‘Candidatus Rhabdochlamydia porcellionis’, an intracellular bacterium from the hepatopancreas of the terrestrial isopod Porcellio scaber (Crustacea: Isopoda)

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Intracellular bacteria were observed in the hepatopancreas of the terrestrial isopod Porcellio scaber. Comparative 16S rRNA gene sequence analysis and electron microscopic observations were used to determine the taxonomic position of these intracellular bacteria. Phylogenetic analysis and a complex developmental cycle affiliate these bacteria to the order Chlamydiales, within which they form a distinctive lineage, close to the family Simkaniaeeae. They share <92% 16S rRNA gene sequence similarity with their closest relative and <88% similarity with other members of the order Chlamydiales. A specific signature oligonucleotide sequence was identified and used as a probe, enabling the identification of intracellular bacteria in infected hepatopancreatic tissue. According to the distinctive morphology of their elementary bodies, which are rod-shaped rather than spherical and contain translucent oblong structures, their genomic properties and their crustacean host, the name ‘Candidatus Rhabdochlamydia porcellionis’ is proposed for intracellular bacteria in the hepatopancreas of P. scaber.

INTRODUCTION

As in many crustaceans (Fryer & Lannan, 1994), tissues of terrestrial isopods (Isopoda, Oniscidea) are often invaded by intracellular bacteria with a complex developmental cycle that is characteristic of chlamydias and Rickettsiella spp. (Weiss et al., 1984). As well as documented infections of terrestrial isopod tissue with Rickettsiella gryllyi (Vago et al., 1970; Federici, 1984; Weiss et al., 1984; Abd El-Aal & Holdich, 1987; Frutos et al., 1994), another intracellular bacterium with a complex developmental cycle was observed in hepatopancreatic cells of the terrestrial isopod Porcellio scaber Latreille, 1804 (Shay et al., 1985; Drobne et al., 1999). Despite obvious similarities in the morphology of the described intracellular bacteria and the pathological changes in infected hepatopancreatic tissue, various authors affiliated these bacteria to different bacterial groups. Thus, Drobne et al. (1999) related the intracellular bacteria to the genus Rickettsiella, due to the rod-like shape of their elementary bodies (Weiss et al., 1984). This was in concert with prevailing reports on the occurrence of this bacterial group in terrestrial isopods (Federici, 1984; Weiss et al., 1984; Abd El-Aal & Holdich, 1987). On the other hand, the condensation of nucleotide in the centre of the intermediate body, the complex developmental cycle and the positive Gimenez staining of the elementary bodies led Shay et al. (1985) to propose that these bacteria were chlamydialae. As no cross-reactivity was observed between the intracellular hepatopancreatic bacteria from P. scaber with Chlamydia trachomatis- and Chlamydia psittaci-specific antisera, the name ‘Chlamydia isopodii’ was proposed (Shay et al., 1985). However, the description of the species was not validly published in any of the journals recommended by the International Committee for Systematic Bacteriology and the name has not been included in either the Approved Lists of Bacterial Names or the List of Bacterial Names with Standing in Nomenclature (Euzeby, 1997).

In order to clarify the phylogenetic position of the hepatopancreatic intracellular bacteria from P. scaber, electron microscopic observations and a molecular approach that included comparative 16S rRNA gene sequence analysis and fluorescence in situ hybridization with 16S rRNA-targeted
oligonucleotide probes were performed. The results, which confirm the chlamydial origin of the intracellular hepatopancreatic bacteria from _P. scaber_ and reveal that they represent a novel phylogenetic lineage among the order _Chlamydiales_, are described in this paper.

**METHODS**

**Animals.** Terrestrial isopods (_P. scaber_) were identified according to the woodlouse determination key (Hopkin, 1991). Animals of both sexes were kept at 20 °C in glass tanks filled with soil, under conditions of high humidity and a 16/8 h day/night cycle. Animals were fed on leaf litter from an unpolluted site for at least 1 month prior to the experiment. Infected animals with macroscopically distinctive white spots in the hepatopancreas were used in the experiment.

**DNA extraction, PCR amplification and cloning.** Infected digestive glands were removed from the animals with fine-tipped sterile forceps. The glands were transferred to 0.5 ml sterile PBS (pH 7.4) and crushed by using a teflon homogenizer. Genomic DNA was extracted from the isolated digestive glands by a method described previously (Kostanješek et al., 2002). The universal forward primer 522-f (5'-CACGAGCCGCGGTAATAC-3', Escherichia coli positions 522–536) (Giovannoni et al., 1988) and the chlamydia-specific forward primer 16S1 (5'-CGGATCTGGAAATTTGAC-3', _E. coli_ positions 2–18) (Pujidič et al., 1997) were used, in combination with the universal reverse primer 1392-r (5'-GYACACAGCGCCGT-3', _E. coli_ positions 1392–1406) (Lane, 1991), for PCR amplification of the 16S rRNA gene (denaturation at 94 °C for 5 min, 30 cycles of 40 s at 95 °C, 30 s at 65 °C and 40 s at 72 °C, followed by a terminal extension of 10 min at 72 °C), which resulted in amplification products of approximately 870 or 1365 bp, respectively. Amplified DNA was checked by agarose electrophoresis and rehydrated by immersing the slides in xylene, and then subsequently into 96, 80 and 50% ethanol, for 3 min each. Sections were hybridized in 18 μl hybridization buffer (Hahn et al., 1992) and 2 μl fluorescent probe (50 pmol) at 46 °C for 4 h in sealed hybridization frames (MI Research). The oligonucleotide probe was synthesized and labelled with the cyanine dye Cy3 by MWG-Biotech AG (Ebersberg, Germany). After hybridization, slides were washed in hybridization buffer for 20 min at 48 °C, rinsed with distilled water and air-dried. Sections were examined by using an Olympus BX50 fluorescent microscope.

**Microscopy.** Light microscopy of Carnoy-B-fixed and haematoxylin/eosin-stained serial sections of infected cells was performed as described previously (Drobne et al., 1999). Ultrastructural observations of the intracellular bacteria were performed by using transmission electron microscopy as described previously (Drobne et al., 1999).

**RESULTS AND DISCUSSION**

**Morphology and life cycle of the intracellular bacteria in hepatopancreatic tissue**

Examination of electron micrographs revealed a chlamydial-like morphology and developmental cycle for the intracellular bacteria in the hepatopancreas of _P. scaber_ (Fig. 1), as defined by Everett et al. (1999). Our observations were congruent with previous descriptions of intracellular bacteria that were given by Shay et al. (1985) and Drobne et al. (1999).

Three distinct forms of intracellular bacteria were observed in infected cells: spherical reticulate bodies, spherical early stages of elementary bodies (known as intermediate bodies) and rod-shaped mature elementary bodies (Fig. 1). Spherical reticulate bodies exhibited a network of fine filaments in the cytoplasm and a cell wall with three layers. They appeared as small reticulate bodies (up to 1 μm in diameter), in which binary fission was observed, and as larger reticulate bodies (1–4 μm in diameter) with electrondense transversal termination in the cytoplasm (Drobne et al., 1999). Rod-shaped mature elementary bodies were approximately 250–700 nm long, with a diameter of 100–150 nm. Detailed observations of mature elementary bodies revealed the presence of a five-layered cell wall, with approximately 16 nm thick transverse laminations in the electron-dense cytoplasm (Fig. 2). Transitional forms between reticulate and elementary bodies were spherical intermediate bodies (approx. 350–650 nm in diameter), with a characteristic electron-dense
central area (Fig. 1). All forms of the hepatopancreatic intracellular bacteria showed the Gram-negative microscopic appearance of a cell wall, without a discernible peptidoglycan layer.

Bacteria in the cytoplasm of infected cells were packed in membrane-bound vacuoles (Fig. 1), which is characteristic of most members of the order *Chlamydiales* (Everett *et al.*, 1999). In the later stages of infection, vacuole size increased, due to multiplication of the intracellular bacteria (see Supplementary Figure in IJSEM Online). At this stage, vacuoles (up to 30 μm in diameter) or aggregations of vacuoles (50–150 μm in diameter) were seen as white spots in the infected hepatopancreas (Drobne *et al.*, 1999). Vacuoles, filled mainly with elementary bodies, were released into the lumen of the hepatopancreas, as described by Drobne *et al.* (1999). Although the feeding rate of infected animals was not affected, infected cells were damaged during the vacuole extrusion (Drobne *et al.*, 1999). It therefore appears to be appropriate that these bacteria should be described as intracellular parasites.

**Phylogenetic analysis**

Intracellular bacteria with complex developmental cycles are found in phylogenetically distant bacterial groups. At first, attempts were made to amplify the ribosomal genes directly from DNA isolated from infected hepatopancreas tissue of *P. scaber* by using a universal primer that anneals at the start [positions 8–26 (Weisburg *et al.*, 1991)] of the 16S rRNA gene, in combination with the universal reverse primer 1392-r. As these attempts were unsuccessful, a universal primer that anneals further downstream (522-f) was used, enabling the amplification of a product of approximately 870 bp.

Restriction profiles, observed after digestion of ten randomly chosen cloned 16S rRNA amplicons with HaeIII and HhaI, were identical, indicating the predominance of a single bacterial species in infected tissue (data not shown). The latter assumption was further supported by the sequencing of two randomly selected cloned amplicons, which provided an identical sequence. As preliminary phylogenetic analysis related the 870 bp sequences obtained to 16S rRNA gene sequences of bacteria in the order *Chlamydiales*, a chlamydiae-specific forward primer, 16S1, was used in combination with the universal primer 1392-r for amplification of a 1366 bp product.

Currently available 16S rRNA gene sequences with highest similarity to the sequence of the intracellular hepatopancreatic bacteria were retrieved from public databases. Pairwise alignments revealed that the sequence obtained is related most closely, with 90.5–91.7 % similarity, to 16S rRNA gene sequences from the ‘environmental chlamydiae lineage’ (ECL) VI group, members of which were retrieved directly from activated sludge (Horn & Wagner, 2001). Similarity to ribosomal sequences from other members of the order *Chlamydiales* ranged from 83.1 to 87.2 %.

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**Fig. 1.** Transmission electron micrograph of intracellular bacteria in membranous vacuoles of an infected hepatopancreatic cell. Black arrowheads indicate rod-shaped mature elementary bodies; white arrowheads indicate spherical reticulate bodies; arrows indicate intermediate bodies. Bar, 2 μm.

**Fig. 2.** Transmission electron micrograph of mature elementary bodies. Black arrowheads indicate a five-layered cell wall; white arrowheads indicate translucent oblong structures in electron-dense cytoplasm. Bar, 100 nm.
Phylogenetic trees, constructed with the parsimony and maximum-likelihood treeing methods, revealed in general the same topology as the neighbour-joining tree (presented in Fig. 3). The tree (Fig. 3) shows that the sequence of the intracellular hepatopancreatic bacteria forms an independent lineage within the order *Chlamydiales*, which is related most closely to cluster ECL VI and, somewhat more distantly, to *Simkania negevensis* Z₁ (= ATCC VR-1471) from the family *Simkaniaceae* (Everett et al., 1999), which shared 86.7% sequence similarity with the sequence of the intracellular hepatopancreatic bacteria.

**In situ hybridization**

A specific oligonucleotide probe, named S-S-RhaC-0992-a-A-20 [according to the proposed standardization of oligonucleotide probe nomenclature that was proposed by Alm et al. (1996)], was designed to be complementary to the characteristic 16S rRNA gene sequence region of the hepatopancreatic intracellular bacteria, positioned at nt 992–1011 (*E. coli* numbering). A probe-check program (Cole et al., 2003) confirmed that the specific oligonucleotide differs in at least 4 nt from any of the 16S rRNA gene sequences of other chlamydia (Table 1). Fluorescence *in situ* hybridization was performed on serial sections of the infected hepatopancreas tissue by using this probe.

Fluorescent microscopy revealed a strong signal in the membrane-bound vacuoles inside infected cells [see Supplementary Figure (b) in IJSEM Online]. Hybridization with the universal probe 522-f (Giovannoni et al., 1988), which was used as a positive control, was also positive.
After hybridization of infected hepatopancreas cells with a non-specific probe (data not shown), attempts to amplify the 16S rRNA gene of the intracellular bacteria with a standard universal primer that anneals at the 5' end of the gene. At least three mismatches can be found in most chlamydial 16S rRNA gene sequences within the otherwise conserved region at positions 8–26 (E. coli numbering), which is commonly used as target for PCR primer fD1 (Weisburg et al., 1991). Affiliation of the intracellular hepatopancreatic bacteria to a novel chlamydial genus is further supported by the unique morphological characteristics of their elementary bodies, i.e. rod-like shape, five-layered cell wall and oblique cytoplasmic structures, which differ clearly from the spherical elementary bodies observed in other members of the order Chlamydiales (Everett et al., 1999).

**Assignment of the intracellular hepatopancreatic bacteria to the order Chlamydiales**

Although phylogenetic analysis of the intracellular bacteria did not rely on a complete 16S rRNA gene sequence, high similarity (> 80%) with ribosomal sequences from members of the order Chlamydiales, as well as the chlamydia-like developmental cycle, clearly indicate that the hepatopancreatic bacteria of *P. scaber* belong to this order (Everett et al., 1999). However, they cannot be assigned to any known genus or family within this order. Similarity between the sequence of the intracellular hepatopancreatic bacteria and ribosomal sequences of type strains in the order Chlamydiales was always < 90% and, therefore, does not exceed the proposed 95% threshold value for distinction of genera in the order Chlamydiales (Everett et al., 1999). Phylogenetic analyses of the retrieved sequences also clarified a reason for the unsuccessful attempts to amplify the 16S rRNA gene of the intracellular bacteria with a standard universal primer that anneals at the 5' end of the gene. At least three mismatches can be found in most chlamydial 16S rRNA gene sequences within the otherwise conserved region at positions 8–26 (E. coli numbering), which is commonly used as target for PCR primer fD1 (Weisburg et al., 1991). Affiliation of the intracellular hepatopancreatic bacteria to a novel chlamydial genus is further supported by the unique morphological characteristics of their elementary bodies, i.e. rod-like shape, five-layered cell wall and oblique cytoplasmic structures, which differ clearly from the spherical elementary bodies observed in other members of the order Chlamydiales (Everett et al., 1999).

**Table 1.** Multiple sequence alignment of the S-S-RhaC-0992-a-A oligonucleotide probe sequence with target sequences from 16S rRNA genes of related bacteria

<table>
<thead>
<tr>
<th>S-S-RhaC-0992-a-A-20 (E. coli positions 992–1012)</th>
<th>GenBank accession no.</th>
<th>Sequence</th>
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<tr>
<td><em>Candidatus</em> Rhabdoblachydia porcellionis</td>
<td></td>
<td>3’-CTTTACGTTTCCCTGTCGTAG-5’</td>
</tr>
<tr>
<td>ECL VI</td>
<td>AF364561, AF364562, AF364570, AF364574, AF364577</td>
<td>5’-GAATTCGAAAGGACAGCATC-3’</td>
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<tr>
<td><em>Simkania negevensis</em></td>
<td>U68460</td>
<td>5’-...CT...G...C...-3’</td>
</tr>
<tr>
<td>ECL III</td>
<td>AF083614</td>
<td>5’-...G...G...C...T-3’</td>
</tr>
<tr>
<td><em>Parachlamydia acanthamoebae</em> Bn3</td>
<td>ATCC VR-1471T</td>
<td>5’-...C...G...A...T-3’</td>
</tr>
<tr>
<td><em>Chlamydia sus</em> S45T</td>
<td>ATCC VR-1474T</td>
<td>5’-...C...G...A...T-3’</td>
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<tr>
<td><em>Chlamydia muridarum</em> MoPt</td>
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<td>5’-...C...G...A...T-3’</td>
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<td><em>Chlamydia trachomatis</em> A/Har-13T</td>
<td>ATCC VR-571B</td>
<td>5’-...C...G...A...T-3’</td>
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<td>AF364563, AF364565</td>
<td>5’-...C...G...A...T-3’</td>
</tr>
<tr>
<td>ECL I</td>
<td>AF364564, AF364569, AF364575</td>
<td>5’-...C...G...A...T-3’</td>
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<td><em>Chlamydophila psittaci</em> 6869</td>
<td>ATCC VR-125</td>
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<td><em>Chlamydophila pecorum</em> ES7</td>
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<td><em>Chlamydophila felis</em> FP Baker</td>
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<td><em>Waddlia chondrophila</em> WSU 86-1044T</td>
<td>ATCC VR-1470T</td>
<td>5’-...C...G...A...T-3’</td>
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<tr>
<td><em>Chlamydia pneumoniae</em> TW-183T</td>
<td>ATCC VR-2282T</td>
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<td>ECL VII</td>
<td>AF364568</td>
<td>5’-...C...G...A...T-3’</td>
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<tr>
<td>ECL V</td>
<td>U68599</td>
<td>5’-...C...G...A...T-3’</td>
</tr>
<tr>
<td>ECL IV</td>
<td>AF308693</td>
<td>5’-...C...G...A...T-3’</td>
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</table>
P. scaber is probably the natural reservoir for these intracellular hepatopancreatic bacteria, as chlamydial infections are generally transferred without an alternative host (Everett et al., 1999). This is supported by the lack of influence on the host feeding rate (Drobne et al., 1999) and by the constant presence of infected animals in natural populations, indicating an asymptomatic state of coexistence of the intracellular bacteria within the host.

Description of ‘Candidatus Rhabdochlamydia porcellionis’

According to Murray & Stackebrandt (1995), properties of obligate symbionts of eukaryotic cells should be recorded by a ‘Candidatus’ designation. For this reason, it is proposed that the intracellular hepatopancreatic bacteria from P. scaber should be designated ‘Candidatus Rhabdochlamydia porcellionis’ [Rhab.do.chla.my]’ di.a. Gr. fem. n. rhabdos stick, rod; N.L. fem. n. Chlamydia taxonomic name of a bacterial genus; N.L. fem. n. Rhabdochlamydia rod-shaped chlamydiae, referring to the rod-like shape of elementary bodies; por.cell.i.o’nis. N.L. gen. n. porcellionis of Porcellio, pertaining to the taxonomic genus name of the host organism (a terrestrial isopod).

‘Candidatus Rhabdochlamydia porcellionis’ comprises intracellular bacteria within membrane-bound vacuoles in the cytoplasm of hepatopancreatic cells of the terrestrial isopod Porcellio scaber. Cells are non-motile, non-cultivable on cell-free media and have the Gram-negative microscopically appearance of a cell wall without a discernible peptidoglycan layer. Morphology of ‘Candidatus Rhabdochlamydia porcellionis’ corresponds to the description of ‘Chlamydia isopodii’ (Shay et al., 1985) and a ‘Rickettsiella-like organism’ (Drobne et al., 1999). Bacteria exhibit a chlamydia-like developmental cycle, in which the cells appear in three morphological forms (reticulate, intermediate and mature elementary bodies) that are packed in membrane-bound vacuoles in the cytoplasm of the host cell. Reticulate bodies with cocoid morphology can be small (up to 1 µm in diameter), which multiply by binary fission, or larger (1–4 µm in diameter), with granular inclusions in the cytoplasm. Morphology of intermediate bodies is cocoid (350–650 nm in diameter), with an electron-dense area in the centre of the cell. Mature elementary bodies have a five-layered cell wall, variable rod-shaped morphology (250–700 nm in length and 100–150 nm in diameter) and oblong structures in the cytoplasm. On the basis of its 16S rRNA gene sequence, ‘Candidatus Rhabdochlamydia porcellionis’ forms a distinctive lineage within the order Chlamydiales, close to the family Simkaniaceae, with an oligonucleotide that is complementary to a unique region of the 16S rRNA gene (5’-GAAATGCAAAGGACACGCATC-3’). Assignment to ‘Candidatus Rhabdochlamydia porcellionis’ is based on the sequence of the 16S rRNA gene (GenBank accession no. AY223862) and the distinctive morphology of the elementary bodies.

ACKNOWLEDGEMENTS

The authors are grateful to Nada Žnidarišč for kindly providing electron micrographs and Boris Sket for constructive comments on nomenclature. This work was supported by grants from the Ministry of Education, Science and Sport of the Republic of Slovenia.

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