Molecular characterization of nocardioform actinomycetes in activated sludge by 16S rRNA analysis

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The analysis of complex microbiota present in activated sludge is important for the understanding and possible control of severe separation problems in sewage treatment such as sludge bulking or sludge foaming. Previous studies have shown that nocardioform actinomycetes are responsible for these conditions, which not only affect the efficiency of sewage treatment but also represent a threat to public health due to spread of pathogens. However, isolation and identification of these filamentous, nocardioform actinomycetes is hampered by their fastidious nature. Most species are still uncultivable and their taxonomy is unresolved. To study the ecology of these micro-organisms at the molecular level, we have established a clone library of 16S rRNA gene fragments amplified from bulk sludge DNA. A rough indication of the predominant flora in the sludge was given by sequencing randomly chosen clones, which revealed a great diversity of bacteria from different taxa. Colony hybridization with oligonucleotide probe MNPI detected 27 clones with 16S rDNA inserts from nocardioform actinomycetes and mycobacteria. The sequence data from these clones together with those from randomly chosen clones were used for comparative 16S rRNA analysis and construction of dendrograms. All sequences differed from those of previously sequenced species in the databases. Phenotypic characterization of isolates of nocardioform actinomycetes and mycobacteria cultivated in parallel from the same activated-sludge sample revealed a large discrepancy between the two approaches. Only one 16S rDNA sequence of a cultured isolate was represented in the clone library, indicating that culture conditions could select species which represent only a small fraction of the organisms in the activated sludge.

Keywords: 16S rRNA, activated sludge, nocardioform actinomycetes, uncultured bacteria

INTRODUCTION

The performance of a sewage treatment plant depends upon the microbial community of the activated sludge. Domestic sewage contains a large number of micro-organisms that play a major role in the biodegradation of organic matter, the removal of inorganic compounds, the inactivation of human or animal pathogens, and the detoxification of pollutants. The composition of activated sludge flocs, consisting of clusters of filamentous and unicellular bacteria, determines the biodegradation efficiency and proper settling in the secondary clarifier. Growth imbalance of filamentous vs floc-forming bacteria leads to problems known as sludge bulking and sludge foaming. The latter condition not only reduces the efficiency of sewage treatment, but also represents a public health problem, due to the spread of pathogens in wind-blown scum (Blackall et al., 1988), and the contamination of the receiving water with opportunistic pathogens, including mycobacteria or nocardioform actinomycetes such as Rhodococcus equi, Nocardia asteroides or Gordona...
bronchialis (Lasker et al., 1992). Several studies indicated that sludge foaming is often caused by an increase in the amount of nocardioform actinomycetes (Lemmer & Kroppenstedt, 1984; Sezgin et al., 1988; Wanner & Grau, 1989). Since nocardioform actinomycetes and other Gram-positive bacteria with high G+C content occur preferentially in sewage treatment plants with enhanced biological phosphorus removal (EBPR) (Wagner et al., 1984), plants of this type are especially susceptible to developing scum. Increasing eutrophication of natural waters is resulting in tougher wastewater legislation and an increasing number of EBPR plants. Thus, scum in wastewater treatment plants is likely to remain a problem in future. A thorough microbial analysis of activated sludge is therefore a prerequisite for the understanding and possible control of the sewage process and the problems which can arise.

Until recently, the analysis of natural microbial communities such as those in activated sludge relied on the cultivation of the resident micro-organisms as a prerequisite for subsequent identification. This classical approach, however, is hampered by the lack of information on appropriate culture conditions for many of the micro-organisms. Earlier studies indicate that only about 10% of a population is cultivable (Jones, 1977; Hoppe, 1978; Ferguson et al., 1984; Atlas, 1983; Pickup, 1991). Recently, comparative sequence analysis of ribosomal RNA has been widely accepted as a tool for the identification and phylogenetic classification of bacteria (Woese et al., 1987; Givovannoni et al., 1988; DeLong et al., 1989; Amann et al., 1990; Hahn et al., 1992; Spring et al., 1992). Comparative 16S rRNA sequence analysis has been applied to studies of natural microbial communities and has resulted in the discovery of unexpectedly high levels of biodiversity (Pace et al., 1986; Weller & Ward, 1989; Giovannoni et al., 1990; Amann et al., 1991; Schmidt et al., 1991; Fuhrman et al., 1992).

In this study we investigated the microbial diversity of an activated-sludge sample from a sewage treatment plant, with particular regard to nocardioform actinomycetes and mycobacteria, by comparative 16S rRNA sequence analysis. A library of in vitro-amplified 16S rRNA genes of activated-sludge bacteria was screened with an oligonucleotide probe in order to detect clones with 16S rDNA signature sequences of nocardioform actinomycetes and mycobacteria, and positive clones were sequenced and analysed. In parallel we isolated actinomycetes from the same activated-sludge sample and compared the partial 16S rRNA sequences of these cultured isolates with those obtained from the clone library.

### METHODS

**Micro-organisms.** An activated-sludge sample was taken from a normally functioning municipal wastewater treatment plant with EBPR at Berlin-Marienfelde, Germany, in October 1992. Isolation of nocardioform actinomycetes was achieved by directly streaking the undiluted sludge onto agar plates with modified Czapek Dox medium (Difco) which is selective for actinomycetes (Lechevalier, 1989). After incubation at 20 °C for one week, colonies were picked at random, transferred to TSBA (trypticase soy broth) agar plates (BBL) and incubated for 2 d at 30 °C. Isolates were identified by gas chromatography (Miller, 1982) on a Hewlett-Packard HP5890 series II using the mts
**Nocardioform actinomycetes in activated sludge**

**Table 2. Comparison of identification of culture isolates by gas chromatography and 16S rRNA sequence analysis**

<table>
<thead>
<tr>
<th>Isolate</th>
<th>GC-identification</th>
<th>Probability (%)</th>
<th>16S rRNA sequence analysis*</th>
<th>Similarity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>Nocardia amarae</td>
<td>34</td>
<td>Mycobacterium fallax</td>
<td>88.4</td>
</tr>
<tr>
<td>M3</td>
<td>Nocardia amarae</td>
<td>41</td>
<td>Mycobacterium fallax</td>
<td>90.7</td>
</tr>
<tr>
<td>M7</td>
<td>Rhodococcus chubensis</td>
<td>50</td>
<td>Mycobacterium fallax</td>
<td>93.9</td>
</tr>
<tr>
<td>M8</td>
<td>Rhodococcus chubensis</td>
<td>61</td>
<td>Mycobacterium fallax</td>
<td>93.9</td>
</tr>
<tr>
<td>M12</td>
<td>Rhodococcus globularis</td>
<td>76</td>
<td>Mycobacterium chlorophenolicum</td>
<td>91.6</td>
</tr>
<tr>
<td>M24</td>
<td>Gordona rubropertinctus</td>
<td>59</td>
<td>Mycobacterium fallax</td>
<td>93.9</td>
</tr>
<tr>
<td>M26</td>
<td>No valid result</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>M28</td>
<td>Rhodococcus rhodochrous</td>
<td>54</td>
<td>Mycobacterium fallax</td>
<td>88.6</td>
</tr>
<tr>
<td>M34</td>
<td>Gordona rubropertinctus</td>
<td>69</td>
<td>Mycobacterium fallax</td>
<td>93.9</td>
</tr>
<tr>
<td>M49</td>
<td>Rhodococcus globularis</td>
<td>63</td>
<td>Mycobacterium chlorophenolicum</td>
<td>91.1</td>
</tr>
</tbody>
</table>

* Closest relationship to 16S rRNA sequences from EMBL or GenBank databases.

**Nucleic acid preparation.** Part of the same activated-sludge sample which was used for isolation of the nocardioform actinomycetes was processed for nucleic acid preparation. The sample was centrifuged, washed twice in an excess of PBS (pH 7.0), and finally resuspended in PBS. DNA was recovered by adding 0.5 ml of the sample to approximately 0.5 ml zirconium beads (0.1 mm diameter) and 0.5 ml phenol. Bacteria were then mechanically disrupted by shaking the tube for 5 min in a Mini-Bead Beater (Biospec Products, Bartlesville, USA) at room temperature. After phase separation (10 min at 15000 g), the aqueous phase was extracted twice by adding 1 vol. phenol/chloroform (1:1, v/v) and 1 vol. chloroform/isooamyl alcohol (24:1, v/v). DNA was precipitated by adding 2 vols ice-cold ethanol (96%). The pellet was dried under vacuum for 10 min, dissolved in 50 μL TE buffer (pH 8.0, 1 mM EDTA) and purified twice on StrataClean resin (Stratagene).

**PCR amplification.** PCR was used to amplify 16S rRNA gene fragments from purified genomic DNA of the culture isolates as well as from the purified genomic DNA of the activated-sludge samples at 95°C for 2 min and subsequent amplification by 30 cycles of denaturing (92°C for 1 min) and elongation (72°C for 1.5 min). Amplification products were purified by agarose gel electrophoresis, eluted by centrifugation using small Mobicol columns (Mobitech), then precipitated with ethanol and resuspended in TE buffer. 16S rRNA gene fragments of culture isolates and type strains were amplified as described above, with the exception of using primers TPU1 and RTU3 without poly linker tails. Direct solid-phase sequencing PCR was performed using biotinylated primers TPU1 or RTU3.

**Cloning.** Purified 16S rDNA PCR products and plasmid vector pUC19 (Pharmacia) were cleaved by a double digest with restriction endonucleases SalI and BamH1 (Pharmacia) following the manufacturer’s specifications. Cleaved products were purified twice on a StrataClean resin. Three ligation reactions using 50, 100 or 200 ng of vector pUC19 were performed. Each reaction contained 6 μl restriction-enzyme-digested PCR product, 1 U T4 DNA ligase (BRL) and 25 mM Tris/HCl buffer (pH 7.8) containing 10 mM MgCl₂, 1 mM DTT and 1 mM ATP, in a final volume of 10 μl. The ligation reactions were incubated at 16°C overnight. Transformation was done by adding 5 μl ligation mix to 100 μl competent E. coli SURE cells (Stratagene) according to the manufacturer’s recommendation. Aliquots (100 μl) of the cell suspension were plated onto LB agar medium (Gibco) containing 100 μg ampicillin ml⁻¹, 0.004% (w/v) of X-Gal (Boehringer Mannheim) and 0.5 mM of IPTG (BRL) and incubated overnight at 37°C.

**Colony hybridization.** Recombinant clones were plated onto LB agar supplemented with 0.1 mg ampicillin ml⁻¹. The resulting colonies were transferred to positively charged Dynabeads nylon membranes (Pall). The bacterial colonies were lysed by standard methods (Sambrook et al., 1989). The oligonucleotide probe MNPl recognizing the target sequence 5'-AGC CTG GGA AAC TGG GTC TAA-3' (corresponding to positions 519–536 in E. coli 16S rRNA (Brosius et al., 1978); the underlined sequence represents restriction sites for EcoRI and SalI) and RE-RTU3 5'-CCG ATG ATC CAA GCT TCG AAT TCG ACA ACA GAG TTT GAT CCT GGC TCA G-3'; corresponding to positions 8–27 in E. coli 16S rRNA (Brosius et al., 1978); the underlined sequence represents restriction sites for BamHI, HindIII and XmaI], 1·5 U Tag polymerase (Gibco BRL) and approximately 10–100 ng DNA in a final reaction volume of 100 μl. Amplification was performed in an automated thermal cycler (model 480, Perkin-Elmer-Cetus) by denaturing the samples at 95 °C for 2 min and subsequent amplification by 30 cycles of denaturing (92°C for 1 min), annealing (50°C for 1 min) and elongation (72°C for 1.5 min). Amplification products were purified by agarose gel electrophoresis, eluted by centrifugation using small Mobicol columns (Mobitech), then precipitated with ethanol and resuspended in TE buffer. 16S rRNA gene fragments of culture isolates and type strains were amplified as described above, with the exception of using primers TPU1 and RTU3 without poly linker tails. Direct solid-phase sequencing PCR was performed using biotinylated primers TPU1 or RTU3.

**16S rDNA sequencing.** Plasmid DNA was purified using the QIAprep-spin Plasmid Kit (QIAGEN) as indicated by the...
Fig. 1. For legend see facing page.
manufacturer. Both insert strands were sequenced by a modified Sanger dideoxy chain-termination protocol using Sequenase (USB) according to the manufacturer's instructions. Biotinylated PCR products were directly sequenced by a solid-phase single-strand sequencing method. Briefly, biotinylated PCR products were incubated with streptavidin-coated paramagnetic beads (Dynabeads, Dynal) and strands were separated by addition of 8 μl 0.5 M NaOH. The tube was placed in a magnetic rack and the supernatant, containing the unbiotinylated strand, was removed. Purified, biotinylated single strands were sequenced using Sequenase, following the manufacturer's recommendations. Primers TPU1 and RTU3 without polylinker tails were used as forward and reverse primers, respectively.

16S rRNA sequence analysis. The 16S rDNA sequences were compared with all currently accessible (June 1994) 16S rDNA sequences in the EMBL and GenBank databases using the program Fasta of the HUSAR 3.0 (Heidelberg Unix Sequence Analysis Resources) program package (DKFZ, Heidelberg, Germany). The clone sequences were aligned with a set of published sequences of several reference bacteria on the basis of conserved primary sequence. The TREECON software package for construction and drawing of evolutionary trees was used for sequence analysis and construction of the dendrograms (Van de Peer & De Wachter, 1993). A 'Single Distance Matrix' was calculated from the first 500 bases of the 16S rRNAs including hypervariable regions, and corrected for superimposed mutations by the method of Jukes & Cantor (1969). The neighbour-joining method of Saitou & Nei (1987) was used for phylogenetic tree construction. The reliability of tree nodes was analysed by bootstrapping. One hundred bootstrap trees were generated, and confidence levels were determined.

RESULTS
Characterization of culture isolates

About 50 culture isolates grown from the activated-sludge sample on Czapek Dox agar were identified by gas chromatography. Isolates showing identical fatty acid profiles were classified in the same group. The 16S rDNA of one representative strain from each of these groups was partially sequenced. GC-identification and 16S rRNA analysis resulted in a different classification of the isolates. The 16S rDNA profiles were classified in the same group. The 16S rDNA clone library of activated sludge bacteria

Bulk DNA extracted from the activated-sludge sample was used as a mixed template for PCR-amplification of the first 500 bases, representing approximately one-third of the whole 16S rRNA gene. Cloning of the PCR products resulted in a 16S rDNA clone library. The cloning efficiency was 2.14 x 10^6 c.f.u. per μg vector DNA for the ligation reaction with 100 ng pUC19 DNA. About 3000 recombinant clones were randomly selected and transferred onto LB plates for further investigations.

Colony hybridization with probe MNPl

Partial 16S rDNA sequences (each about 500 bp) obtained by direct sequencing of PCR products from 13 nocardioform strains (Table 1) and 10 culture isolates (Table 2) were aligned. A sequence motif common to all 16S rDNA sequences from these strains and isolates was selected for the construction of oligonucleotide probe MNPl. A search in the EMBL and GenBank databases confirmed that this sequence was found within 16S rRNA genes of most members of the genera Corynebacterium, Gordonia, Mycobacterium, Nocardia and Rhodococcus and also within a few members of other genera of the high-G + C group of Gram-positive bacteria. The 16S rDNA sequences of M. celatun, M. leprae, M. komossense, M. shimoidei, R. fascians and Tsukamuraella paurometabola showed one mismatch with probe MNPl. To identify the clones containing 16S rDNA inserts from nocardioform actinomycetes and mycobacteria, all recombinants of the gene library were screened by colony hybridization with radiolabelled probe MNPl. By using high-stringency conditions 27 out of 3000 clones were identified, all of which contained the full target sequence as determined by sequencing of the plasmid inserts.

Sequence analysis of the clone library

The composition of the 16S rDNA clone library from activated sludge was estimated by sequencing 24 randomly selected recombinant clones. Comparative sequence analysis of the resulting 16S rDNA sequences revealed a range of identities from Gram-positive and Gram-negative bacteria. None of the clone sequences showed identity with any of the 16S rRNA sequences found within EMBL or GenBank databases. The phylogenetic relationship of the bacteria represented in the clone library is represented in Fig. 1, which shows that most of the sequences were related to 16S rDNA sequences from members of the class Proteobacteria. Sequence analysis of the 27 MNPl-positive clones resulted in the identification of 13 different 16S rDNA sequences. Several clones contained identical sequences, whereas others showed slight differences. About 400 bp of both strands at the 5'-end of 16S rRNA genes were sequenced. Comparative sequence analysis with rRNA sequences from the EMBL and GenBank databases revealed that all the sequences could be related to the group of nocardioform actinomycetes and mycobacteria (Fig. 2), with the exception of one sequence (SMKN1), which represented a high-G + C Gram-positive bacterium not belonging to that group. None of the sequences showed 100% identity with any of the sequences retrieved from databases. However, one clone sequence (SMKN35) was identical to that of an isolate (M49) grown in pure culture from the activated-sludge sample. Sequence SMKN41
Fig. 2. Dendrogram indicating the phylogenetic relationships among selected Gram-positive bacteria and clones (SMKN) identified by probe MNP1. One representative from each group of identical clone sequences is shown (numbers in brackets indicate the number of identical sequences). The dendrogram is rooted by outgroup *Bacillus anthracis*. The scale bar represents 10% difference in nucleotide sequence determined by taking the sum of the length of the horizontal line segments connecting two organisms. The numbers above each node are confidence levels (%) generated from 100 bootstrap trees (Van de Peer & De Wachter, 1993).
was chimeric, consisting of two different 16S rDNA fragments, and it was used for further analysis after deleting the part of the 3'-end which did not match in the alignment.

**DISCUSSION**

Cultivable bacteria represent only a small proportion of natural microbial communities. Therefore, we have chosen the comparative sequence analysis of rRNA to analyse cultivable and uncultivable bacteria from activated sludge. Although this strategy has been successfully applied to characterize other microbial habitats, it should be stressed that this molecular genetic approach is not completely unbiased. Several points have to be considered for correct interpretation of the data. Assuming that all the bacteria present in an activated-sludge sample were uniformly disrupted by mechanical treatment to release DNA, and assuming further that this purified DNA from the different bacteria was amplified with the same efficiency, the resulting 16S rDNA clone library should represent a cross-section of all of the bacteria present in the activated-sludge sample. By restricting the number of clones analysed to about 3000, only those bacteria that occur in high numbers in the activated sludge have a good probability of being represented. A further source of error is the possible loss of amplified 16S rDNA fragments of bacteria that possess 16S rRNA genes containing internal restriction sites which may be digested prior to the cloning reaction. We attempted to circumvent this problem by using restriction enzymes *BamHI* and *SacI*, cleavage sites for which are only rarely found within 16S rRNA genes (Weisburg *et al.*, 1991; Liesack & Stackebrandt, 1992). However, because most of the 16S rRNA gene sequences isolated from the activated sludge were novel, possible cleavage of other PCR products cannot be excluded. Furthermore, it has been shown that the use of different cloning protocols can affect the composition of the resulting clone library (E. Stackebrandt, personal communication), producing altered distributions in the library of 16S rDNA sequences derived from different community members.

PCR artifacts such as the formation of hybrid molecules (chimeric sequences) can occur when amplifying genomic DNA from mixed cultures. This is especially true when low-M_r genomic DNA is used for cloning. The use of a bead-beater in genomic DNA preparation increases the probability of chimeric gene artifacts simply because DNA fragments resulting from this type of extraction are very small. The resulting chimeras may lead to an erroneous interpretation by describing sequences of organisms that do not actually exist in the sample investigated (Liesack *et al.*, 1991). Therefore, a critical analysis of the sequences using e.g. the program CHECKCHIMERA (Olsen *et al.*, 1992), is necessary.

The finding that none of the partial 16S rDNA sequences from the randomly chosen recombinants of the 16S rDNA clone library was identical to any from the EMBL or GenBank databases suggests that only a few of the bacterial species in the activated sludge complex have been described by classical bacteriological methodologies (Wayne *et al.*, 1987; Olsen, 1990; Ward *et al.*, 1990).

It should be noted that our analysis of the activated-sludge community was not intended to be comprehensive. The comparative sequence analysis of randomly selected recombinants from our 16S rDNA clone library represented only a small sample of the diverse micro-organisms present in the activated-sludge sample, but agreed with reports from other groups using 16S rRNA analysis to investigate complex microbial communities (Ward *et al.*, 1990; Schmidt *et al.*, 1991; Liesack & Stackebrandt, 1992).

It might be argued that complete 16S rRNA sequences would be necessary for a thorough analysis of the phylogeny of the species from which the cloned 16S rRNA gene fragments originated. However, it has been found that comparison of partial sequences is sufficient for an approximate phylogenetic assignment (Lane *et al.*, 1985; Schmidt *et al.*, 1991; Ward *et al.*, 1990; Choi *et al.*, 1994; Hillis *et al.*, 1994).

An indication of the biases of different methods was shown when the results of culture and molecular genetic analysis were compared. With the exception of one sequence (SMKN1), probe MNP1 detected only sequences of nocardioform actinomycetes and mycobacteria in the clone library from the activated-sludge sample, confirming the results of the database search. The finding that only 27/3000 recombinant clones were detected by this probe indicated that these sequences were not representative of the predominant flora in the activated-sludge sample tested. The comparison of the clone sequences with those from the cultured isolates revealed only one identical sequence, namely SMKN35 (cf. isolate M49). This may lead to the assumption that the cultured isolates represented only a small fraction of the organisms present in the activated sludge, obviously selected by the culture conditions.

Inconsistencies in the identification of the cultured isolates by 16S rRNA sequence analysis and gas chromatography probably reflect the bias associated with these methods, which is mainly due to the limited size of the databases used for identification. Better results and greater agreement would be achieved by expanding the databases.

The results reported in this paper from comparative sequence analysis suggest that most of the 16S rDNA sequences derived from nocardioform actinomycetes and mycobacteria in the activated sludge represent unknown and as yet uncultivated organisms. The identification, phylogenetic classification and successful cultivation of these nocardioforms is a prerequisite for the elucidation of their physiological role in activated sludge and determination of their true taxonomic position.

**Concluding remarks**

The observation that wastewater treatment plants with EBPR are especially susceptible to the development of scum (Wanner & Grau, 1989) correlates with the increased number of nocardioform actinomycetes and other
high-G+C Gram-positive bacteria in sewage treatment plants of this type. This observation and the fact that these micro-organisms contain polyphosphate inclusions indicate that they may play a greater role in biological phosphate removal than anticipated (Wagner et al., 1994).

Fluorescently labelled rRNA probes have been applied successfully for the monitoring of bacterial populations in activated sludge as demonstrated by Wagner et al. (1994). The use of a whole set of specific oligonucleotide probes derived from the 16S rRNA sequences reported here would be of great help in the identification and enumeration of the organisms directly in sludge samples. With better knowledge of the taxonomic position of relevant nocardioforms in activated sludge, it should be possible to draw conclusions about their growth and nutritional requirements (Wanner & Grau, 1989). Rapid identification procedures and detailed knowledge of nutritional requirements will be important in controlling growth of these micro-organisms and in preventing the danger of scum formation in activated-sludge plants.

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REFERENCES


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