Azotobacter vinelandii: a Pseudomonas in disguise?

Azotobacter vinelandii is a widely distributed free-living soil bacterium. This Gram-negative, strictly aerobic bacterium has many interesting features, including the ability to grow on a wide variety of carbohydrates, alcohols and organic acids, alginate production and nitrogen fixation. A. vinelandii synthesizes three different types of nitrogenase enzymes. Unlike most diazotrophs, A. vinelandii is able to fix nitrogen in the presence of atmospheric oxygen concentrations. To protect its nitrogenase enzymes from oxygen inactivation, this bacterium is equipped with particular physiological mechanisms, such as a high respiration rate. Currently, Azotobacter is classified as a genus of the family Pseudomonadaceae (http://www.azotobacter.org).

Using in vivo expression technology (IVET), we screened a nitrogen-fixing Pseudomonas stutzeri strain for genes specifically expressed in rice rhizosphere (Rediers et al., 2003). Sequence analysis of these genes revealed high sequence similarity not only to genes of several other Pseudomonas strains but also to A. vinelandii genes. These observations and the availability of a (draft) genome sequence of A. vinelandii and several Pseudomonas species urged us to inspect the phylogenetic relationship of A. vinelandii to Pseudomonas sensu stricto.

Analysis of 16S rRNA gene sequences is often used and generally accepted for analysing phylogenetic relationships. A phylogenetic tree based on partial 16S rRNA gene sequences (nucleotides 135–1475 of the Pseudomonas aeruginosa PAO1 16S rRNA gene) assigns A. vinelandii to the P. aeruginosa clade (Fig. 1a). The 16S rRNA gene sequences of P. aeruginosa PAO1 and A. vinelandii share higher identity with each other (96 %) than they do with the corresponding sequences of other Pseudomonas strains. This is in line with the following observations. To detect Pseudomonas sensu stricto in different environments, a highly sensitive PCR protocol was developed to amplify 16S rRNA genes (Widmer et al., 1998). Members of the genus Pseudomonas display three distinct HaeIII RFLP patterns of the amplified PCR products. We found by in silico analysis that A. vinelandii and P. aeruginosa PAO1 indeed share the same HaeIII RFLP pattern. In another study, it was shown that the 16S rRNA gene sequences of Pseudomonas strains contain repeating elements which are highly conserved (Purohit et al., 2003). We confirmed that these repeating elements were also found in A. vinelandii, while only five out of eight were found in Escherichia coli.

However, it is debatable whether a phylogenetic tree based on the comparison of a single gene is sufficient to accurately represent the evolution of bacterial species. Furthermore, since the 16S rRNA gene shows an extremely low rate of evolution, the degree of resolution obtained is not sufficient to infer intragenic relationships. This can be circumvented by phylogenetic analysis of protein-encoding genes. In several studies, housekeeping genes have proven to be an appropriate target to assess phylogenetic relationships between bacteria, because these genes are usually highly expressed, highly conserved and evolve more rapidly than rRNA genes, resulting in a desirable resolution in evolutionary relationships between species (Coenye & Vandamme, 2003; Lerat et al., 2003; Wertz et al., 2003). For example, it has been shown that the highly conserved DNA recombinase (RecA) can be used to infer phylogeny (Eiken, 1995). RecA of P. aeruginosa PAO1 shows highest amino acid sequence identity (91 %) with the A. vinelandii homologue. This observation was also reflected in a dendrogram based on the RecA amino acid sequences (not shown). Likewise, the sequences of both GyrB, encoding a DNA gyrase, and RpoD, encoding the σ70 sigma factor, have been used to reconstruct a phylogenetic tree of the genus Pseudomonas (Yamamoto et al., 2000). Again, for both proteins as well as for the concatenated GyrB–RpoD amino acid sequences we noticed that A. vinelandii clusters with P. aeruginosa PAO1.

As the number of completely sequenced bacterial genomes has increased, there has been an increasing interest in the use of these genome sequence data to assess evolutionary relationships among bacterial species. We used data retrieved from the complete genome sequences of P. aeruginosa PAO1, Pseudomonas putida KT2440 and Pseudomonas syringae pv. tomato str. DC3000 and from draft sequences of Pseudomonas fluorescens Pf0-1 and P. syringae pv. syringae B728a to scrutinize the taxonomic position of A. vinelandii strain OP (http://www.azotobacter.org). For phylogenetic tree construction, respective sequences of Vibrion cholerae El Tor N16961 were used as outgroup. We analysed the phylogenetic relationships between these seven species for several proteins/enzymes with housekeeping functions: AroK and DapB, involved in the synthesis of aromatic amino acids and lysine/peptidoglycan, respectively; CarB (large subunit of carbamoylphosphate synthetase), which is involved in arginine and pyrimidine nucleotide biosynthesis; protein synthesis (AlaS, a tRNA charger, and RplA, a ribosomal protein); peptidoglycan synthesis (MurD); secretion (SecA); stringent response (RelA, involved in ppGpp metabolism); intracellular ATP-dependent proteolysis (FtsH); co-enzyme biosynthesis (HemB and ThiE, involved in tetrahydrolefolate and thiamin biosynthesis, respectively); fatty acid synthesis (AccD, acetyl-CoA carboxylase subunit); glycolysis (FruK, phosphofructokinase); gluconeogenesis (PckA, phosphoenolpyruvate carboxykinase); heat-shock proteins (DnaK, GroEL and GrpE); purine nucleotide biosynthesis (PurF); regulation (GacA, response regulator); DNA modification (GyrB, RecA); DNA transcription (RpoN and RpoD, sigma factors); and energy metabolism (AtpA, a component of ATP synthase, and AceA, pyruvate dehydrogenase component E1).

Generation of phylogenetic trees for all the proteins in our dataset revealed that the A. vinelandii homologues clustered within, or close to, the Pseudomonas clade (data not shown). In most cases the A. vinelandii proteins were most closely related to the P. aeruginosa PAO1 orthologues. Based on tree topologies of the 16S rDNA nucleotide and the 25 protein alignments, a consensus tree was built (Fig. 1b). This tree revealed an identical topology compared to the 16S rDNA-based dendrogram when only the seven mentioned species are considered. The concatenated sequence alignments of
all proteins in our dataset (consisting of 12,537–12,581 amino acid residues) yielded a phylogenetic tree with the same topology as the 16S rDNA and consensus trees (Fig. 1c).

Until now, the major outer-membrane protein OprF has been found only in Pseudomonas sensu stricto species and may be considered a diagnostic protein for Pseudomonas (De Mot et al., 1994; Vermeiren et al., 1999). A. vinelandii has an OprF orthologue which showed high amino acid identity with the P. aeruginosa PAO1 OprF (68%), while identity between the Pseudomonas fuscovaginae and the

Fig. 1. Phylogenetic relationships between A. vinelandii and Pseudomonas species (sensu stricto) based on comparison of 16S rRNA gene sequences (a) and the concatenated amino acid sequences of 25 proteins/enzymes with housekeeping functions (c). Nucleotide accession numbers are given in parentheses. Nucleotide sequences designated (*) were retrieved from the DOE Joint Genome Institute (http://www.jgi.doe.gov/). Nucleotide and amino acid sequence alignments were carried out with the program CLUSTAL W 1.8. Dendrograms were generated with TREECON (Van de Peer & De Wachter, 1994) using the neighbour-joining algorithm with Poisson correction. V. cholerae El Tor N16961 orthologues were used as outgroups for phylogenetic tree reconstruction. The percentage of trees from 1000 bootstrap resamples supporting the topology is indicated when above 50. A consensus tree (b) was generated based on the separate phylogenetic trees of the 16S rRNA gene sequences and of the 25 proteins with ECONSENSE of the PHYLIP software package. The numbers at the forks indicate the number of times the group, consisting of the species which are to the right of that fork, occurred among the 26 trees.
P. aeruginosa PAO1 OprF was only 49%. Construction of a phylogenetic tree based on OprF sequences confirmed the close relationship between P. aeruginosa PAO1 and A. vinelandii (not shown). Like OprF of P. aeruginosa PAO1, the A. vinelandii orthologue appears to be a ‘cysteine-type’ OprF, as it contains a central domain with four conserved cysteine residues, which is absent in several other OprF proteins (De Mot et al., 1994). Alginate production is a common feature of A. vinelandii and Pseudomonas species (Rehm & Valla, 1997). Homology searches of P. aeruginosa PAO1 AlgX (a protein involved in alginate biosynthesis) revealed that AlgX orthologues are only present in other Pseudomonas strains and in A. vinelandii.

In conclusion, these data strongly suggest that A. vinelandii belongs to the genus Pseudomonas sensu stricto. Originally, nitrogen-fixing ability was considered a major physiological characteristic differentiating A. vinelandii from Pseudomonas species. The occurrence of nitrogen fixation in Pseudomonas species has been long debated, but in recent years several genuine Pseudomonas strains that can fix nitrogen have been identified (Kulakov et al., 2003; Vermeiren et al., 1999). Most likely, the nitrogen-fixing genes were acquired by lateral gene transfer. This hypothesis is supported by NifH phylogenies (Vermeiren et al., 1999). Deduced amino acid sequences of the P. stutzeri A15 nifHDK operon revealed highest identity (87–91%) with the respective A. vinelandii homologues (Desnoyes et al., 2003). Moreover, it was shown that the gene organization in the nifH region of A. vinelandii was identical to the gene organization of P. stutzeri A15.

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