**Phenylobacterium lituiforme** sp. nov., a moderately thermophilic bacterium from a subsurface aquifer, and emended description of the genus *Phenylobacterium*

Sungwan Kanso and Bharat K. C. Patel

Microbial Discovery Research Unit, School of Biomolecular and Biomedical Sciences, Faculty of Science, Griffith University, Brisbane, Queensland 4111, Australia

A facultative anaerobic bacterium, strain Fail3\(^T\), was isolated from samples collected from the free-flowing waters of a bore well (Fairlea Bore, registration number 3768) which taps into the Australian Great Artesian Basin subsurface thermal aquifer. Strain Fail3\(^T\) developed yellow to pale-yellow colonies (0-5–1-5 mm) after 48 h. The non-spore forming rods (0-5 × 1–3 μm) were slightly curved, occurred singly and as pairs and were motile with a single polar flagellum. Cells tended to form clumps in liquid medium and rosettes were commonly observed. The cells stained Gram-negative and electron micrographs of thin sections revealed a multi-layered complex Gram-negative cell wall structure. Strain Fail3\(^T\) grew optimally at 40–41 °C, with growth observed at 45 °C but not at 50 °C. The pH growth range was between pH 6 and 9 and optimal growth occurred between pH 6 and 6-5. Strain Fail3\(^T\) grew best with yeast extract as the sole carbon and energy source. Peptone, yeast extract, acetate, xylose, sucrose, glucose, glycogen, succinate, butyrate, lactate, fumarate, citrate, L-phenylalanine, cellobiose and gelatin supported growth but maltose, fructose, glycine, ethanol, benzoate and oxalate did not. Tyrosine was produced from L-phenylalanine. Strain Fail3\(^T\) was catalase-positive and oxidase-negative and did not hydrolyse starch. Growth was inhibited by neomycin, tetracycline, streptomycin, chloramphenicol, ampicillin, vancomycin and spectinomycin. The G+C content was determined to be 66.5 ± 0.5 mol%.

On the basis of the 16S rRNA gene sequence analysis, strain Fail3\(^T\) was assigned as a novel species of the genus *Phenylobacterium*, *Phenylobacterium lituiforme* sp. nov. in the order *Caulobacterales*, subclass α-Proteobacteria, class Proteobacteria. The type strain is Fail3\(^T\) (=ATCC BAA-294\(^T\) = DSM 14363\(^T\)).

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**Abbreviation**: GAB, Great Artesian Basin.

The GenBank/EMBL/DDBJ accession number for the 16S rRNA gene sequence of *Phenylobacterium lituiforme* strain Fail3\(^T\) (=ATCC BAA-294\(^T\) = DSM 14363\(^T\)) is AY594887.
Samples were collected by completely filling sterile glass containers with water emitted from the mouth of the outflow of Fairlea Bore (temperature 42 °C and pH 8.2), which is located in Longreach district, Queensland. The bottles were then capped and transported to the laboratory at Griffith University and stored at room temperature until used. For strain isolation, modified RouF’s medium agar (pH 7.1) plates were spread with 10, 50 and 100 µl each of the bore water sample and the plates incubated at 37, 40 and 50 °C for 24 h. Modified RouF’s medium (Mulder & Deinema, 1992) contained (per 1000 ml distilled water) 1 g yeast extract, 0.2 g MgSO₄·7H₂O, 0.05 g CaCl₂, 0.15 g ammonium iron (III) citrate, 0.05 g MnSO₄·4H₂O, 0.01 g FeCl₃·4H₂O, 17 g agar, 10 ml Wolin vitamin solution (Wolin et al., 1963) and 1 ml Zeikus’s trace element solution (Zeikus et al., 1979). Based on the colony morphology and pigmentation, a representative colony from each of the five different colony types that developed was picked and streaked onto new plates. This procedure was repeated at least twice before the isolates were deemed to be pure. The isolates were finally subcultured in liquid RouF’s medium which lacked agar, sterile glycerol added to a final concentration of 50 %, and the isolates frozen as stock cultures at −20 °C. Strain FaiI3ᵀ, which produced 0.5–1.5 mm yellow colonies after 48 h incubation at 37 °C, was selected for further characterization. Carotenoids with absorbance peaks at A₄60–A₄68 were detected from acetone-extracted cell-free supernatants using a Cintra20 Spectrophotometer (GBC Scientific Equipment). The colonies of strain FaiI3ᵀ were circular and convex with entire edges, had a smooth surface and possessed a sticky texture, which emulsified in water easily. An odour was present. Cellular characterization and sporulation tests performed as described previously (Kanso & Patel, 2003) showed that the cells of strain FaiI3ᵀ stained Gram-negative, occurred singly or in pairs and short chains of three cells were rarely observed. The cells were usually short to slightly curved rods (0.5 × 1–3 µm), but filamentous cells (4–7 µm) were also present. Cell rosettes were frequently observed. Strain FaiI3ᵀ was motile with a single polar flagellum (Fig. 1a). Electron microscopic examination of thin sections revealed a Gram-negative type cell wall ultrastructure (Fig. 1b). Spores were never observed and cells were heat sensitive.

Strain FaiI3ᵀ was a facultative anaerobe as it also grew in anaerobic liquid RouF’s medium (pH 7.1), which had been prepared by boiling, cooling and dispensing 10 ml aliquots into Hungate tubes under a stream of oxygen-free N₂. Further proof of the strain’s facultative nature comes from our observation that the strain grew along the stab in RouF’s deep agar slants.

Maximal RouF’s medium lacking agar and containing 5 g yeast extract l⁻¹ instead of 1 g l⁻¹ was used to determine optimum growth conditions and inhibitory effects of antibiotics and NaCl. Strain FaiI3ᵀ grew optimally at 40–41 °C with growth occurring at 45 °C but not at 50 °C. The pH growth range was between pH 6 and 9 with an optimum between pH 6 and 6.5. Strain FaiI3ᵀ had a generation time of 4 h under optimal growth conditions. Strain FaiI3ᵀ grew best without NaCl and as little as 0.5 % NaCl inhibited 75 % of its growth. Neomycin, tetracycline, streptomycin and chloramphenicol at 10 µg ml⁻¹ and ampicillin, vancomycin and spectinomycin at 50 µg ml⁻¹ completely inhibited growth of strain FaiI3ᵀ.

Characterization studies performed by adding appropriate substrates from 2 or 3 M sterile stock solutions to a final concentration of 20 mM to RouF’s minimal medium (10 ml) containing 0.006 % (w/v) yeast extract and lacking peptone and agar indicated that strain FaiI3ᵀ grew on a wide range of substrates (Table 1). Inoculation of API 20E (bioMérieux) and BBL Crystal E/NF identification kits (Becton Dickinson) with strain FaiI3ᵀ, following the manufacturer’s recommended protocols, showed weak acid production from glucose and arabinose but not from mannose, sucrose, melibiose, rhamnose, sorbitol, mannitol, adonitol, galactose, amygdalin or inositol. In addition, nitroanilidase, glucosidase and catalase were produced but not oxidase, urease, tryptophan deaminase, ornithine decarboxylase, arginine dihydrolase, H₂S, lysine...
decarboxylase, β-galactosidase, arabinosidase, glucuronidase, glucuronamidase, xylosidase, indole from tryptophan or acetoin. Nitrate was reduced to nitrogen. Casein but not starch was hydrolysed as determined by the method of Smibert & Krieg (1994).

Growth in RouF’s minimal medium containing either 0.06 % or 0.006 % yeast extract and L-phenylalanine (0.5 g L⁻¹) was determined over a 76 h incubation period at 41 ℃ by measuring growth at OD₆₀₀ and the formation of tyrosine using the modified method of Lowry et al. (1951). An uninoculated culture medium served as control. An increase in the growth of strain FaiI3 T with the concomitant increase in tyrosine was observed in minimal RouF’s media (Fig. 2).

The fact that strain FaiI3 T has an optimum growth temperature of 41 ℃ reflects closely its environmental habitat of the moderately thermal waters (42 ℃) of the GAB of Australia, a deep subsurface aquifer. Strain FaiI3 T was isolated by plating aquifer samples that had been collected directly from the bore source without surface contamination. Both these observations suggest that the primary habitat of the strain is the aquifer. Strain FaiI3 T uses a wide range of organic substrates including the aromatic amino acid L-phenylalanine for growth. The later is a rare characteristic not commonly reported in bacteria. The ability of strain

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>P. lituiforme strain FaiI3 T* (= ATCC BAA-294 T = DSM 14363 T)</th>
<th>P. immobile strain E T † (= DSM 1986 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecology</td>
<td>Water from subsurface aquifer</td>
<td>Soil</td>
</tr>
<tr>
<td>Pigmentation, cell shape and size (μm)</td>
<td>Yellow to pale-yellow, rods, 0.5 × 1–3</td>
<td>Colourless, rods to coccoid rods, 0.7–1 × 1–2</td>
</tr>
<tr>
<td>Motility</td>
<td>Motile</td>
<td>Non-motile</td>
</tr>
<tr>
<td>Flagella</td>
<td>Single, polar</td>
<td>None</td>
</tr>
<tr>
<td>O₂ requirement</td>
<td>Facultative anaerobe</td>
<td>Obligate aerobes</td>
</tr>
<tr>
<td>Growth temperature (℃)</td>
<td>Range 25–45, no growth at 50, optimum 40–41</td>
<td>Optimum 28–30, no growth at 37</td>
</tr>
<tr>
<td>pH growth range</td>
<td>6–9, optimal at 6–6.5</td>
<td>6.5–8, optimal at 6.8–7</td>
</tr>
<tr>
<td>NaCl growth range</td>
<td>Optimal at 0 %, no growth at 1 %</td>
<td>Optimal at 0 %, no growth at 1 %</td>
</tr>
<tr>
<td>Oxidase activity</td>
<td>–</td>
<td>+ (weak)</td>
</tr>
<tr>
<td>Gelatin hydrolysis</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Growth on substrates:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glucose</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Sucrose</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Xylose</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Glycerol</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Acetate</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Succinate</td>
<td>+</td>
<td>+ (slow)</td>
</tr>
<tr>
<td>Citrate</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>G+C (mol%)</td>
<td>66 ± 0.5 – 65.5</td>
<td>65.5</td>
</tr>
</tbody>
</table>

* RouF’s medium containing 0.006 % yeast extract did not support growth of strain FaiI3 T and was therefore used for substrate utilization tests. Growth was measured after incubation for up to 48 h at 41 ℃ at OD₆₀₀. Strain FaiI3 T utilized yeast extract (the best growth substrate), peptone, acetate, pyruvate, succinate, butyrate, lactate, citrate, fumarate, L-phenylalanine, xylose, sucrose, glucose, glycerol and cellobiose but not maltose, fructose, glycine, ethanol, benzoate, oxalate, aesculin or nitrilotriacetate.
† Data from Lingens et al. (1985).
FaiI3T to grow on such a wide range of organic compounds may reflect its survival and adaptation on organic matter released from decomposing dead cells in the otherwise pristine GAB waters.

Genomic DNA was prepared using a modified method (Marmur, 1961) in which achromopeptidase (final concentration 1 mg ml\(^{-1}\)) was used for cell lysis and RNase (20 \(\mu\)g ml\(^{-1}\)) used to digest RNA. The DNA was dissolved overnight at 4°C in 0.1 \(\times\) SSC to a concentration of 20 \(\mu\)g ml\(^{-1}\). Its thermal denaturation temperature \(T_m\) was determined to be 66.5 ± 0.5 mol% using a Cintra20 spectrophotometer (GBC Scientific Equipment). Escherichia coli genomic DNA prepared in the same manner was used as reference DNA.

The methods used for 16S rRNA gene amplification and sequencing have been reported previously (Andrews & Patel, 1996). Partial sequences generated in this investigation were assembled and the consensus sequence corrected manually for errors using BioEdit v5.0.1 (Hall, 1999). The most closely related sequences against GenBank and Ribosomal Database Project II were identified using BLAST (Altschul et al., 1997) and the Sequence Match program (Maidak et al., 2001); sequences were then extracted, aligned and manually adjusted according to the 16S rRNA secondary structure using BioEdit. Sequence uncertainties were omitted and phylogenetic reconstruction achieved using TreeCon (Van de Peer & De Wachter, 1994) in which pairwise evolutionary distances were computed from percentage similarities (Jukes & Cantor, 1969) and phylogenetic trees constructed from the evolutionary distances using the neighbour-joining method (Saitou & Nei, 1987). FastDNAml was also used in phylogenetic reconstruction (Olsen et al., 1994). Tree topology was re-examined by using the bootstrap method of resampling (Felsenstein, 1985) using 1000 bootstraps.

16S rRNA gene sequence of strain FaiI3T showed the greatest similarity to members of the order Caulobacterales, subclass \(\alpha\)-Proteobacteria, class Proteobacteria. The closest relatives were Phenyllobacterium immobile (similarity value of 96 %) and members of the genera Caulobacter (Abraham et al., 1999) and Brevundimonas (mean similarity value of 94 %) (Fig. 3). The low level of similarity between strain FaiI3T and Caulobacter and Brevundimonas is in itself indicative that it is a distinct species. However, the ability of strain FaiI3T to grow optimally at 41°C in the absence of NaCl differentiates it from members of the genera Caulobacter and Brevundimonas, which grow optimally at 20–25°C but not above 35°C and require NaCl for optimal growth (Abraham et al., 1999; Lingens et al., 1985).

Both strain FaiI3T and \(P.\) immobile, the sole member of the genus Phenyllobacterium, share the ability to metabolize the aromatic amino acid L-phenylalanine for growth, have a G + C content of 65–66 mol%, are sensitive to growth in the presence of 0.5 % NaCl, have a similar antibiotic sensitivity profile, possess a similar cell wall ultra-structure and are close phylogenetic relatives. However, there are numerous phenotypic differences between them, which provide evidence of distinctness (Table 1). Strain FaiI3T is a facultative anaerobe which grows optimally at 41°C (maximum growth temperature of 45°C), is actively motile with a single flagellum and its colonies are yellow, whereas \(P.\) immobile is an obligate aerobe which grows optimally between 28 and 30°C with no growth occurring at 37°C, is non-motile and the colonies are non-pigmented. In addition, \(P.\) immobile grows well only on restricted and specialized substrates, which include, in addition to L-phenylalanine, the herbicides chloridazon, antipyrin and pyramidon. In contrast, strain FaiI3T grows on a much wider range of substrates including carbohydrates such as glucose, sucrose and xylose, glycine and gelatin as well as fatty acids, which include acetate, succinate and butyrate. Furthermore, \(P.\) immobile is a slow-growing bacterium and requires 2–3 weeks incubation for colony development (Lingens et al., 1985) whereas the colonies of strain FaiI3T develop within 36–48 h incubation at 41°C. However, the 16S rRNA gene sequence similarity of 96% in itself is clearly sufficient to justify the inclusion of strain FaiI3T as a new species of the genus Phenyllobacterium. Based on the evidence presented above, we propose to emend the description of the genus Phenyllobacterium and assign strain FaiI3T as a new species, Phenyllobacterium lituiforme sp. nov.

Emended description of Phenyllobacterium

Lingens et al. 1985

Cells stain Gram-negative, are non-spore forming straight to slightly curved rods, cocccobacilli or cocci measuring 0.7–1.0 × 1.0–2.0 \(\mu\)m and occur singly, in pairs or short chains. Strains may form rosettes. Filamentous cells tend to form in old cultures. Species may be strict aerobes or facultative anaerobes and may be motile or non-motile. Cells do not form sheaths or prosthecae and are not acid-fast. The members of the genus grow on L-phenylalanine. Based on the 16S rRNA gene sequence analysis, members of this genus form a monophyletic group within the order Caulobacterales, subclass \(\alpha\)-Proteobacteria of the class Proteobacteria. The DNA base ratio is 65 ± 1 mol% G+C. Isolated from soil and water.

The type species is Phenyllobacterium immobile Lingens et al. 1985 (strain ET\(^{T}\) = DSM 1986\(^{T}\)).

Description of Phenyllobacterium lituiforme sp. nov.

Phenyllobacterium lituiforme (li.tu.i.for’me. L. masc. n. litu us curved rod of the augurs; L. neut. adj. suffix -forme having the form of; N.L. neut. adj. lituiforme formed like a curved rod).

Strain FaiI3T is a facultative anaerobe isolated from water collected from a free-flowing bore well, tapping the underground water of the Great Artesian Basin of Australia. Yellow to pale-yellow colonies (0.5–2 mm) develop on...
Phenylobacterium lituiforme sp. nov.

Fig. 3. Dendrogram showing the phylogenetic position of Phenylobacterium lituiforme strain Fail3T (=ATCC BAA-294T=DSM 14363T) as a member of the family Caulobacteraceae, order Caulobacterales, subclass α-Proteobacteria in class Proteobacteria. The dendrogram was constructed by using the neighbour-joining method and Jukes & Cantor evolutionary distance matrix data obtained from 1381 unambiguous aligned nucleotides. The sequences were extracted from the Ribosomal Database Project (RDP) version 8.0 and GenBank database, release 121. The clusters indicated as triangles for Caulobacter species represent Caulobacter vibrioides VKM-B1496T (AJ009957), Caulobacter fusiformis ATCC 15257T (AJ227759) and Caulobacter henricii ATCC 15253T (AJ227758) and for Brevundimonas species represent Brevundimonas vesiculans IAM 12105T (AB021414) and Brevundimonas diminuta IAM 12691T (AB021415). The triangle representing sequences for the order Sphingomonadales were used as outgroups and includes Zymomonas mobilis subsp. mobilis ATCC 10988T (RDP, unpublished), Blastomonas natatoria ATCC 35951T (X73043), and Sandaracino bacter sibiricus strain RB16-17T (Y10678). Bootstrap values (from 100) are indicated at the nodes. GenBank/EMBL/DDJB accession numbers for the sequences are shown in parentheses. Scale bar indicates 10 substitutions per 100 nucleotides.

RouF’s agar plates after 48 h at 41 °C. Colonies are circular, convex, with an entire edge and smooth surface, are sticky in texture, fairly easily emulsified and odour is present. The cells are non-spore-forming straight to slightly curved rods (0.5 by 1–3 μm), motile with a single polar flagellum, occur mainly singly, some in pairs and short chains. Cells often tend to clump in liquid medium to form rosettes. The cells stain Gram-negative and electron micrographs of thin sections reveal a multi-layered complex Gram-negative cell wall. Sheaths and prosthecae are not produced. Strain FaiI3T grows optimally at 40–41 °C and growth is observed at 45 °C but not at 50 °C. The pH range for growth is 6–9 and optimal growth occurs between pH 6 and 6.5. Strain Fail3T is very sensitive to NaCl and growth is inhibited by 0.5% (w/v) NaCl. Strain Fail3T grows best with yeast extract as the sole carbon and energy source. Peptone, yeast extract, acetate, pyruvate, xyllose, sucrose, glucose, glycerol, succinate, butyrate, lactate, citrate, fumarate, l-phenylalanine, cellobiose and gelatin support growth but maltose, fructose, glycine, ethanol, benzoate and oxalate do not. Tyrosine is produced from l-phenylalanine. Strain Fail3T is catalase-positive, oxidase-negative and does not hydrolyse starch. Growth is inhibited by neomycin, tetracycline, streptomycin, chloramphenicol, ampicillin, vancomycin and spectinomycin. The G+C content is 66.5 ± 0.5 mol%.

The type strain is Fail3T (=ATCC BAA-294T=DSM 14363T).

References


