Phylogenetic Evidence that the Gram-Negative Nonsporulating Bacterium *Tissierella (Bacteroides) praecucuta* Is a Member of the *Clostridium* Subphylum of the Gram-Positive Bacteria and Description of *Tissierella creatinini* sp. nov.

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The 16S rRNA gene sequence of the type strain of *Tissierella praecucuta* (formerly *Bacteroides praecucuta*) was determined by PCR direct sequencing. A comparative sequence analysis showed that *T. praecucuta* is a member of the *Clostridium* subphylum of the gram-positive bacteria and has a close phylogenetic affinity with the species that form the *Clostridium* clusters XI and XII (M. D. Collins, P. A. Lawson, A. Willems, J. J. Cordoba, J. Fernandez-Garayzabal, P. Gaillot, H. Hippe, and J. A. E. Farrow, Int. J. Syst. Bacteriol. 44:812–826, 1994). Although *T. praecucuta* is gram negative and does not produce endospores, 16S RNA sequence data showed that it is closely related genealogically (level of sequence similarity, 99.9%) to *Clostridium hastiforme*. On the basis of our results and the results of previous studies, a second species of *Tissierella*, *Tissierella creatinini* sp. nov., is described.

*Tissierella praecucuta* (formerly *Bacteroides praecucuta*) consists of obligately anaerobic, gram-negative, nonsporulating, rod-shaped organisms and was originally isolated from infant feces and described by Tissier in 1908 (25). In addition to occurring in human feces, *T. praecucuta* has been isolated, although rarely, from a variety of clinical sources, including lung abscesses, gangrenous lesions, and blood (1, 2, 11). Although well characterized, *T. praecucuta* has had an unsettled taxonomic history; at various times it has been assigned to the genera *Coccobacillus* (25), *Zuberaella* (21), *Fusobacterium* (9), and *Bacteroides* (19). Shah and Collins (23), in a chemo- taxonomic survey of the family *Bacteroidaceae*, showed that there were major differences between *B. praecucutus* and the group of species that belong to the genus *Bacteroides sensu stricto* (the “*Bacillus fragilis* group”). For example, *B. praecucutus* differs from the *Bacteroides* species by lacking melenquinones, by lacking several key metabolic enzymes, and by having significantly lower DNA G+C content. Accordingly, Collins and Shah (4) transferred *B. praecucutus* to a new monospecific genus, the genus *Tissierella*. Although the genus *Tissierella* clearly differs from the *Bacteroides* and its relatives phenotypically, the higher phylogenetic associations of this taxon remain unknown.

There has been considerable progress in recent years in elucidating the phylogenetic relationships of the genus *Bacteroides* and other obligately anaerobic gram-negative bacteria by using 16S rRNA sequence analysis (20). Therefore, in this study we determined the 16S rRNA gene sequence of the type strain of *T. praecucuta* in order to elucidate the higher phylogenetic affiliations of this organism. A comparative sequence analysis demonstrated that *T. praecucuta* is a member of the *Clostridium* subphylum of the gram-positive bacteria and is closely related genealogically to the type strain of *Clostridium hastiforme*. On the basis of the results of this study and previous studies a new creatinine-degrading species of the genus *Tissierella*, *Tissierella creatinini*, is described.

**MATERIALS AND METHODS**

*Bacterial strains*. The type strains of *T. praecucuta* (ATCC 25539, NCTC 11158) and *C. hastiforme* (ATCC 33268, DSM 5675, NCTC 11832) were obtained from the American Type Culture Collection, Rockville, Md., the National Collection of Type Cultures, London, United Kingdom, and the Deutsche Sammlung von Mikroorganismen and Zellkulturen, Braunschweig, Germany, and were cultured as recommended in the culture collection catalogs.

**Isolation of creatinine-degrading strain BN11**. Strain BN11(T = type strain) was isolated from anaerobic enrichment cultures that had been inoculated with sediment from a wastewater pool at a sugar refinery in Norten-Hardenberg, Germany. Enrichment medium AM0.1 contained (per liter) 1.17 g of NaCl, 0.4 g of MgCl₂·6H₂O, 0.3 g of KO₃, 0.15 g of CaCl₂·2H₂O, 0.27 g of NaH₂PO₄·0.2 g of KH₂PO₄·2.84 g of Na₂SO₄·1 ml of trace element solution SL-10 (26), 1 ml of 10⁻⁶ M Na₂SeO₃, 0.5 g of yeast extract, 7.5 g of creatine·H₂O, 0.001 g of resazurin, 10 ml of vitamin solution (28), 4.5 g of NaHCO₃, and 0.5 g of L-cysteine hydrochloride; the pH of this medium was 7.5. The medium was prepared anaerobically by the Hungate technique under an 80% N₂,20% CO₂ gas atmosphere. During autoclaving, 75% of the creatine was converted to creatinine (18). Enrichment cultures in completely filled 50-ml screw-cap bottles were incubated at 30°C. After two transfers, a sample was streaked onto bicarbonate-free creatinine-containing AM0.1 agar plates and incubated in an anaerobic jar. Single colonies which produced a strong alkaline reaction when they were smeared on phenol red indicator paper were picked and purified by repeated streaking on agar plates of the same composition. Several isolates were obtained, and one strain, strain BN11T, was selected for further study.

**Physiological and biochemical tests**. Tests to determine production of lipase, lecithinase, urease, and indole, hemolysis, hydrolysis of gelatin, and digestion of milk and meat were performed as described by Holdeman et al. (10) and Krieg (14). Utilization of sugars and some other substances was determined in AM0.1 medium and in peptone-yeast extract medium at pH 6.8 and 8.6. Utilization of creatinine and structurally related compounds was determined by using AM0.1 medium containing 0.5% yeast extract at pH 8.3. Cultures were checked for spore production after growth in different liquid media or on agar media by phase-contrast microscopy and by performing heating tests. The pH and temperature optima and ranges for growth were determined in AM0.1 medium containing 3% yeast extract and 50 mM N-methylglycyldiamine as the substrate. Different pH values were obtained by using only 1 g of sodium bicarbonate per liter and buffering the preparations with 0.02 M potassium phosphate or Tris-HCl buffer at pH values ranging from 5.8 to 9.5. A model TN2 temperature gradient incubator (Tokyo Kagaku Sangyo, Ltd., Japan) was used to incubate cultures at temperatures ranging from 18 to 50°C.

**Analytical techniques**. Acetate contents were determined by gas chromatography; creatinine and N-methylglycyldiamine contents were determined by high-performance liquid chromatography; sarcosine contents were determined enzimatically with sarcosine oxidase and peroxidase; and N-carbamoylsarcosine contents were determined with N-carbamoylsarcosine hydrolyase in a coupled reaction with sarcosine oxidase as described previously (7). Ammonia levels were determined colorimetrically by the Berthelot reaction by using Merck’s colorimetric reagent (E. Merck, Darmstadt, Germany).
DNA base composition. The G + C content of strain BN11T was determined by the thermal denaturation method with a Gilford model 2600 spectrophotometer equipped with a model 2527 thermoprocessor and was calculated by using the equation of Marmur and Doty (17) as modified by De Ley (5). Escherichia coli K-12 strain DSM 485 (G + C content, 51.7 mol%) was used as the control.

16S rRNA gene sequence determination. Genomic DNA was extracted from mid-logarithmic-phase cells and was purified as described by Lawson et al. (15). 16S rRNA gene fragments were generated by a PCR, purified, and sequenced as described previously (12).

Analysis of sequence data. The sequence of T. praeacuta NCTC 11158T was aligned with 235 previously determined clostridial (3, 16) and reference sequences obtained from the EMBL and Ribosomal Database Project database and was analyzed by using the DNADIST program of the PHYLIP package (6). The distance matrix which we obtained was corrected for substitution rates by using Kimura’s parameters (13). A phylogenetic tree was constructed by the neighbor-joining method of Saitou and Nei (22) with a VAX computer. The stability of relationships was assessed by using the programs SEQBOOT, DNA-DIST, NEIGHBOR, and CONSENSE of the PHYLIP package. A total of 1,000 bootstrap trees were generated for the data set.

Nucleotide sequence accession numbers. The nucleotide sequences of the 16S rRNAs of T. praeacuta NCTC 11158T and ATCC 25539T and C. hastiforme DSM 5675T have been deposited in the EMBL data library under accession numbers X80832, X80833, and X80841, respectively.

RESULTS

The 16S rRNA gene of T. praeacuta NCTC 11158T was amplified by a PCR, and its nucleotide sequence was determined. The sequence, which we determined consisted of 1,475 nucleotides representing approximately 96% of the complete 16S rRNA primary structure. This 16S rRNA sequence was compared with the sequences of other 16S rRNAs available from the EMBL Data Library and the Ribosomal Database Project. Very low levels of sequence relatedness (generally <77%) were found with members of the genus Bacteroides and related gram-negative anaerobes. Much higher levels of sequence similarity were observed with members of the low-G+C-content subphylum of the gram-positive bacteria. Surprisingly, the 16S rRNA sequence of T. praeacuta NCTC 11158T was found to be almost identical (level of similarity, 99.9%, corresponding to 1 base difference in a comparison of 1,475 positions) to the sequence of the gram-positive spore-forming organism C. hastiforme DSM 5675T. To eliminate the possibility of incorrect collection strains or culture contamination, cultures of the type strains of T. praeacuta (ATCC 25539) and C. hastiforme (ATCC 33268 and NCTC 11832) held in other collections were sequenced, and the original data were confirmed.

To determine the phylogenetic position of T. praeacuta within the Clostridium subphylum, the sequence of this organism was compared with previously published sequences of more than 200 clostridial species and non-spore-forming relatives of these organisms. A matrix of representative similarity values based on an approximately 1,330-nucleotide region of the 16S rRNA is shown in Table 1. In addition to its close genealogical affinity with C. hastiforme, T. praeacuta exhibited high levels of sequence relatedness with species belonging to Clostridium cluster XII (groups of Collins et al. [3]), which includes Clostridium acidurici, Clostridium parnorphilicum, "Clostridium filamentosum," Eubacterium angustum, and the previously unnamed non-spore-forming organism strain BN11T. A phylogenetic tree constructed by using the neighbor-joining method is shown in Fig. 1; this tree confirms the placement of T. praeacuta within this cluster.

DISCUSSION

The recovery of T. praeacuta within the Clostridium subphylum of gram-positive bacteria was somewhat unexpected as T. praeacuta stains gram negative and does not produce spores (4). However, there is a growing recognition that Gram-staining and spore formation are not necessarily good indicators of relatedness. For example, several genera that traditionally have been considered to be gram negative have now been shown to be related to gram-positive bacteria (e.g., members of the genera Pectinatus, Megasphaera, Selenomonas, and Sporomusa), while the phylogenetic intermixing of spore-forming and non-spore-forming taxa is now well established (3, 24, 27).

To our knowledge, however, this combination of differences in Gram staining and sporulation characteristics has not been reported previously in such phylogenetically closely related organisms. Although it is now recognized that the occurrence of identical (or nearly identical) 16S rRNA sequences does not necessarily imply that species are identical, the data demonstrate that T. praeacuta and C. hastiforme are either the same species or very closely related species. In the past C. hastiforme has been phenotypically associated with the group IV organisms Clostridium botulinum and Clostridium subterminale. Chromosomal DNA-DNA pairing studies are clearly necessary to determine whether T. praeacuta and C. hastiforme represent different species and the latter organism should be reclassified. The previously unnamed creatinine-degrading organism strain BN11T (7, 8), which was isolated from a wastewater pool at a sugar refinery, exhibited >95% sequence relatedness to T. praeacuta. Interestingly, strain BN11T differs from T. praeacuta by being gram positive. Furthermore, unlike T. praeacuta, which has a wall based on meso-diaminopimelic acid, the wall of strain BN11T contains d-ornithine as the dibasic amino acid. There are, however, now numerous examples of organisms which are genealogically closely related or members of the same genus but which differ in wall composition. Some examples within the Clostridium subphylum include the genus Clostridium sensu stricto (cluster I [3]), which contains species with meso-diaminopimelic acid and species with L-diaminopimelic acid; and Clostridium paradoxum and Clostridium thermalcalphium, which exhibit approximately 2% 16S rRNA sequence divergence and have walls based on meso-diaminopimelic acid and ornithine, respectively. Despite differences in staining and wall composition, T. praeacuta and strain BN11T resemble each other in many ways, including the fact that they are both rod shaped and nonfermentative (carbohydrates are not utilized), the fact that they do not have endospores and respiratory menaquinones, and the fact that they have low DNA base compositions (28 to 32 mol% G+C). Thus, these similarities, together with the observed level of 16S rRNA sequence divergence (<5%), indicate that strain BN11T should be included in the genus Tissierella. It is worth noting that grouping of strain BN11T with T. praeacuta occurred in all 1,000 bootstrapped trees; these data support the close phylogenetic relationship of these organisms. Of the remaining species in Clostridium cluster XII, "C. filamentosum" exhibited approximately 10% sequence divergence with T. praeacuta and therefore in terms of evolutionary distance probably is peripheral to, or lies outside the boundaries of, the genus Tissierella. A relationship between "C. filamentosum" and the genus Tis- sierella was observed in only 83% of the bootstrapped trees. As pointed out previously (3), "C. filamentosum" could conceivably represent a distinct subline worthy of separate generic status. To avoid an undesirable proliferation of new genera, the genus Tissierella could be considered a possible genus of convenience for "C. filamentosum," although phenotypic information supporting this association would be required. C. acidurici, C. parnorphilicum, and E. angustum are in a distantly related group within cluster XII, exhibiting levels of sequence relatedness of >93% with each other. Significantly lower levels of sequence similarity (<90%) were observed with T. praeacuta and its relatives. The levels of sequence divergence and tree branching.
| % Similarity to: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 |
|----------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| T. pruettiae | 99.9 | 96.2 | 90.6 | 90.1 | 90.5 | 90.9 | 95.5 | 96.9 | 96.8 | 98.3 | 98.4 | 99.0 | 99.3 | 99.4 | 99.6 | 99.7 | 99.8 | 99.9 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| C. butyricum | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| T. roseopersicina | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| E. coli | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| C. homologum | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| C. perfringens | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| S. aureus | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| B. subtilis | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |
| E. coli | 95.1 | 90.1 | 90.3 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 | 90.2 |

*Abbreviations: T., Tissierella; C., Clostridium; E., Eubacterium; H., Helcococcus; P., Peptostreptococcus.*
**FIG. 1.** Dendrogram showing the relationship of \textit{T. praecut} to other members of the \textit{Clostridium} subphylum of gram-positive bacteria. The tree was constructed by using the neighbor-joining method, and bootstrap values were calculated from 1,000 trees. Numbers are the percentages of bootstrap replicates.

**FIG. 2.** Phase-contrast micrograph of strain BN1T. (Inset) India ink preparation showing slime capsules of cells. Bar = 10 \(\mu\text{m}\).

Considerations support the view that \textit{C. acidurici}, \textit{C. purinolyticum}, and \textit{E. angustum} represent a new genus that is related to, but nevertheless is separate from, the genus \textit{Tissierella}.

**Taxonomic proposals.**

(i) Emendation of the genus \textit{Tissierella} (Collins and Shah). The description of the genus \textit{Tissierella} given by Collins and Shah (4) should be emended as follows. Gram negative or gram positive: meso-Diaminopimelic acid or \(\varepsilon\)-ornithine is present in the cell wall peptidoglycan. The cellular fatty acids are primarily straight-chain saturated and iso-methyl branched-chain or unsaturated fatty acids. Strains preferentially growing on creatinine typically produce acetate, sarcosine, \(N\)-carbamoylsarcosine, ammonia, and \(CO_2\). The G+C content of the DNA is 28 to 32 mol%.

(ii) Description of \textit{Tissierella creatinini} sp. nov. \textit{Tissierella creatinini} (cre.a.ti.ni'ni. N. L. gen. n. creatinini, of creatinine). Cells are rod shaped (1.0 by 3.5 \(\mu\text{m}\)) and occur mostly singly or in pairs and rarely in chains of four to six cells (Fig. 2). Cells are nonmotile, and spores are not observed. Cells are gram positive and are surrounded by a slime capsule that is easily detectable in India ink preparations. Grows anaerobically in AM0.1 medium containing 0.05% yeast extract, 0.05% Trypticase, and creatinine or \(N\)-methylhydantoin. Growth is stimulated fivefold by the addition of formate (40 mM), twofold by the addition of serine (2 g/liter) or threonine (2 g/liter), and threefold by the addition of arginine (2 g/liter) and serine (2 g/liter), but not by the addition of arginine alone. In the absence of creatinine or \(N\)-methylhydantoin, formate and amino acids do not support growth. No stimulation of growth is produced by lactate, malate, succinate, glycerol, or \(H_2\). Yeast extract (optimal concentration, 0.5 to 1.0%) is required for growth and cannot be replaced by Casamino Acids or pep-
The medium used was AM0.1 medium containing 0.5% yeast extract. Optical densities of cultures grown in Hungate tubes were determined directly for gelatin hydrolysis, production of lipase, lecithinase, indole, and hemolysis are negative. Grows at 20 and 39°C, and optimum growth occurs at 37°C. The pH range for growth is pH 7.67 to 8.0. The pH optimum is pH 8.3 (determined with N-methylhydantoin).


