Paucibacter toxinivorans gen. nov., sp. nov., a bacterium that degrades cyclic cyanobacterial hepatotoxins microcystins and nodularin

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Thirteen bacterial isolates from lake sediment, capable of degrading cyanobacterial hepatotoxins microcystins and nodularin, were characterized by phenotypic, genetic and genomic approaches. Cells of these isolates were Gram-negative, motile by means of a single polar flagellum, oxidase-positive, weakly catalase-positive and rod-shaped. According to phenotypic characteristics (carbon utilization, fatty acid and enzyme activity profiles), the G+C content of the genomic DNA (66.1–68.0 mol%) and 16S rRNA gene sequence analysis (98.9–100% similarity) the strains formed a single microdiverse genospecies that was most closely related to Roseateles depolymerans (95.7–96.3% 16S rRNA gene sequence similarity). The isolates assimilated only a few carbon sources. Of the 96 carbon sources tested, Tween 40 was the only one used by all strains. The strains were able to mineralize phosphorus from organic compounds, and they had strong leucine arylamidase and chymotrypsin activities. The cellular fatty acids identified from all strains were C₁₆ : ₀ (9.8–19 %) and C₁₇ :₁₀₇ c (<1–5.8 %). The other predominant fatty acids comprised three groups: summed feature 3 (1<1–2.2 %), which included C₁₄ : ₀ 3-ΩH and C₁₆ : ₁ iso l, summed feature 4 (54–62 %), which included C₁₆ :₁₀₇ c and C₁₅ : ₀ iso OH, and summed feature 7 (8.5–28 %), which included 07 c, 09 c and 121 t forms of C₁₈ : ₁ . A more detailed analysis of two strains indicated that C₁₆ :₁₀₇ c was the main fatty acid. The phylogenetic and phenotypic features separating our strains from recognized bacteria support the creation of a novel genus and species, for which the name Paucibacter toxinivorans gen. nov., sp. nov. is proposed. The type strain is 2C20T (=DSM 16998T =HAMBI 2767T =VYH 193597T ).

Hepatotoxic microcystins and nodularin belong to the large group of bioactive peptides produced by cyanobacteria. In dense accumulations of cyanobacteria in water, very high concentrations (up to 25 mg l⁻¹) of these toxins have been reported (Sivonen & Jones, 1999). Microcystins and nodularin are considered to be relatively resistant to degradation owing to their ring structure and to the presence of several unusual amino acids in the molecule. Indications of bacteria that degrade microcystins have been reported from sewage effluent, lake and river water, lake sediments and infiltration soil areas of lake water (Sivonen & Jones, 1999; Holst et al., 2003), but only a few bacterial strains with degradative ability towards microcystins have been isolated. Jones et al. (1994), Park et al. (2001), Saito et al. (2003) and Ishii et al. (2004) described the isolation of four Sphingomonas sp. or sphingomonad-like strains that degraded microcystins. Lahti et al. (1998) isolated 17 bacterial strains capable of degrading microcystins.
Degradation of nodularin was tested with three of these strains, and they all degraded this toxin. The strains were isolated from sediment (16 strains) and water (one strain) of eutrophic lakes Tuusulanjärvi (15 strains) and Vihnusjärvi (two strains), southern Finland, on 10 % (v/v) Z8 mineral medium supplemented with 1-2 % agar (Difco) and solid-phase fractionated extract of microcystins (8 mg l⁻¹). The cultures were stored at −80 °C in skimmed milk tubes (20 g skimmed milk, LaBM MC 27, in 100 ml deionized water, sterilized at 115 °C for 10 min). The strains were strictly aerobic, and they were routinely grown on R2A plates or in liquid R2 medium. They grew well at 20–30 °C, but failed to grow at 37 °C and on rich growth media such as tryptica soy agar (TSA; Difco). On the basis of whole-cell fatty acid profiles and partial 16S rRNA gene sequencing (500 bp) Lahti et al. (1998) tentatively identified one of the 17 strains as a *Sphingomonas* sp. strain, but the two other strains investigated could only be classified as members of the β-Proteobacteria.

Thirteen of these 17 microcystin-degrading strains were characterized in this study. Cells were observed under a phase-contrast light microscope (Diaplan, DMRXA2; Leica) at 1000 x. Gram-staining of the cells was performed according to Hucker (Murray, 1981). The motility of the strains was studied on casitone-yeast extract agar according to Ward et al. (1986) using incubation for 7 days at 30 °C. Flagella were observed from silver-nitrate-stained cells of strain 2C20² that were grown for 44 ± 4 h at 20 ± 2 °C on R2A slants overlaid with sterile deionized water. After cultivation, the water was collected from the surface of the slants and left to stand at 20 ± 2 °C for 2 h before staining. Oxidase and catalase tests were performed according to standard methods (APHA, 1985). The presence of bacteriochlorophyll a (BChl a) was examined from the cells of strain 2C20² grown on R2A plates for 68 ± 4 h at 20 ± 2 °C in the dark. Absorption spectra (340–1100 nm) were recorded spectrophotometrically (Hitachi U-2000) from intact cells suspended in sucrose solution (5 g sucrose in 3·5 ml deionized water) and acetone extract of the cells. Cells were Gram-negative, oxidase-positive (0·5–0·7 × 1·3–5·0 μm) and motile by means of a single polar flagellum. Cells were weakly catalase-positive when tested with a 3 % oxygen peroxide solution. When grown on R2A plates at 20 ± 2 °C for 68 ± 4 h they formed greyish colonies with a maximum size of 1 mm, and no BChl a was observed.

Physiological characteristics of the strains were studied using API 20NE and API ZYM tests (bioMérieux) and GN MicroPlate tests (Biolog Inc.). The sensitive fluorogenic test kit (Vepsäläinen et al., 2001) utilizing substrate analogues labelled with 4-methylumbelliferone compounds was used for the measurement of 12 enzyme activities (arylsulphatase, phosphomonoesterase, phosphodiesterase, cellulobioisidase, α- and β-glucosidase, β-xylosidase, chitinase or α-galactosidase activities were detected. Thus, the strains were efficient in mineralization of phosphorus and could release glucose by cutting sugar monomers from cellulose, but could not release D-xylene from 1,4-β-D-xylene, degrade cellulbiose by hydrolysis of 1,4-β-D-glucose bonds, release sugar monomers from starch or glycogen, release sulphur from organic molecules or degrade chitin, galactose oligosaccharides, galactomannans or galactolipids. Two strains (S1030 and 7A; Supplementary Table S1) had β-glucuronidase activity, which is used as a specific detection test at elevated temperatures for *Escherichia coli* in water samples (Sartory & Howard, 1992).

Some discrepancies were detected in the results of the enzyme activities measured with different methods. The strains had weak esterase and lipase activities in the API tests, but in the more sensitive fluorogenic tests these activities were strong. Fluorogenic analysis yielded positive reactions for β-glucosidase, and hydrolysis of aesculin (i.e. β-glucosidase activity) was observed in the API 20NE tests but not in the API ZYM test strips. β-Galactosidase activity was observed in most of the strains in the API 20NE tests.
but not with the API ZYM test strips. Activity of β-glucuronidase was detected in strains S1030 and 7A with the fluorogenic substrate analogues but not in the API tests. It is probable that the generally higher activities in the measurements based on fluorescence were due to the higher sensitivity of the fluorogenic method and possibly to differences in pH and the substrate used in the tests. Chemical degradation of the fluorogenic substrates was not observed, because in the buffered sterile control media the increase in absorbance was insignificant compared with that in the bacterial cultures.

The isolates used a limited number of carbon sources. Maltose and gluconate were the only carbon sources that most of the isolates assimilated in the API tests (Supplementary Table S1). In the Biolog tests, after incubation for 21 ± 3 h, all the strains showed the ability to use Tween 40 as a carbon source. Six strains (2C23, 2B3, 2B15, 2B5, 15B and 2) were also able to use β-hydroxybutyric acid. Additionally, strain 2B15 used DL-lactic acid and p-hydroxyphenylacetic acid, and strain 2 used DL-lactic acid and γ-hydroxybutyric acid. Even after incubation for 96 ± 4 h (Supplementary Table S2) clearly positive reactions of all strains were detected only with Tween 40.

For whole-cell fatty acid analysis the strains were cultivated for 21 ± 3 h (Supplementary Table S3) and for 96 ± 4 h (Supplementary Table S2) clearly positive reactions of all strains were detected only with Tween 40.

Genomic DNA was isolated from the strains using the commercial RDtract DNA–RNA purification kit (BioLabs). The 16S rRNA genes were sequenced with the DNA cycle sequencing system (Promega) as described by Kalmbach et al. (1997). We used BLAST searches (Altschul et al., 1997) of the GenBank database for the sequences, and they were aligned using the BIOEDIT program. Datasets of 1430 bp including gaps were analysed with PAUP* (Swofford, 2001). Anaabena sp. 90 was used as an outgroup. Phylogenetic trees were inferred using neighbour-joining (NJ) and maximum-parsimony (MP) criteria. The NJ tree was constructed on the basis of distance values calculated by the F84 model. In the MP criterion, 10 heuristic searches and random addition sequence starting trees were used. The validity of the groups was tested by analysing 1000 bootstrap replicates. The G+C content of the genomic DNA was determined at the DSMZ by using HPLC (Mesbah et al., 1989). On the basis of the 16S rRNA gene sequences all isolates were very similar to each other (98.9–100 %). They formed five distinct sublinesages with G+C content varying from 66.1 to 68.0 mol% (Supplementary Table S2). On the basis of 16S rRNA gene sequence analysis, the closest relatives of the strains were Roseateles depolymerans DSM 11814 and DSM 11813T (Suyama et al., 1999) with 95.7–96.3 % similarity and Matsuebacter chitosanotabidus DSM 2001 (Park et al., 1999) with 96.1–96.8 % similarity. The other seven closest relatives of the strains (Fig. 1) are poorly characterized, and they have been isolated from various sources. Whereas the two closest relatives, β-proteobacterial strains R-8875 (97.0–97.1 % similarity) and CD12 (96.5–96.8 % similarity), were isolated from microbial mats of Antarctic lakes (van Trappen et al., 2002) and a cryoconite hole in Antarctica (Christner et al., 2003), Pseudomonas saccharophila DSM 654T (95.4–96.0 % similarity) was isolated from ultra pure water in industrial systems (Kulakov et al., 2002), and the β-proteobacterial strain MBIC3293 (96.7–97.5 % similarity) from the surface of iron. Pseudomonas saccharophila is not included in the cluster of Pseudomonas (sensu stricto) and has been recommended to be transferred to another genus (Anzai et al., 2000). Strain MBIC3293 has tentatively been assigned as Leptothrix sp. (http://seasquirt.mbio.co.jp/mbic/browse/bd_ccstrain.php?strainnumber=3557), but

Fig. 1. Neighbour-joining tree based on 16S rRNA gene sequence analysis, illustrating the phylogenetic position of Paucibacter toxinivorans gen. nov., sp. nov. The most closely related β-proteobacterial strains and type strains of the most closely related species are included in the tree. Neighbour-joining and maximum-parsimony bootstrap values (>80 %) based on 1000 replicates are indicated at the nodes. The outgroup strains used were Sphingomonas sp. ACM 3962 (GenBank accession no. AF411072) and Y2 (AB084247) and Anaabena sp. 90 (AJ133156, not shown in the figure).
according to our phylogenetic analysis the strain is closely related to *Roseateles* and ‘*Matsuebacter*’. According to the information obtained from GenBank, the β-proteobacterial strain ASRB1 was isolated from fronds, and is resistant to arsenic. No information other than that for the 16S rRNA gene sequence from GenBank could be obtained for the unidentified β-proteobacterial strains A1040 and A0647.

The degradation ability of several isolates from different phylogenetic sublineages (strains S1030, F36, 2C20T, 2 and 2C23) towards microcystins and nodularin was tested using extracts of toxic cyanobacterial strains obtained from the Finnish Environment Institute (*Microcystis* 764 producing microcystins -LR and -YR and *Nodularia* 790 producing nodularin). Previously, the degradation of nodularin had been preliminarily tested with two strains (G44 and F36) of the group, and degradation of microcystins had been studied using mainly one demethyl variant of microcystin-RR (Lahti et al., 1998). The closest relative of the isolates, *R. depolymerans* DSM 11813T, was also tested. All degradation tests were made in sterilized water that originated from an oligotrophic lake (Lake Päijänne). Toxin extracts from the cyanobacterial cells were partly purified using BondElut C18 cartridges (Varian) as described by Rapala et al. (2002), and were added (800–4300 μg l⁻¹) to the lake water. During the degradation tests, toxin concentrations were determined using the protein phosphatase inhibition assay (Rapala et al., 2002) and colony-forming unit counts were made after 7 days of incubation on R2A plates at 20 ± 2°C.

All tested isolates degraded nodularin, with maximum rates of 35–87 μg l⁻¹h⁻¹ (3–560 fg cell⁻¹ h⁻¹), and the mixture of microcystins -LR and -YR, with maximum rates of 4–16 μg l⁻¹h⁻¹ (2–30 fg cell⁻¹ h⁻¹). *R. depolymerans* DSM 11813T did not degrade the toxins. Previously, only three of our isolates (strains G44 and F36 belonging to the β-Proteobacteria and the siphonomonad F38; Lahti et al., 1998) and the *Sphingomonas* sp. strain 7CY isolated in Japan (Ishii et al., 2004) have been reported to degrade nodularins. Strain 7CY degraded a variant of nodularin (nodularin-Har) only in the presence of microcystin-RR, whereas our strains degraded nodularin without addition of microcystin.

The closest relatives of our toxin-degrading isolates possess specific enzyme activities. *R. depolymerans* was originally isolated from river water as a degrader of poly(hexamethylene carbonate) (PHC) (Suyama et al., 1999). In addition to PHC the bacterium can utilize other biodegradable plastics. ‘*Matsuebacter chitosanotabidus*’ was characterized as a species producing the enzyme chitosanase, which catalyses the hydrolysis of glycosidic bonds of chitosan, a totally or partially deacylated derivative of chitin (Park et al., 1999). The more distant *Ideonella dechloratans* is able to metabolize chlorate (Danielsson Thorell et al., 2003). From the same samples from Antarctica where CD12 was originally isolated, clones of cyanobacteria belonging to the genera *Chamaesiphon*, *Leptolyngbya* and *Phormidium* were sequenced and isolated. Because microcystins have been detected also from Antarctica (Hitzfeld et al., 2000), it would have been interesting to study the potential of CD12 to degrade microcystins. However, CD12 could not be obtained, and such tests could not be performed. Instead, some of the isolated Antarctic cyanobacterial strains were tested in our laboratory for the presence of microcystins, but none of the strains produced them (data not shown). *Pseudomonas saccharophila* is facultatively oligotrophic, and contains a nitrogen fixation gene *nifH*. The more distant *Ideonella* is also capable of fixing nitrogen (Elbeltagy et al., 2001). Similarly to these nitrogen-fixing bacteria, our strains preferred oligotrophic conditions, as they failed to grow on rich growth media, such as complete TSA (Lahti et al., 1998). Whether our strains possess *nif* genes and thus are capable of fixing nitrogen remains to be determined.

The bacteria characterized in this study could not be assigned to any recognized genus in the β-Proteobacteria. On the basis of the phylogenetic and physiological differences between the strains and their closest relative *R. depolymerans*, we propose the creation of a novel genus and species, *Paucibacter toxinivorans* gen. nov., sp. nov., to accommodate these strains. *R. depolymerans* and *Paucibacter toxinivorans* share 95.7–96.3% similarity based on 16S rRNA gene sequence analysis. These two genera differ in their reactions in the catalase test, in the colour of their colonies (pink versus greyish), in the production of BChl a and in the ability to utilize different carbon sources. Whereas *R. depolymerans* grows heterotrophically on several carbon sources commonly found in nature (glucose, fructose, galactose, sucrose, mannitol, acetate, citrate and succinate), *Paucibacter toxinivorans* was able to use only a few carbon sources. All 13 strains studied used Tween 40 and 11 strains (85%) used β-hydroxybutyric acid. The other carbon sources that more than half of the strains used were maltose and gluconate. Additionally, *R. depolymerans* was not able to degrade cyanobacterial hepatotoxins microcystins and nodularin, whereas all *Paucibacter toxinivorans* strains did.

**Description of *Paucibacter* gen. nov.**

*Paucibacter* [Pau.ci.bacter. L. adj. paucus few/little; N.L. masc. n. *bacter* rod; N.L. masc. n. *Paucibacter* a rod that is content with a few (carbon sources)].

Cells are rod-shaped and motile by means of a single polar flagellum. Gram-negative, oxidase-, alkaline phosphatase-, chymotrypsin- and leucine arylamidase-positive. Weak catalase-positive reaction. Grow heterotrophically under aerobic conditions. Can grow using Tween 40 as a sole carbon source, but utilize few other carbon sources. The main cellular fatty acids are C16:0; summed feature 4 (C16:1ω7c) and summed feature 7 (ω9c, ω9t and ω12t forms of C18:1ω9t). G+C content of the genomic DNA is 66–1–68.0 mol% (HPLC). The type species is *Paucibacter toxinivorans*. 
Description of *Paucibacter toxinivorans* sp. nov.

*Paucibacter toxinivorans* (tox.i.ni.vo’rans. N.L. n. *toxinum* toxin; L. part. adj. *vorans* devouring; N.L. part. adj. *toxinivorans* eating toxins, pertaining to its ability to degrade cyanobacterial hepatotoxins).

Displays the following properties in addition to those given in the genus description. Forms greyish colonies on R2A plates. After incubation for 65 h at 20 ± 2 °C on R2A, colonies are ≤ 1 mm in diameter. Cell size is 0.5–0.7 × 1.3–5.0 μm. Fails to grow on rich media, such as TSA. Grows well at 20–30 °C but does not grow at 37 °C. Oxidase-positive. Weakly catalase-positive. Positive for acid and alkaline phosphatases, naphthol-AS-BI-phosphohydrolase and phosphodiesterase. Most of the strains are positive for cysteine and valine arylamidases. Utilization of carbon sources other than Tween 40 is rare. Degrades microcystins and nodularin (cyanobacterial hepatotoxins). The main cellular fatty acids are C16:0 (10–19 %), C16:1ω7c, which is included in summed feature 4 (54–62 %), and summed feature 7 (8–28 %), which includes ω7c, ω9c and ω12t forms of C18:1. G+C content of the genomic DNA is 66.1–68.0 mol% (HPLC).

The type strain is 2C20T (DSM 16998T = HAMBI 2767T = VYH 193597T). DNA G+C content of the type strain is 66.9 mol%. Isolated from sediment of eutrophic lake Tuusulanjärvi, southern Finland.

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References


