Z [13]. Hty has been found in diverse cyanobacterial compounds, such as aeruginosins, cyanopeptolins and microginins [9,43]. Hph was detected in pahayokolides [44] and microcystin [45]. Some microcystins, spumigins, lyngbyazothrins, tychonamides, schizotrin A, portoamides and anabaenopeptins contain Hph and/or Hty in their chemical structure [9,15,46–48]. HphA, HphB and HphCD were shown to be involved in the synthesis of Hph from L-Phe in Nostoc punctiforme PCC 73102 [14]. Interestingly, Escherichia coli containing the cyanobacterial hph genes could also convert L-Tyr to Hty [14]. Phormidium sp. LP904c does not encode enzymes for the biosynthesis of homo-amino acids and it is plausible that the McyB¹ and McyC adenylation domains activate the homo-amino acids produced as part of the biosynthesis of anabaenopeptins.

3.3. Microcystin Gene Cluster from Phormidium

The microcystin gene cluster has been described from Microcystis, Planktothrix, Dolichospermum, Nostoc and Fischerella [5–8,49]. In this study, the microcystin biosynthetic gene cluster from Phormidium sp. LP904c is presented. The Phormidium microcystin biosynthetic enzymes have high similarity to Planktothrix amino acid sequences and it is as well mostly unidirectional, with exception of mcyI (dehydrogenase) and mcyJ (methyltransferase) (Figure 4 and Supplementary Table S4). However, the thioesterase McyT present in Planktothrix agardhii CYA 126 [6] is absent in the Phormidium microcystin gene cluster. The new mcy gene cluster sequence further expands the known genetic diversity of the microcystin family and will allow methods to detect the toxin based on gene sequences to be further refined.

The adenylation domains from the NRPSs McyB, and McyC are responsible for the selection and activation of the amino acid to be incorporated in the positions X and Z of microcystin, respectively [5–8]. In the present study, the gene regions of mcyB1 and mcyC from Phormidium sp. LP904c were analyzed to address their variation compared with previously described adenylation domains binding pockets. The adenylation domains have eight to ten amino acids responsible for the substrate specificity in the NRPS [31,50,51]. The binding pocket in the McyB1 and McyC adénylation domains from Phormidium sp. LP904c is unusual compared to other adénylation domains from other strains producing microcystins (Tables 2 and 3). The McyC binding pocket is predicted to activate leucine, even though no microcystins with a leucine in the position Z were detected. The adénylation domains of McyA1, McyA2, McyB1 and
McyC were found to be affected by recombination events which might have resulted in the high number of chemical variants in the positions 7, 1, 2 and 4 of the microcystin, respectively [10,11,13,52–57]. The adenylation domain sequences of McyB1 and McyC from *Phormidium* sp. LP904c might have gone through recombination events because their sequences group with sequences from different enzymes (Supplementary Figure S10). Adenylation domains from nostopeptolide [58] and cyanopeptolin [59] biosynthetic pathways have been shown to activate more than one amino acid. The synthesis of high numbers of microcystin variants could be attributed to the multispecificity of the adenylation domains, specificity-regulation and gatekeeping function of the condensation domains, tolerance of the condensation domains for recombination and point mutations after recombination events that change the specificity of the adenylation-condensation domains [60]. Further analysis based on biochemical assays of adenylation domains could improve the knowledge of amino acids incorporated by these systems.

### 3.4. Lack of Microcystin from *Phormidium* sp. DVL1003c

*Phormidium* sp. DVL1003c was first analyzed by our group for the synthesis of microcystin in 2005 and documented on the microcystin variants and *mcy* synthetase genes. In addition, Izaguirre and collaborators (2007) reported the synthesis of microcystin-LR by this strain [24]. Surprisingly, the culture maintained in the University of Helsinki Culture Collection is no longer able to produce microcystins. Other *Phormidium* strains which have been cultivated under identical conditions still produce almost the same microcystins variants as DVL1003c was able to produce (Supplementary Figure S8). Thus, this study presents one example of a cyanobacterial strain which loses the ability to synthesize a natural product under laboratorial conditions.

### 3.5. Diversity of Benthic *Phormidium* Strains

*Phormidium* spp. isolated from Egypt, USA, Brazil and Spain have been reported to produce microcystins [23–25]. In the phylogenetic tree constructed with 16S rRNA gene sequences, microcystin-producing strains of *Phormidium* are grouped together with other Oscillatoriales such as *Oscillatoria* and *Lyngbya* (Figure 5). The low taxonomic agreement among these strains opens the possibilities for discovery of new benthic cyanobacteria yet to be assigned to some genera and that can be a potential microcystin producer.

### 4. Materials and Methods

#### 4.1. Cultivation of *Phormidium* Strains

The *Phormidium* strains were isolated from Riverside County, California, USA: DVL1003c was isolated from a freshwater reservoir, strains LM603a (5–11b) and LM603d (12–29d) were isolated from Lake Mathews, strain LP904c (3–7b) from Lake Perris and strain LS703b (1–2) from Lake Skinner [24]. The cultures were grown in 50 mL of Z8 medium at 22 °C under constant light.

#### 4.2. Chemical Analysis

Freeze dried cyanobacterial biomass was extracted with methanol as previously described [13]. Methanol extracts were analyzed with low resolution HPLC-ESI-ITMS (Agilent 1100 Series LC/MSD Ion Trap XCT Plus, Agilent Technologies, Palo Alto, CA, USA) to obtain the chromatographic data and product ion spectra of protonated microcystins. A 10 µL sample was injected into a Zorbax C8 column (4.6 × 150 mm, 5 µm, Agilent technologies, Palo Alto, CA, USA) which was eluted for 7.5 min isocratically with 5% isopropanol (+0.05% trifluoracetic acid (TFA)) (solvent B) in 0.05% TFA then to 16% of B in 2.5 min, to 46% of B in 40 min, to 100% of B in 10 min and finally isocratically for 5 min at 40 °C with a flow rate of 0.6 mL min⁻¹ so that the total length of the elution program was 65 min. Mass spectral data was accumulated in Ultra Scan positive electrospray ionization mode (26,000 m/z s⁻¹) at scan range of m/z 100–1200 and by averaging three spectra.
High resolution UPLC-QTOF (Acquity I-Class UPLC-Synapt G2-Si HDMS, Waters Corp., Milford, MA, USA) analyses of microcystins were performed from the methanol extract of *Phormidium* sp. LP904c (3–7b). One µL sample was injected to Cortecst UPLC® C18+ column (2.1 x 50 mm, 1.6 µm, Waters) which was eluted at 40 °C with a flow rate of 0.3 mL min⁻¹ from 20% acetonitrile (+0.1% HCOOH) (solvent B) in 0.1% HCOOH to 95% of B in 5 min, was kept there for 2 min, then back to 20% of B in 0.5 min and finally kept there for 2.5 min before next run. QTOF was calibrated with sodium formate giving a calibrated mass range of m/z 91.036–1178.651. Leucine enkephalin was used at 10 s intervals as a lock mass reference compound. Mass spectral data was accumulated in positive electrospray ionization Resolution Mode at scan range of m/z 50–1200.

The chemical characterization of certain microcystin variants was analyzed based on HPLC-ESI-ITMS and UPLC-QTOF results. Microcystin structures derived from mass spectral data was matched with chromatographic retention behavior. Polar surface areas of microcystins were calculated with a topological method [30], which gave TPSA (topological polar surface area) values for the microcystins.

4.3. DNA Extraction, PCR and Genome Sequencing and Assembly

The genomic DNA extraction from strain *Phormidium* sp. DVL1003c was obtained as described in [10]. Fragments of the 16S rRNA (JQ771628.1) and mcyB1CDE genes were obtained by PCR and sequenced as described in [10]. Alternatively, the genomic DNA extraction from strain *Phormidium* sp. LP904c was obtained as described in [15,61]. An isolated DNA sample from *Phormidium* sp. LP904c was checked using a NanoDrop 1000 spectrophotometer (Thermo Scientific) to measure the concentration and an Agilent TapeStation (Agilent Technologies) to assess the quality. High-molecular DNA was subjected to library (Illumina TruSeq® PCR Free 350bp, Illumina, San Diego, CA, USA) construction and sequenced by Illumina HiSeq2500 platform (Illumina, San Diego, CA, USA) with a paired ends 100 cycles run. The genome data (1 Gb) of *Phormidium* sp. LP904c was firstly checked by Spades (version 3.7.1) [62] for read correction and removal of erroneous ones, and then assembled using Newbler (version 3.0) [63]. Non-cyanobacterial sequences from contaminants were identified by Kraken 1.0 [64] and removed using a custom script. The accession number of complete sequences of the microcystin gene cluster from *Phormidium* sp. LP904c is MK870090 and the mcyB1CDE genes from *Phormidium* sp. DVL1003c are MK924153-MK924156.

4.4. Bioinformatics Analysis

These sequences obtained from mcyB1C were translated using BioEdit [65]. The predictions of the binding pockets of McyC and McyB1 adenylation domains was performed using the bioinformatics tool PKS/NRPS analysis [66], alignment of the sequences using BioEdit [47] and NRPSpredictor2 [32,33]. The phylogenetic tree based on 16S rRNA gene sequences was constructed in Molecular Evolutionary Genetic Analysis (MEGA) 5 [67] using the maximum likelihood method (K2+G+I model) and 1000 bootstrap replicates. A concatenated phylogenetic tree constructed using McyD and McyE sequences was obtained using the neighbor-joining method (Poisson model + G) and 1000 bootstrap replications. The same parameters were used to construct the phylogenetic tree using adenylation and condensation domains from McyB1 and McyC.

5. Conclusions

Benthic cyanobacteria belonging to *Phormidium* genus isolated from freshwater environments were shown to produce microcystin containing homo-amino acids. This finding increases the knowledge of microcystin variants produced by *Phormidium*. Furthermore, we describe the microcystin biosynthetic genes from *Phormidium* sp. LP904c, which resembles the ones found in *Planktothrix* strains. Interestingly, *Phormidium* sp. DVL1003c ceased the synthesis of microcystins during the laboratorial maintenance in our laboratory. Further work is necessary to unveil why two strains kept under the same cultivation conditions had different fates.
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