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Multilocus Sequence Analysis of Phylogroup 1 and 2 Oral Treponeme Strains

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ABSTRACT More than 75 "species-level" phylotypes of spirochete bacteria belonging to the genus *Treponema* reside within the human oral cavity. The majority of these oral treponeme phylotypes correspond to as-yet-uncultivated taxa or strains of uncertain standing in taxonomy. Here, we analyze phylogenetic and taxonomic relationships between oral treponeme strains using a multilocus sequence analysis (MLSA) scheme based on the highly conserved 16S rRNA, *pyrH*, *recA*, and *flaA* genes. We utilized this MLSA scheme to analyze genetic data from a curated collection of oral treponeme strains (*n* = 71) of diverse geographical origins. This comprises phylogroup 1 (*n* = 23) and phylogroup 2 (*n* = 48) treponeme strains, including all relevant American Type Culture Collection reference strains. The taxonomy of all strains was confirmed or inferred via the analysis of ca. 1,450-bp 16S rRNA gene sequences using a combination of bioinformatic and phylogenetic approaches. Taxonomic and phylogenetic relationships between the respective treponeme strains were further investigated by analyzing individual and concatenated *flaA* (1,074-nucleotide [nt]), *recA* (1,377-nt), and *pyrH* (696-nt) gene sequence data sets. Our data confirmed the species differentiation between *Treponema denticola* (*n* = 41) and *Treponema putidum* (*n* = 7) strains. Notably, our results clearly supported the differentiation of the 23 phylogroup 1 treponeme strains into five distinct "species-level" phylotypes. These respectively corresponded to "*Treponema vincentii*" (*n* = 11), *Treponema medium* (*n* = 1), "*Treponema sinensis*" (*Treponema* sp. IA; *n* = 4), *Treponema* sp. IB (*n* = 3), and *Treponema* sp. IC (*n* = 4). In conclusion, our MLSA-based approach can be used to effectively discriminate oral treponeme taxa, confirm taxonomic assignment, and enable the delineation of species boundaries with high confidence.

IMPORTANCE Periodontal diseases are caused by persistent polymicrobial biofilm infections of the gums and underlying tooth-supporting structures and have a complex and variable etiology. Although *Treponema denticola* is strongly associated with periodontal diseases, the etiological roles of other treponeme species/phylotypes are less well defined. This is due to a paucity of formal species descriptions and a poor understanding of genetic relationships between oral treponeme taxa. Our study directly addresses these issues. It represents one of the most comprehensive analyses of oral treponeme strains performed to date, including isolates from North America, Europe, and Asia. We envisage that our results will greatly facilitate future metagenomic efforts aimed at characterizing the clinical distributions of oral treponeme species/phylotypes, helping investigators to establish a more detailed understanding of their etiological roles in periodontal diseases and other infectious diseases. Our results are also directly relevant to various polymicrobial tissue infections in animals, which also involve treponeme populations.

Oral treponeme bacteria (genus *Treponema*) constitute a small but significant part of the "normal" human oral microbiota (1). This genus of spirochete bacteria shares a distinctive helical or flat-wave cell morphology, and many species are highly motile in liquid or semisolid environments, locomoting via a corkscrew-like motion (2–4). They typically occupy anaerobic niches, especially within dental plaque located in the gingival crevice: the narrow gap between the gingivae (gums) and the base of the crown of the tooth (5, 6). Their proportions are often highly elevated within diseased periodontal sites, and clinical studies have consistently associated them with various forms of periodontal disease, especially chronic periodontitis (7–12). High levels of treponeme taxa are also frequently detected within endodontic infections and oral-implant infections (e.g., peri-implantitis) (13–17).

Nine species of oral treponemes have been formally characterized in the scientific literature (the reporting year is indicated in parentheses): *Treponema denticola* (1993) (18); *Treponema pectinovorum* (1983) (19); *Treponema socranskii* (1998; three subspecies: *socranskii*, *paredis*, and *buccale*) (20); *Treponema maltophilum* (1996) (21); *Treponema medium* (1997) (22), whose description was amended in 2003 (23); *Treponema amylovorum* (1997) (24); *Treponema lecithinolyticum* (1999) (25); *Treponema parvum* (2001) (26); and *Treponema putidum* (2004) (27). "*Treponema vincentii*" is also generally considered to constitute an oral treponeme species, having been studied and reported in the scientific literature for more than 60 years (28–31). However, in the absence of a recent systematic characterization, its precise taxonomic definition remains obscure (9, 30).

Dewhirst et al. proposed a taxonomic framework for the classification of oral treponemes, based on shared 16S rRNA gene homology (32), which has become widely adopted by the scientific community. This places oral treponeme taxa within 10 different "phylogroups" (phylogenetic clusters) that respectively share more than 90% 16S rRNA gene sequence similarity (over a 500-bp region). At this time, more than 75 *Treponema* "species-level" phylotypes have been identified in the human oral cavity using 16S rRNA gene sequence-based approaches (1, 33). Many phylotypes have been assigned human oral taxon (HOT) codes, as part of the Human Oral Microbiome Database (HOMD) classification scheme (1). However, roughly three-quarters of identified oral treponeme phylotypes remain to be cultivated and formally described.

Placed within phylogroup 2, clinical investigations have consistently associated the presence or abundance of *T. denticola* cells with the occurrence and severity of periodontal disease (10–12, 34, 35). This phylogroup also contains *T. putidum*, a poorly studied treponeme that has been detected within periodontitis, acute necrotizing ulcerative gingivitis (ANUG), and endodontic lesions (27, 36). Notably, phylogroup 2 treponemes share high levels of phylogenetic similarity with *Treponema pallidum*, *Treponema phagedenis*, and *Treponema pedis* (31, 37), as well as many other isolates and as-yet-uncultivated taxa commonly found in polymicrobial tissue infections in livestock animals (38, 39).

The species *T. medium* and *T. vincentii* both belong to phylogroup 1. Consensus results from previous molecular clinical investigations have indicated that treponeme taxa belonging to phylogroup 1 are particularly prevalent, abundant and diverse within human subgingival plaque (33, 40). Furthermore, several phylogroup 1 taxa and species have previously been associated with periodontal disease (12, 33, 41, 42).

Complete genome sequences for *T. putidum* OMZ 758^T (ATCC 700334^T) and *Treponema* sp. strain OMZ 838 ("*Treponema sinensis*" [ATCC 700772]) have recently been published (43, 44). Furthermore, in as-yet-unpublished work, researchers working under the auspices of the Human Microbiome Project (45) have recently deposited genome sequence data for the type strain of *T. medium* (ATCC 700293, NCBI Genome BioProject no. 169490, sequenced by the Broad Institute), as well as for two strains of *T. vincentii* (ATCC 35580, NCBI Genome BioProject no. 34095, sequenced by the J. Craig Venter Institute; and F0403/N9, NCBI Genome BioProject no. 169493, sequenced by the Broad Institute). However, due to the relative paucity of genetic and genomic data for treponeme

TABLE 1 Summary of oral treponeme strains included in MLSA

Phylogroup and species (no. of strains)	Strains
Phylogroup 1	
T. vincentii (11)	ATCC 35580 (OMZ 293, LA-1), ATCC 700013 (OMZ 779, N9, F0403), ATCC 700765 (OMZ 800, DSM16788), ATCC 700774 (OMZ 860), OMZ 801, OMZ 802, OMZ 858, OMZ 859, OMZ 861, OMZ 862, OMZ 863
T. medium (1)	ATCC 700293^T (ex. G7201, OMZ 824)
T. sinensis IA (4)	ATCC 700772 (OMZ 838, DSM 16789), OMZ 855, OMZ 856, OMZ 857
Treponema sp. IB (3)	OMZ 305 (*T. vincentii* Ritz A), OMZ 805, ATCC 700767 (OMZ 806, DSM 16787)
Treponema sp. IC (4)	ATCC 700766 (OMZ 804, MH1F1), OMZ 803, OMZ 899, OMZ 906
Phylogroup 2	
T. denticola (41)	ATCC 35405^T (strain a, OMZ 661, DSM 14222), ATCC 35404 (strain c, TD-4, OMZ 663), ATCC 33521 (strain 11, OMZ 662), ATCC 33520 (strain W), ATCC 700771 (OMZ 834), ATCC 700768 (OMZ 830), CD-1 (OMZ 294), S2, OTK, OKA3, OT2B, MS25, GM-1, ST10 (OMZ 829), NY531, NY535, NY545, NY553, F0402, OMZ 823, OMZ 845, OMZ 849, OMZ 850, OMZ 852, OMZ 853, OMZ 854, OMZ 898, OMZ 905, OMZ 908, OMZ 910, H1-T (HMS-570), SP37 (HMS-569), SP44, SP33, SP32, SP23, AL-2 (HMS-575), ASLM (HMS-574), US-Trep (HMS-573), MYR-T (HMS-572), H-22 (HMS-571)
T. putidum (7)	ATCC 700334^T (OMZ 758), OMZ 730, OMZ 835, OMZ 844, OMZ 846, OMZ 847, OMZ 848

isolates belonging to phylogroup 1, the unambiguous identification and classification of taxa within this group remains highly problematic.

Multilocus sequence analysis (MLSA) and related multilocus sequence typing (MLST) approaches have previously been successfully used to delineate boundaries between closely related spirochete species, subspecies, and component strains. This has included *Borrelia* (46, 47), *Brachyspira* (48), and *Leptospira* (49) spp. and treponemes associated with digital dermatitis in cloven-hoofed animals (38, 50). Phylogenetic analysis of the 16S rRNA gene and 16S-23S rRNA intergenic spacer regions have also been commonly used for the analysis of *Treponema* spp. within animal foot and soft tissue lesions (see, for example, references 51 and 52).

Here, we used a four-gene MLSA approach to delineate genetic similarities and differences between oral treponeme reference strains and clinical isolates belonging to phylogroups 1 and 2. Our data suggest that several isolates previously classified as *T. vincentii* and *T. medium* should be placed within other taxonomic groupings, some of which most probably constitute novel species.

RESULTS

Obtaining gene sequences data sets from phylogroup 1 and 2 oral treponeme strains. A total of 71 human oral treponeme strains belonging to oral phylogroups 1 and 2 were included in our MLSA (Table 1). This included *T. denticola* (*n* = 41), *T. putidum* (*n* = 7), *T. medium* (*n* = 1), and *T. vincentii* (*n* = 11), as well as treponeme strains of uncertain standing in taxonomy (*n* = 11). These treponeme strains were originally isolated from various (diseased) oral sites, predominantly periodontitis lesions, from individuals who lived in North America, Europe, or Asia. This included all relevant ATCC (and DSMZ) oral treponeme reference strains. Additional details about the origins of these strains are summarized in Table S1 in the supplemental material.

Four genes were selected for analysis in each oral treponeme strain: the 16S rRNA gene (*rrs*), as well as the *flaA*, *recA*, and *pyrH* coding DNA sequences (CDSs). The *recA* gene encodes the main DNA homologous recombination and repair protein in bacteria, recombinase A (53). The *pyrH* gene encodes uridylate kinase (UMP kinase), which plays a key role in nucleotide metabolism in bacteria (54). The *flaA* gene encodes the FlaA flagellar outer sheath protein, which coats the core of the (periplasmic) flagellar

TABLE 2 Primers used for PCR amplification of target gene sequences

Gene	Primer	Sequence (5′–3′)	$T_m{}^a$ (range in °C)	Description (source or reference)
16S rRNA	TPU1 C90	AGAGTTTGATCMTGGCTCAG GTTACGACTTCACCCTCCT	56–53	All treponeme strains (33)
pyrH	TvpyrH-F TvpyrH-R	ATGGTACGGGTCTTATCGGTAG TTAACCTATCGTTGTGCCTTTAA	55–49	All phylogroup 1 treponemes and primers are based on *T. vincentii* ATCC 35580 (this study)
	pyrH-F pyrH-R	ATGGTAACTGTTTTGTCGGT TTAGCCGATTACCGTTCCTT	54–47	All phylogroup 2 treponemes and primers are based on *T. denticola* ATCC 35405 (56)
recA	TvrecA-F TvrecA-R	ATGGCAAAAACAAAATCAGAAA TTAAAAGAGCTCGTTGTCGC	55–52	All phylogroup 1 treponemes and primers are based on *T. vincentii* ATCC 35580 (this study)
	recA-F1 recA-R1	GTGGCAAAAGCAAAAAACGAAG TTAAAAAAGACTGTCGTCCGCC	55–52	Most phylogroup 2 treponemes except *T. denticola* ATCC 700771, ATCC 700768, and MS25 and primers are based on *T. denticola* ATCC 35405 (56)
	recA-F2 recA-R2	TTCATATTGGCCGCATTTG TTGTGTACTCATAATGCCGCTC	54–47	*T. denticola* ATCC 700768 and MS25 and primers are based on regions 117 bp upstream and 69 bp downstream of *recA* gene on *T. denticola* ATCC 35405 chromosome (56)
	recA-F1 recA-R2	GTGGCAAAAGCAAAAAACGAAG TTGTGTACTCATAATGCCGCTC	55–49	*T. denticola* ATCC 700771 and primers are as described above (56)
flaA	TvflaA-F TvflaA-R	ATGAAAAGAACAAGCATACTTGTAG CTATTGCTTTGTATTTTCGGC	55–49	All phylogroup 1 treponemes except *Treponema* sp. IB and primers are based on *T. vincentii* ATCC 35580 (this study)
	TvflaA-F 305flaA-R	ATGAAAAGAACAAGCATACTTGTAG TTAGTTTGCAGCCTCTGTTG	55–49	*Treponema* sp. IB treponemes and the 305flaA-R primer are based on the *flaA* gene extracted from genome sequence data for *Treponema* sp. strain OMZ 305 (this study)
	TDE1712-F TDE1712-R	ATGAAAAAAACATTTATACTTGTTG TTATTGTTGGTTCTTTTCGG	52–46	All phylogroup 2 treponemes and primers are based on *T. denticola* ATCC 35405 (56)

^{a}Touchdown PCRs were performed, with the annealing temperature decreased by ca. 0.5 to 1°C every cycle for the first six cycles (according to the range of temperatures indicated in the T_m column), thereafter using the lowest temperature within the range shown for the remaining 27 cycles.

filament, which is comprised of the FlaB protein (55). The 16S rRNA gene is present in two identical copies (*rrsA* and *rrsB*) in *Treponema* taxa (37). The others are single-copy CDSs, which correspond to the following three loci in the genome-sequenced *T. denticola* ATCC 35405^T strain: *pyrH* (TDE2085; 696 bp), *flaA* (TDE1712; 1,050 bp), and *recA* (TDE0872; 1,245 bp) (37). These three CDSs were selected based on the results obtained from our previous phylogenetic analysis of 20 *T. denticola* strains (56).

We were able to obtain full-length gene sequence data for *flaA*, *recA*, and *pyrH* from 36 oral phylogroup 1 and 2 strains by searching the publically accessible nucleotide sequence depositories. Using these data, various sets of PCR primers were designed to amplify full-length *flaA*, *recA*, and *pyrH* gene sequences from phylogroup 1 and 2 oral treponeme strains (summarized in Table 2). In addition, a total of 35 phylogroup 1 and 2 oral treponeme strains from our curated collection were cultivated, and full-length gene sequences were successfully obtained for these strains. The primer sequences and PCR conditions used are summarized in Table 2. Near-full-length (~1,450-bp) regions of the 16S rRNA gene from each cultivated treponeme strain were also obtained. The accession codes for all gene sequences used in this study are summarized in Table S2 in the supplemental material.

Assignment of taxonomy and phylogeny of oral treponeme strains based on the 16S rRNA gene. We first assigned taxonomy for each oral treponeme strain (*n* = 71) to the species or phylotype level by analyzing the 16S rRNA gene sequence data sets using a maximum-likelihood (ML) phylogenetic approach. This included 23 phy-

logroup 1 strains and 48 phylogroup 2 strains (listed in Table 1). *T. phagedenis* F0421 and *T. pallidum* subsp. *pallidum* strain Nichols were included for comparative purposes, and *T. lecithinolyticum* ATCC 700332^T (which belongs to phylogroup 4) was used as an outgroup. The GTR+I+G nucleotide substitution model was determined to be optimal for the analysis of 16S rRNA data sets according to jModelTest (57). The ML tree generated is shown in Fig. 1. For clarity, the respective treponeme species (or proposed species) are indicated with different colors. The corresponding human oral taxon (HOT) numbers, as defined by the HOMD (58), are also indicated for each strain.

It may be seen in the phylogram (Fig. 1) that the 41 *T. denticola* (HOT 584; dark blue) and 7 *T. putidum* (HOT 743; red) strains were well separated from each other based on their 16S rRNA gene sequences. Both of these phylogroup 2 species were well separated from *T. pallidum* (HOT 805), *T. phagedenis*, and the phylogroup 1 treponeme strains. This was as expected and is in good accordance to analogous phylogenetic analyses of oral treponeme populations reported in previous studies (1, 27, 31–33). Six of the seven *T. putidum* strains, including the ATCC 700334^T strain, clustered together. The OMZ 848 strain appeared to be slightly divergent, being more closely related to *T. denticola* strains. It should be noted that our analysis includes every *T. putidum* strain that has been characterized and reported in the literature (27).

The phylogroup 1 treponeme strains formed four well-separated clades with good bootstrap support. The *T. medium* type strain (ATCC 700293, ex. [formerly] G7201 [22, 23]) formed a single taxon branch. All 11 *T. vincentii* strains formed a single clade (HOT 029; light green in Fig. 1). This clade included four American Type Culture Collection (ATCC) reference strains: ATCC 35580 (LA-1), 700013 (F0403, N9), 700774 (OMZ 860), and 700765 (OMZ 800). The three other clades were designated *Treponema* sp. IA (purple), *Treponema* sp. IB (light blue), and *Treponema* sp. IC (orange), respectively. The IA and IC phylotypes both corresponded to HOT 231, whereas the IB phylotypes corresponded to HOT 667, which also contains *T. medium* ATCC 700293^T.

It has been proposed (C. Wyss, unpublished data) that *Treponema* sp. strain ATCC 700772 (OMZ 838), whose full genome sequence has recently been reported (44), as well as three other *Treponema* strains—OMZ 855, OMZ 856, and OMZ 857—correspond to a new species that has tentatively been named *Treponema sinensis* (to reflect the strain's Chinese origins) (59). These four *T. sinensis* strains correspond to *Treponema* sp. IA and are well separated from the other phylotypes and species. Furthermore, since the respective *T. medium*, *T. vincentii*, *T. sinensis* (IA), and *Treponema* sp. IB and IC taxa are all well segregated into distinct phylogenetic lineages in the ML tree in Fig. 1, it appears to be valid to refer to these respective clades or single branch taxa as "species-level" phylotypes.

To further investigate taxonomic and phylogenetic relationships between phylogroup 1 treponeme strains, we performed a further ML phylogenetic analysis incorporating an additional set of $n = 41$ 16S rRNA gene sequences, which were previously obtained from a plasmid library of (human) oral treponeme 16S rRNA gene amplicons (33). These were representatives of 265 unique cloned amplicon sequences based on a 99% similarity cutoff. This plasmid library was constructed in an analogous manner to the procedure employed for this study, using DNA extracted from pooled subgingival plaque samples obtained from a cohort of periodontitis patients ($n = 10$) and periodontitis-free individuals ($n = 10$). The section of the ML phylogram generated, which contains all oral phylogroup taxa is shown in Fig. 2. The corresponding oral treponeme phylotypes that have been previously defined by Dewhirst et al. (32) and You et al. (33) are indicated for comparative purposes.

It may be seen that the overall topology (branching pattern) of the ML tree generated from the 16S rRNA data set that included all the additional (uncultivated) treponeme phylotypes was very similar to that of the ML tree shown in Fig. 1. Specifically, the phylogenetic arrangements and strain compositions of the five respective species or "species-level" phylotypes—*T. vincentii* (HOT 029), *T. medium* (HOT 667), *Treponema* sp. IB (HOT 667), *T. sinensis* (*Treponema* sp. IA; HOT 231), and *Treponema* sp. IC (HOT 231)—were well preserved after the addition of the uncultivated oral trepo-
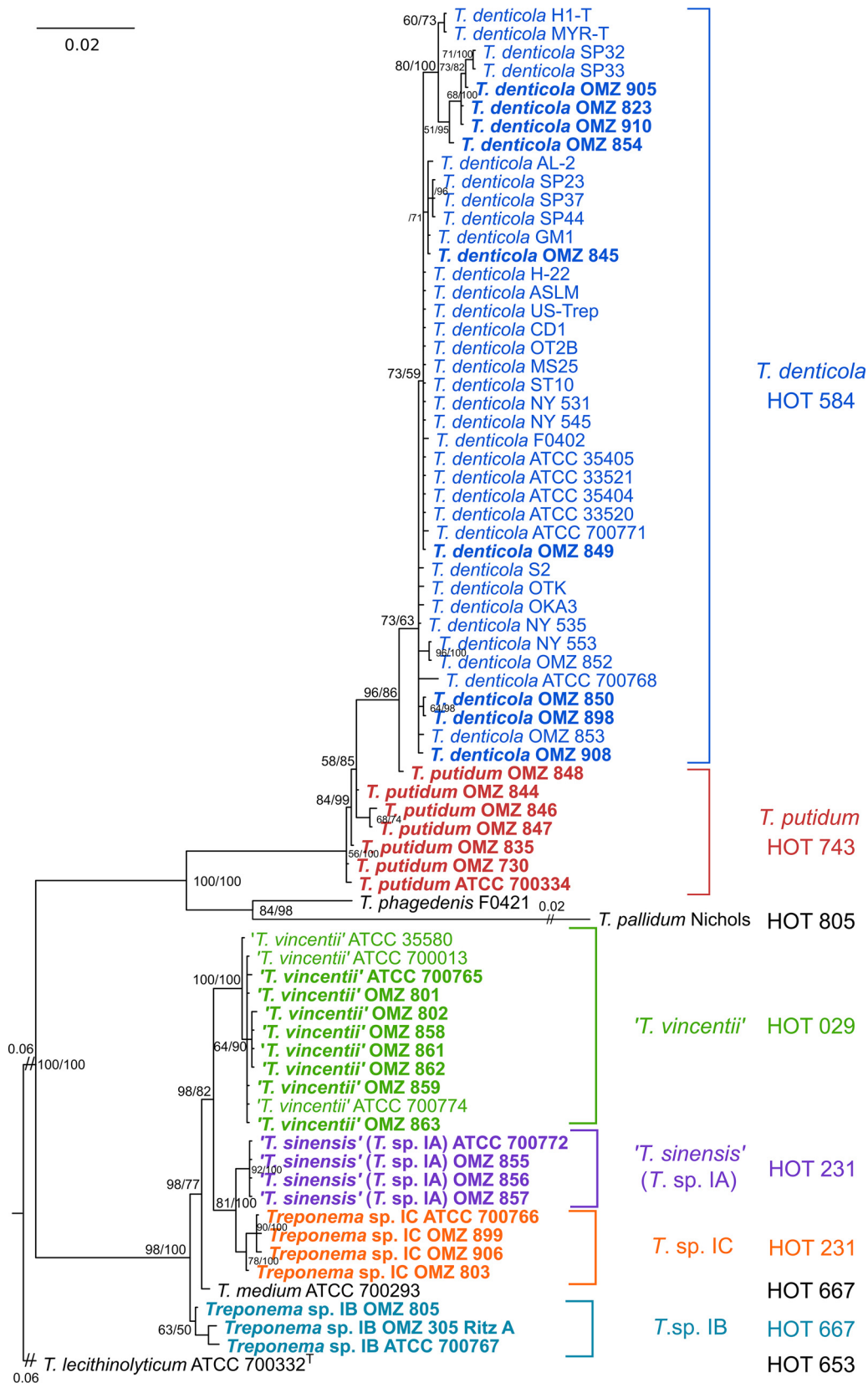
FIG 1 ML phylogenetic tree of oral treponeme 16S rRNA genes. The maximum clade credibility tree topology is supported by bootstrapping for 1,000 replicates (first number) and Bayesian posterior probabilities (second number) separated with a forward slash "/" symbol in percentages; only values over 40% are shown beside the branch nodes. Sequences generated in this study are in boldface type. A scale bar indicates the nucleotide changes per position. Excessively long branches were

neme taxa. The *T. vincentii* clade contained the *Treponema* sp. clone 5H35 (GenBank accession no. JQ654120) (33). The *T. sinensis* (*Treponema* sp. IA) clade contained the *Treponema* sp. clone 3P51 (JQ654121) (33). The *Treponema* sp. IC clade contained the "group 01 cluster G (I:G:T21)" (AF023055) (32), and the *Treponema* sp. clones 2H5 (JQ654110), 3H21 (JQ654104), and 7H36 (JQ654103) (33). The *T. medium* clade contained the "group 01 cluster B (I:B:C7)" (AF023051) (32), and the *Treponema* sp. IB clade contained the *Treponema* sp. clone 9P33 (JQ654130) (33). The *Treponema* sp. clones 10P23 (JQ654158), 2H16 (JQ654117), 9P45 (JQ654206), and 8P69 (JQ654174) and the "group 01 cluster AA (1:AA:DW001)" (AY005082) (32) were closely related to, but distinct from, the *T. sinensis* and *Treponema* sp. IC clades.

Phylogenetic analyses of individual *flaA*, *recA*, and *pyrH* genes. Individual ML trees were calculated for the *flaA*, *recA*, and *pyrH* genes to investigate phylogenetic relationships between oral treponeme strains at three different genetic loci. The optimal nucleotide substitution models were determined to be GTR+G for *flaA*, and GTR+I+G for *recA* and *pyrH* according to jModelTest (57). In the *flaA* (Fig. 3) and *pyrH* (see Fig. S1B in the supplemental material) ML phylogenetic trees, the seven *Treponema putidum* strains were closely clustered and well separated from *T. denticola* strains. Interestingly, *T. denticola* ATCC 700768 was more closely related to *T. putidum* in the *pyrH* ML tree and was an outlier in the *flaA* ML tree. The *recA* ML tree (see Fig. S1A in the supplemental material) had a different topology, with the seven *T. putidum* strains forming three clades that were intertwined with *T. denticola* strains. The branching patterns for the *T. denticola* strains exhibited considerable variation between the three respective single gene ML trees.

For the phylogroup 1 oral treponemes, there was consistency in the branching patterns observed in the respective *flaA*, *recA*, and *pyrH* ML trees (Fig. 3 and see Fig. S1 in the supplemental material). In each tree, there were four clusters that respectively contained the *T. vincentii*, *T. sinensis* (*Treponema* sp. IA), *Treponema* sp. IB, and *Treponema* sp. IC taxa. The topologies were analogous to those present in the 16S rRNA ML tree, with only two minor differences. The *Treponema* sp. IB OMZ 305 (Ritz A) strain was distinct from the other *Treponema* sp. IB taxa and formed a clade with the *T. medium* type strain (ATCC 700293, ex. G7201) in the *recA* ML tree (see Discussion for the details of further analyses). The *T. vincentii* ATCC 700013 (F0403, N9) strain differed from the other *T. vincentii* strains in the *pyrH* ML tree by being more closely related to the other phylogroup 1 strains outside the *T. vincentii* clade. The phylogeny of these three genetic loci consistently showed that *T. medium* ATCC 700293^T was closely related to the *Treponema* sp. IB taxa.

Phylogenetic analyses of concatenated two-gene and three-gene sequence data sets. ML phylogenetic analysis was next performed on three different combinations of two-gene concatenations (i.e., *flaA-recA* [2,360 bp], *flaA-pyrH* [1,667 bp], and *recA-pyrH* [2,017 bp]) in order to determine which pair of protein-coding genes may be most effective for the delineation of phylogroup 1 and 2 treponeme strains. The best nucleotide substitution model for *flaA-recA* and *recA-pyrH* was GTR+I+G, with GTR+G being optimal for *flaA-pyrH*. The three ML phylogenetic trees generated are shown, respectively, in Fig. S2A to C in the supplemental material. In the ML trees generated from all three of the two-gene combinations, the 23 phylogroup 1 taxa showed the same clustering patterns, with *T. vincentii*, *Treponema* sp. IA, *Treponema* sp. IB, and *Treponema* sp. IC taxa each forming individual clades. *T. medium* ATCC 700293^T formed a single branch, which was most closely related to the *Treponema* sp. IB clade. The 42 phylogroup 2 strains showed very similar clustering patterns in all three of the two-gene ML trees, which were analogous to those present in the individual *flaA* and

FIG 1 Legend (Continued)

trimmed in proportion to the scale bar (indicated by "//" on the branches). The respective oral treponeme species (phylogroups) are indicated with different color shadings. The corresponding HOT numbers are also indicated as follows: *T. denticola* (HOT 584), dark blue; *T. putidum* (HOT 743), red; *T. vincentii* (HOT 029), light green; *Treponema* sp. IA (HOT 231), purple; *Treponema* sp. IB (HOT 667), light blue; and *Treponema* sp. IC (HOT 231), orange.
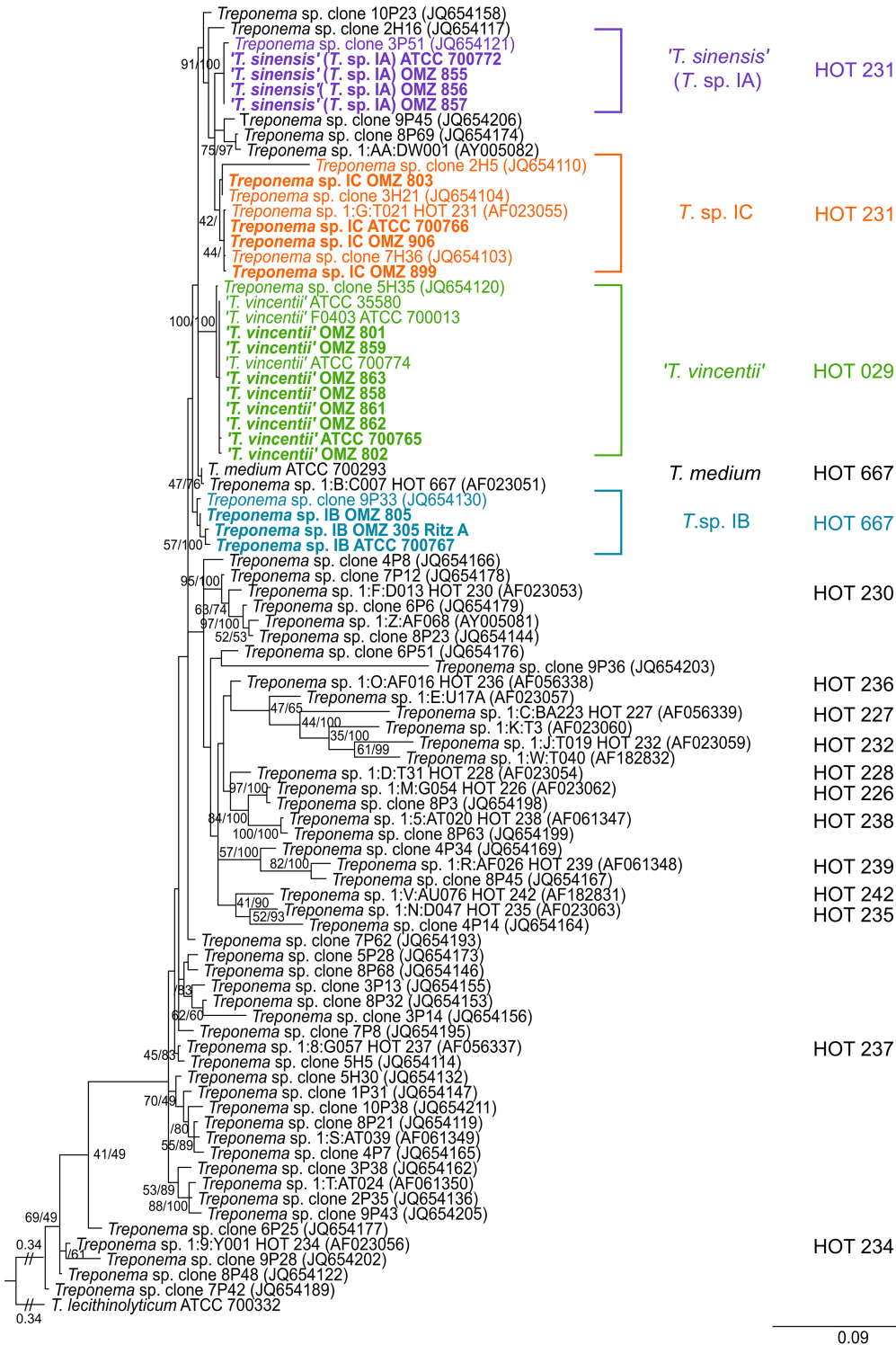
Treponema sp. clone 10P23 (JQ654158)
Treponema sp. clone 2H16 (JQ654117)
Treponema sp. clone 3P51 (JQ654121)
'T. sinensis' (*T.* sp. IA) ATCC 700772
'T. sinensis' (*T.* sp. IA) OMZ 855
'T. sinensis' (*T.* sp. IA) OMZ 856
'T. sinensis' (*T.* sp. IA) OMZ 857
91/100

'T. sinensis'
(*T.* sp. IA)   HOT 231

Treponema sp. clone 9P45 (JQ654206)
Treponema sp. clone 8P69 (JQ654174)
75/97   *Treponema* sp. 1:AA:DW001 (AY005082)
Treponema sp. clone 2H5 (JQ654110)
Treponema sp. IC OMZ 803
Treponema sp. clone 3H21 (JQ654104)
Treponema sp. 1:G:T021 HOT 231 (AF023055)
Treponema sp. IC ATCC 700766
Treponema sp. IC OMZ 906
Treponema sp. clone 7H36 (JQ654103)
Treponema sp. IC OMZ 899
42/
44/

T. sp. IC   HOT 231

100/100
Treponema sp. clone 5H35 (JQ654120)
'T. vincentii' ATCC 35580
'T. vincentii' F0403 ATCC 700013
'T. vincentii' OMZ 801
'T. vincentii' OMZ 859
'T. vincentii' ATCC 700774
'T. vincentii' OMZ 863
'T. vincentii' OMZ 858
'T. vincentii' OMZ 861
'T. vincentii' OMZ 862
'T. vincentii' ATCC 700765
'T. vincentii' OMZ 802

'T. vincentii'   HOT 029

T. medium ATCC 700293
47/76 *Treponema* sp. 1:B:C007 HOT 667 (AF023051)

T. medium   HOT 667

Treponema sp. clone 9P33 (JQ654130)
Treponema sp. IB OMZ 805
Treponema sp. IB OMZ 305 Ritz A
57/100 **Treponema sp. IB ATCC 700767**

T. sp. IB   HOT 667

Treponema sp. clone 4P8 (JQ654166)
Treponema sp. clone 7P12 (JQ654178)
95/100
Treponema sp. 1:F:D013 HOT 230 (AF023053)
63/74   *Treponema* sp. clone 6P6 (JQ654179)
97/100   *Treponema* sp. 1:Z:AF068 (AY005081)
52/53   *Treponema* sp. clone 8P23 (JQ654144)
Treponema sp. clone 6P51 (JQ654176)
Treponema sp. clone 9P36 (JQ654203)

HOT 230

Treponema sp. 1:O:AF016 HOT 236 (AF056338)
Treponema sp. 1:E:U17A (AF023057)
47/65   *Treponema* sp. 1:C:BA223 HOT 227 (AF056339)
44/100   *Treponema* sp. 1:K:T3 (AF023060)
35/100   *Treponema* sp. 1:J:T019 HOT 232 (AF023059)
61/99   *Treponema* sp. 1:W:T040 (AF182832)
Treponema sp. 1:D:T31 HOT 228 (AF023054)
97/100 *Treponema* sp. 1:M:G054 HOT 226 (AF023062)
Treponema sp. clone 8P3 (JQ654198)
84/100   *Treponema* sp. 1:5:AT020 HOT 238 (AF061347)
100/100   *Treponema* sp. clone 8P63 (JQ654199)
57/100   *Treponema* sp. clone 4P34 (JQ654169)
82/100   *Treponema* sp. 1:R:AF026 HOT 239 (AF061348)
Treponema sp. clone 8P45 (JQ654167)
Treponema sp. 1:V:AU076 HOT 242 (AF182831)
41/90   *Treponema* sp. 1:N:D047 HOT 235 (AF023063)
52/93   *Treponema* sp. clone 4P14 (JQ654164)

HOT 236
HOT 227
HOT 232
HOT 228
HOT 226
HOT 238
HOT 239
HOT 242
HOT 235

Treponema sp. clone 7P62 (JQ654193)
Treponema sp. clone 5P28 (JQ654173)
Treponema sp. clone 8P68 (JQ654146)
83   *Treponema* sp. clone 3P13 (JQ654155)
Treponema sp. clone 8P32 (JQ654153)
62/60   *Treponema* sp. clone 3P14 (JQ654156)
Treponema sp. clone 7P8 (JQ654195)
45/83   *Treponema* sp. 1:8:G057 HOT 237 (AF056337)
Treponema sp. clone 5H5 (JQ654114)
Treponema sp. clone 5H30 (JQ654132)
70/49   *Treponema* sp. clone 1P31 (JQ654147)
Treponema sp. clone 10P38 (JQ654211)
/80   *Treponema* sp. clone 8P21 (JQ654119)
55/89   *Treponema* sp. 1:S:AT039 (AF061349)
Treponema sp. clone 4P7 (JQ654165)
41/49   *Treponema* sp. clone 3P38 (JQ654162)
53/89   *Treponema* sp. 1:T:AT024 (AF061350)
88/100   *Treponema* sp. clone 2P35 (JQ654136)
Treponema sp. clone 9P43 (JQ654205)
Treponema sp. clone 6P25 (JQ654177)
69/49   0.34 *Treponema* sp. 1:9:Y001 HOT 234 (AF023056)
/61   *Treponema* sp. clone 9P28 (JQ654202)
Treponema sp. clone 8P48 (JQ654122)
Treponema sp. clone 7P42 (JQ654189)
0.34 *T. lecithinolyticum* ATCC 700332

HOT 237

HOT 234

0.09

FIG 2 ML phylogenetic tree of 16S rRNA genes from phylogroup 1 oral treponemes. Refer to Fig. 1 legend for explanatory details.

pyrH ML trees. *T. denticola* ATCC 700768 was more closely related to *T. putidum* in the *recA-pyrH* ML tree and was an outlier in the *flaA-recA* and *flaA-pyrH* ML trees.

The optimum nucleotide substitution model for the ML phylogenetic analysis of the concatenated *flaA-recA-pyrH* three-gene data set (3,022 bp) was determined to be GTR+I+G. The phylogenetic analysis revealed a very clear distinction between phylo-
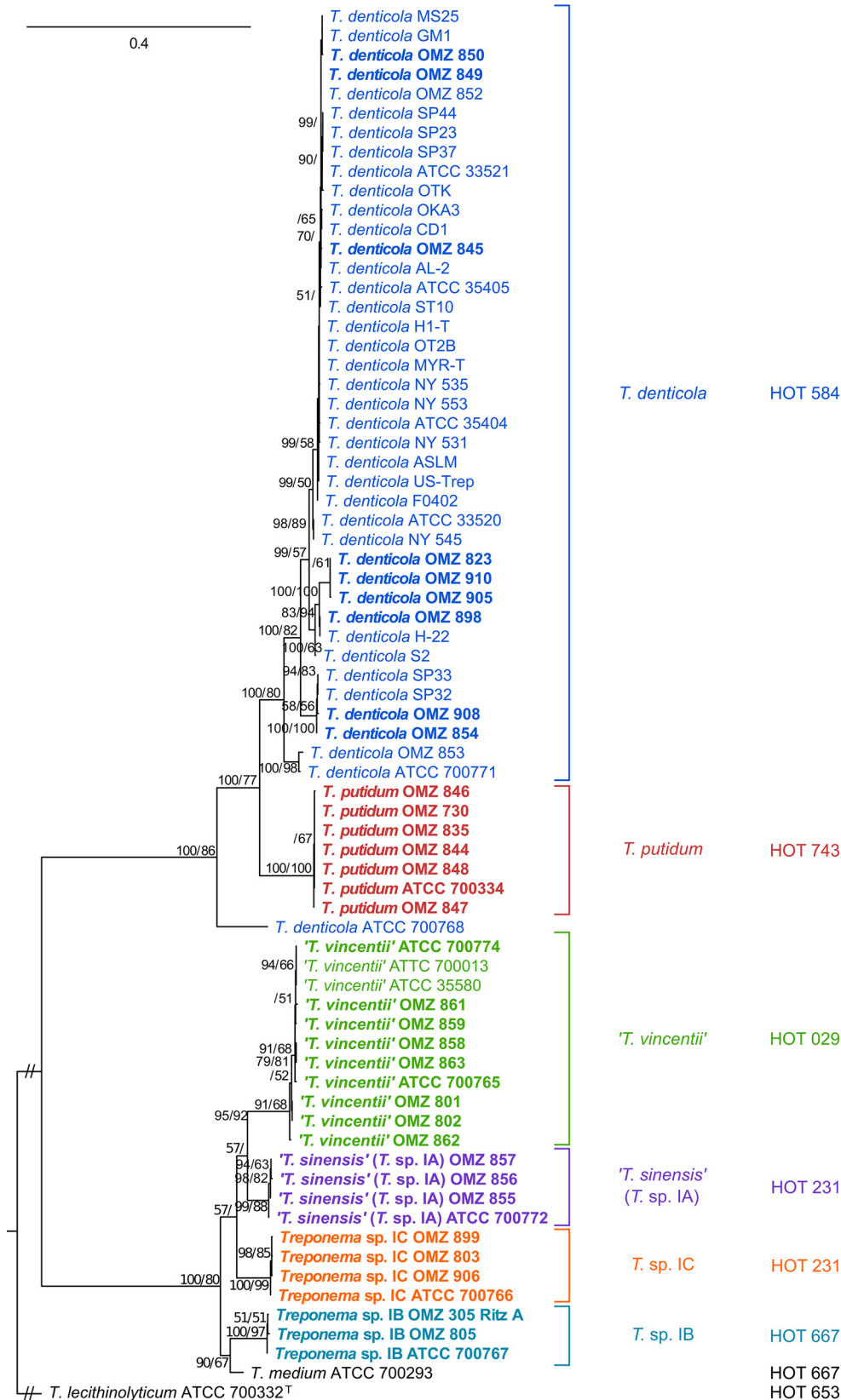
FIG 3 ML phylogenetic tree of individual *flaA* genes. Refer to Fig. 1 legend for explanatory details.

groups 1 and 2 and also well-defined clades within each phylogroup, all with high bootstrap and Bayesian posterior probability support values (Fig. 4). The concatenated three-gene ML tree had a very similar overall topology as the *recA-pyrH* ML tree, but with generally higher statistical support for the branches. As noted above, *T. denticola* ATCC 700768 was a notable outlier in the three-gene ML tree, being more closely related to the *T. putidum* strains. All 11 of the *T. vincentii* strains formed a separate clade, with the ATCC 700013 strain appearing somewhat distinct from the others. The respective *T. sinensis* and *Treponema* sp. IC taxa formed very clearly demarcated clades, with very high levels of statistical support. The distinction between *T. medium* ATCC 700293 and the three *Treponema* sp. IB taxa was less well defined, especially regarding the phylogenetic position of the *Treponema* sp. IB Ritz A (OMZ 305) strain.

Bioinformatic analysis of 16S rRNA, *flaA*, *recA*, and *pyrH* gene sequences. The respective lengths of the 16S rRNA gene sequences obtained were highly consistent with the taxonomic assignment (Table 3). All of the *T. denticola* strains had 16S rRNA genes 1,497 bp in length, making them distinct from the *T. putidum* strains, which encoded 16S rRNA genes that were 1,496 bp in length. All of the phylogroup 1 treponeme strains had 16S rRNA genes 1,502 bp in length. There were only relatively minor differences in the mean G+C content of the 16S rRNA genes present in the respective species/phylotypes, ranging from ca. 51.9 to 52.5% (Table 3).

The lengths of the *pyrH* gene sequences (obtained from databases or determined experimentally here) were strictly conserved within the phylogroup 1 and phylogroup 2 strains, respectively (Table 3). The *pyrH* gene was 696 bp in length for all phylogroup 2 (*T. denticola* and *T. putidum*) strains and was 687 bp in all phylogroup 1 taxa (*T. vincentii*, *T. medium*, *T. sinensis* [*Treponema* sp. IA], *Treponema* sp. IB, and *Treponema* sp. IC). The *flaA* genes in all phylogroup 2 strains were 1,050 bp in length. However, this was one to four codons shorter than the corresponding *flaA* genes in phylogroup 1 strains, which were different in each of the species or phylotypes: *T. vincentii* (1,062 bp), *T. medium* (1,068 bp), *T. sinensis* (1,059 bp), *Treponema* sp. IB (1,068 bp), and *Treponema* sp. IC (1,062 to 1,065 bp). Similarly, the length of *recA* gene was identical within all phylogroup 2 strains (1,245 bp) but varied among the phylogroup 1 phylotypes. The *recA* gene sequences within the phylogroup 1 strains were notably longer (1,326 to 1,368 bp) than those from phylogroup 2. The respective *recA* gene lengths were consistent within *T. vincentii* (1,326 bp) and *T. sinensis* (1,338 bp) phylotypes but varied slightly within the *Treponema* sp. IB (1,359 to 1,368 bp) and *Treponema* sp. IC (1347 to 1350 bp) phylotypes. The *recA* gene in *T. medium* (1,362 bp) was distinct from the other phylotypes.

There were notable trends in the respective G+C contents of the *flaA*, *recA*, and *pyrH* genes. The respective G+C contents of the individual *flaA*, *recA*, or *pyrH* genes within the respective treponeme phylotypes or species were very similar ($\pm$ 0-0.76%). However, the respective G+C contents of the *flaA*, *recA*, and *pyrH* genes in the oral phylogroup 1 treponemes were all ca. 4 to 7% higher than the corresponding genes in *T. denticola* and *T. putidum*. For example, the mean G+C content for the *pyrH* gene in *T. denticola* strains was 41.8 $\pm$ 0.38%, whereas in *T. vincentii* it was 47.5 $\pm$ 0.76%. In addition, in all strains studied, the respective G+C content of the *recA* gene was ca. 4 to 5% higher than that of the corresponding *flaA* or *pyrH* genes (Table 3).

Nucleotide diversity, polymorphism, and evolutionary conservation of codon sites. The respective levels of nucleotide diversity (π) and the number of polymorphic sites were calculated for all four genes at the phylogroup level and at the species/phylotype level. The evolutionary conservation of codon sites was calculated for the *flaA*, *pyrH*, and *recA* genes (since the 16S rRNA gene does not encode a protein). The results are summarized in Table 4 (see also Table S3 in the supplemental material).

The proportions of polymorphic sites were equivalent in the 16S rRNA gene sequences from the respective sets of oral phylogroup 1 strains (2.52%) and oral phylogroup 2 strains (2.74%). Within the respective species (phylotypes) there was considerable variation in the numbers (%) of 16S rRNA polymorphic sites present. The

FIG 4 ML phylogenetic tree constructed from concatenated *flaA-recA-pyrH* gene data sets. Refer to Fig. 1 legend for explanatory details. The geographical origins of the respective clinical treponeme isolates are indicated with the corresponding countries' flags.

TABLE 3 Average gene length and G+C content of oral treponeme 16S rRNA, *flaA*, *pyrH*, and *recA* genes analyzed

Species (no. of strains) and parameter	Mean gene length and G+C content			
	16S rRNA	*flaA*	*recA*	*pyrH*
T. vincentii (11)				
Mean gene length in bp (range)	1,502 (1,502)	1,062 (1,062)	1,326 (1,326)	687 (687)
Mean gene G+C content (%) ± SD	51.9 ± 0.03	45.4 ± 0.07	50.5 ± 0.10	47.5 ± 0.76
T. medium (1)				
Mean gene length in bp (range)	1,502 (1,502)	1,068 (1,068)	1,362 (1,362)	687 (687)
Mean gene G+C content (%) ± SD	52.3	45.3	50.8	45.0
T. sinensis (4)				
Mean gene length in bp (range)	1,502 (1,502)	1,059 (1,059)	1,338 (1,338)	687 (687)
Mean gene G+C content (%) ± SD	52.5 ± 0.00	44.7 ± 0.13	50.7 ± 0.19	46.3 ± 0.14
Treponema sp. IB (3)				
Mean gene length in bp (range)	1,502 (1,502)	1,068 (1,068)	1,362 (1,359−1,368)	687 (687)
Mean gene G+C content (%) ± SD	52.4 ± 0.15	46.5 ± 0.12	51.3 ± 0.17	46.7 ± 0
Treponema sp. IC (4)				
Mean gene length in bp (range)	1,502 (1,502)	1,064 (1,062−1,065)	1,348 (1,347−1,350)	687 (687)
Mean gene G+C content (%) ± SD	52.3 ± 0.00	45.4 ± 0.13	50.6 ± 0.17	46.0 ± 0.25
T. denticola (41)				
Mean gene length in bp (range)	1,497 (1,497)	1,050 (1,050)	1,245 (1,245)	696 (696)
Mean gene G+C content (%) ± SD	52.4 ± 0.09	40.6 ± 0.40	45.6 ± 0.44	41.8 ± 0.38
T. putidum (7)				
Mean gene length in bp (range)	1,496 (1,496)	1,050 (1,050)	1,245 (1,245)	696 (696)
Mean gene G+C content (%) ± SD	52.3 ± 0.18	39.8 ± 0.05	45.0 ± 0.61	40.1 ± 0.04

numbers of polymorphic sites present within the 41 strains of *T. denticola* (1.72%) were broadly comparable to those present in the 7 *T. putidum* strains (1.38%). The proportions of polymorphic sites were considerably lower in the respective phylogroup 1 species, ranging from 0.00% across the 4 *T. sinensis* strains to 0.41% across the 11 *T. vincentii* strains. The number of 16S rRNA polymorphic sites was ca. 11% across all the treponeme strains analyzed, reflecting the considerable phylogenetic distance between phylogroups 1 and 2.

The overall proportions of polymorphic sites in the respective *flaA*, *pyrH*, and *recA* genes were broadly equivalent in the two respective phylogroups, ranging from ca. 19 to 25%. However, this masked considerable differences in the degree of gene polymorphism in these three respective genes within the respective species or phylotypes. For example, 10.99% of sites in the *recA* genes from *T. putidum* were polymorphic, which is considerably higher than levels present in *flaA* (0.19%) or *pyrH* (0.41%). An analogous situation was observed for the *Treponema* sp. IB taxa. However, in *T. vincentii* the levels of nucleotide polymorphisms were much higher in the *pyrH* gene (14.6%) than in the *flaA* (1.79%) or *recA* genes (1.71%). The numbers of polymorphic sites in the respective *flaA*, *pyrH*, and *recA* genes ranged from ca. 39 to 46% across all of the treponeme strains analyzed. The levels of nucleotide diversity (π) for the respective *flaA*, *pyrH*, and *recA* genes were slightly higher in the phylogroup 1 strains (0.078 to 0.098) than in the phylogroup 2 strains (0.042 to 0.064), which probably reflects the imbalance in the strains analyzed.

Mean global omega (ω) values, which are equivalent to the ratio of nonsynonymous (*dN*) to synonymous (*dS*) mutations (i.e., *dN/dS*) for each codon site, were calculated for the *flaA*, *recA*, and *pyrH* genes within the respective sets of oral phylogroup 1 and 2 strains to gauge the evolutionary pressures. These are reported with the corresponding 95% confidence intervals (CI). The ω values were fairly similar for the corresponding *flaA* and *pyrH* genes in oral phylogroup 1 and 2 strains. However, the ω values for the *recA* gene were higher in phylogroup 1 strains (ω = 0.300; 95% CI = 0.276 to 0.326), compared to phylogroup 2 strains (ω = 0.103; 95% CI = 0.087 to 0.121). The means ω

TABLE 4 Summary of polymorphic sites, nucleotide diversity per site, global rate ratios, and positively/negatively selected codon sites[a]

Species (no. of strains)	Gene	No. of nt	No. of codons	No. (%) of polymorphic sites	Mean nucleotide diversity (π) ± SD	Mean dN/dS (global ω; 95% CI)	No. of sites (%) Negatively selected	No. of sites (%) Positively selected
T. vincentii (11)	flaA	1,062	353	19 (1.79)	0.006 ± 0.0010	0.103 (0.032–0.239)	1 (0.28)	0
	recA	1,326	441	24 (1.71)	0.004 ± 0.0005	0.060 (0.019–0.139)	0	0
	pyrH	687	228	106 (14.60)	0.031 ± 0.0194	0.067 (0.042–0.102)	0	0
	16S	1,450	NA	6 (0.41)	0.001 ± 0.0004	NA	NA	NA
T. medium (1)	flaA	1,068	355	NA	NA	NA	NA	NA
	recA	1,362	453	NA	NA	NA	NA	NA
	pyrH	687	228	NA	NA	NA	NA	NA
	16S	1,450	NA	NA	NA	NA	NA	NA
T. sinensis (4)	flaA	1,059	352	5 (0.47)	0.003 ± 0.0008	0.058 (0.003–0.257)	0	0
	recA	1,338	445	50 (3.57)	0.019 ± 0.0066	0.052 (0.019–0.112)	0	0
	pyrH	687	228	23 (3.17)	0.017 ± 0.0051	0.183 (0.078–0.357)	0	0
	16S	1,450	NA	0 (0.00)	0.000 ± 0.0000	NA	NA	NA
Treponema sp. IB (3)	flaA	1,068	355	5 (0.47)	0.003 ± 0.0010	0.074 (0.004–0.328)	0	0
	recA	1,368	455	124 (8.85)	0.061 ± 0.0282	0.052 (0.019–0.112)	0	0
	pyrH	687	228	0 (0.00)	0.000 ± 0.0000	0.001 (0.00–10000)	0	0
	16S	1,450	NA	6 (0.41)	0.003 ± 0.0008	NA	NA	NA
Treponema sp. IC (4)	flaA	1,065	354	6 (0.56)	0.003 ± 0.0006	0.148 (0.025–0.456)	0	0
	recA	1,350	449	40 (2.86)	0.016 ± 0.0043	0.108 (0.052–0.195)	0	0
	pyrH	687	228	10 (1.38)	0.009 ± 0.0021	0.061 (0.102–0.190)	1 (0.44)	0
	16S	1,450	NA	4 (0.28)	0.001 ± 0.0006	NA	NA	NA
T. denticola (41)	flaA	1,050	349	218 (20.76)	0.029 ± 0.0070	0.121 (0.097–0.149)	13 (3.71)	0
	recA	1,245	414	185 (13.20)	0.035 ± 0.0030	0.094 (0.076–0.115)	58 (13.98)	1
	pyrH	696	231	149 (20.52)	0.031 ± 0.0067	0.082 (0.061–0.106)	31 (13.36)	0
	16S	1,450	NA	25 (1.72)	0.003 ± 0.0005	NA	NA	NA
T. putidum (7)	flaA	1,050	349	2 (0.19)	0.001 ± 0.0002	0.00 (0.00–0.263)	0	0
	recA	1,245	414	154 (10.99)	0.058 ± 0.0064	0.122 (0.091–0.160)	9 (2.17)	0
	pyrH	696	231	3 (0.41)	0.001 ± 0.0004	NA	0	0
	16S	1,450	NA	20 (1.38)	0.005 ± 0.0016	NA	NA	NA

[a]NA, not applicable; nt, nucleotides; 95% CI, 95% confidence interval.

values for the *flaA* and *pyrH* genes in all the strains included (*n* = 71) was calculated to be <0.12, whereas the mean ω value for *recA* gene was 0.21. This indicates that there was a strong purifying selective pressure to conserve the function of these three proteins, although *recA* was under slightly less selective pressure than *flaA* and *pyrH*.

The respective numbers of negatively and positively selected codon sites were also calculated for the *flaA*, *recA*, and *pyrH* genes the at the phylogroup level. Negative (purifying) selection indicates the conservation of gene sequence and function, while positive selection indicates evolutionary pressure for gene sequence change and adaptation. There were similar proportions of negatively selected codon sites in the *flaA* and *pyrH* genes within both phylogroup 1 and phylogroup 2 strains (ca. 7% and ca. 13%, respectively). For the *recA* gene, there were more negatively selected codon sites within the phylogroup 2 strains (17.9%) compared to phylogroup 1 (11.9%). Notably, there was a single positively selected site in the *recA* gene in *T. denticola*. This corresponded to the amino acid residue Val-8 (see Fig. S3 in the supplemental material). The specific role of the Val-8 in the biological activities of the RecA protein remains obscure (53).

Intraspecific and interspecific sequence similarity. The intraspecific and interspecific sequence similarities for each of the four genes (16S rRNA, *flaA*, *recA*, and *pyrH*) were calculated for each of the respective treponeme species/phylotypes. These are summarized in Fig. 5 and Fig. S4 in the supplemental material. Here, we defined intraspecific gene sequence similarity as that which occurs between strains belonging to the same species or phylotype. Correspondingly, interspecific gene sequence simi-
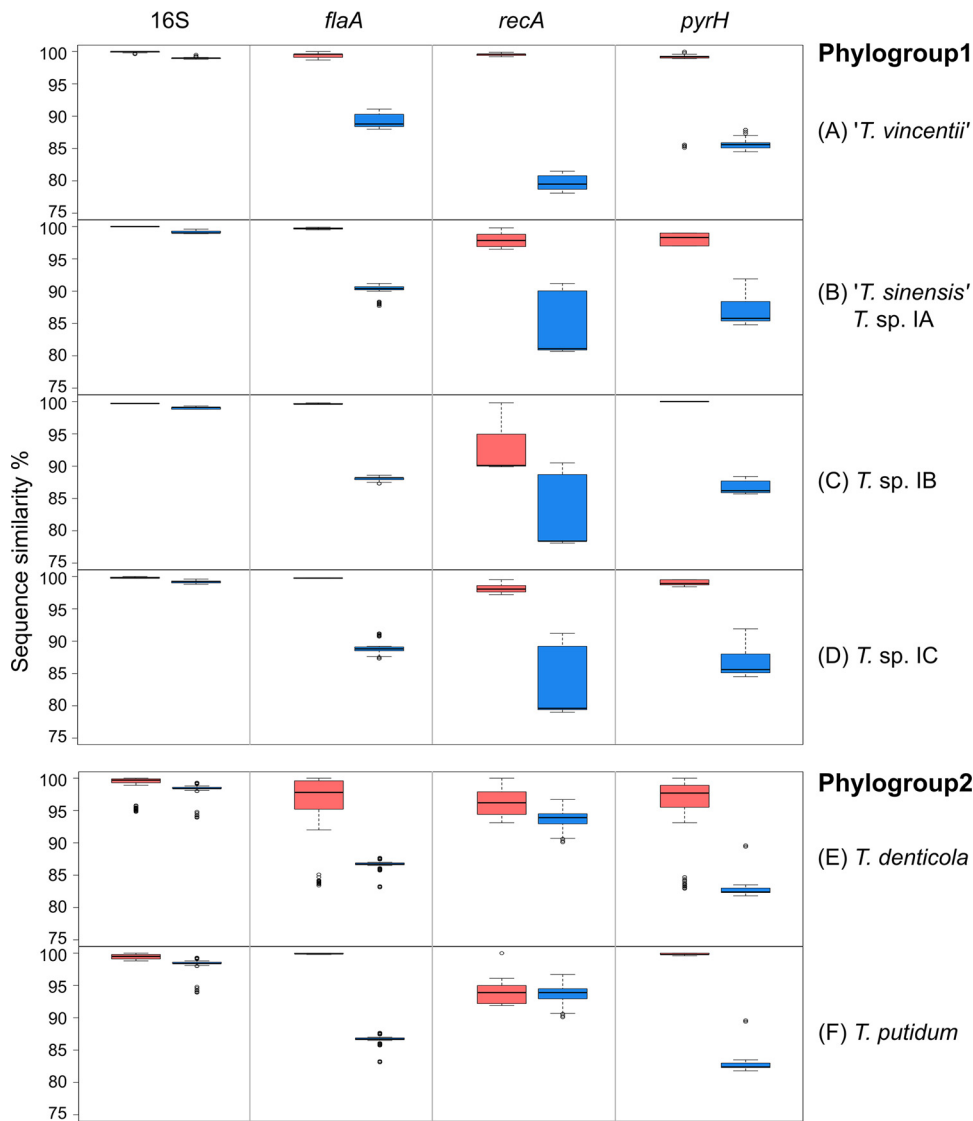
FIG 5 Intra- and interspecific sequence similarity (%) for individual treponeme phylogroups. The respective levels of intra- and interspecific sequence similarity (in %) for the 16S rRNA, *flaA*, *recA*, and *pyrH* genes are shown for *T. vincentii* (A), *T. sinensis* (*Treponema* sp. IA; panel B), *Treponema* sp. IB (C), *Treponema* sp. IC (D), *T. denticola* (E), and *T. putidum* (F). Interspecific gene sequence similarity is indicated by blue shading, and intraspecific gene sequence is indicated by pink shading. The boxes indicates the lower/upper quartiles and the median, and the whiskers indicate the maximum and minimum values (Q3 + 1.5 IQR and Q1 − 1.5 IQR), excluding the outliers, which are indicated as open circles.

larity was defined as that which occurred between taxa belonging to different species or phylotypes. In accordance with the phylogenetic analysis described above, *T. medium* ATCC 700293^T was treated as a unique taxon. It should be carefully noted that gene sequence similarity does not directly correlate with phylogenetic distances due to their different calculation/estimation methods.

The average intraspecific sequence similarities for each of the four genes, within each of the six respective species/phylotypes are shown in Fig. S4 in the supplemental material. Each species/phylotype is represented with the same color scheme used in the ML phylograms shown in Fig. 1 to 4, and error bars are excluded, to aid visual comparison. As expected, the 16S rRNA gene showed the lowest levels of sequence variation (or highest similarity) within each of the respective species/phylotypes. The ranges of intraspecific sequence similarities were very small, especially for the phylogroup 1 species (99.5 to 100%). The 11 *T. vincentii* taxa shared 99.8 to 100% similarity,

TABLE 5 Interspecific 16S rRNA gene sequence similarities between species or phylotypes

Phylogroup and species	% gene sequence similarities (range)			
	T. vincentii	*T. sinensis* (*Treponema* sp. IA)	*Treponema* sp. IB	*Treponema* sp. IC
Phylogroup 1				
T. medium	98.9 (98.8–99.0)	98.9	99.3 (99.2–99.6)	99.0 (99.0–99.1)
T. vincentii		98.6 (98.5–98.7)	98.7 (98.4–99.0)	98.5 (98.3–98.8)
T. sinensis			98.9 (98.8–99.0)	99.3 (99.2–99.5)
Treponema sp. IB				99.0 (98.8–99.1)
	T. putidum			
Phylogroup 2				
T. denticola	98.4 (97.8–99.3)			

the four *T. sinensis* taxa had identical 16S rRNA sequences, and the three *Treponema* sp. IB and four *Treponema* sp. IC strains shared 99.5 to 99.6% and 99.7 to 99.9% 16S rRNA gene sequence similarities, respectively. There were higher levels of 16S rRNA gene sequence variation within the *T. denticola* and *T. putidum* taxa; these variations ranged from 98.9 to 100.0% and from 98.7 to 99.9%, respectively. These data are consistent with those presented in Table 5 and Table S4 in the supplemental material, as well as with the general topology of the 16S rRNA ML tree in Fig. 1.

The respective levels of intraspecific sequence similarity for the *flaA*, *recA*, and *pyrH* genes varied considerably across the six treponeme species/phylotypes. The general patterns of gene sequence similarity/variation mirrored those reported above and summarized in Table 5. Overall, the *recA* gene showed the highest levels of sequence variation across the six species/phylotypes, followed by *pyrH* and then *flaA*.

The ranges of intraspecific and interspecific gene sequence similarity for the 16S rRNA, *flaA*, *recA*, and *pyrH* genes, for each of the six species/phylotypes are shown using a standard box-plot format in Fig. 5 and Fig. S5 in the supplemental material. Such plots can be used to establish "cutoff" points to help delineate species or other taxonomic groupings. The data have been analyzed and presented in three different ways. Figure 5A to D shows the interspecific and intraspecific gene sequence similarity relationships for phylogroup 1 treponemes only. Figure 5E and F shows the equivalent data for phylogroup 2 treponemes only. Figure S5 in the supplemental material shows the interspecific and intraspecific gene sequence similarity relationships for both phylogroup 1 and 2 treponemes.

As seen in Fig. 5 and Fig. S5 in the supplemental material, the "cutoff" between *T. denticola* and *T. putidum* taxa may be placed at ca. 99% 16S rRNA gene sequence similarity. The "species" boundaries appear to be tighter for phylogroup 1 oral treponemes, since it requires a similarity cutoff greater than ca. 99.5% to separate the respective species or phylotypes based on their 16S rRNA sequences (Fig. 5 and see Fig. S5).

For the *flaA*, *recA*, and *pyrH* genes, gene sequence similarity levels greater than ca. 90% are generally sufficient to separate the respective treponeme species/phylotypes. Of the three CDSs, the *recA* gene had the widest range of intraspecific sequence similarities (visualized by larger pink Q1 to Q3 boxes in Fig. 5 and Fig. S5 in the supplemental material). Thus, it can effectively distinguish different *Treponema* strains within the same species/phylotypes. However, the intra-/interspecific boundaries for the *recA* gene were often ambiguous (visualized by overlap between the pink and blue boxes in Fig. 5 and Fig. S5), that would hinder taxonomic assignation based on these criteria alone. In this regard, the *flaA* and *pyrH* gene sequences may offer better discrimination between the species/phylotypes. It should also be noted that the majority of the outliers (indicated with open circles in Fig. 5 and Fig. S5) correspond to *T. denticola* ATCC 700768, which is highly phylogenetically distinct from the other *T. denticola* strains.

DISCUSSION

Taxa belonging to the genus *Treponema* represent a significant proportion of the bacterial diversity present within the human oral cavity. Of the 75 oral treponeme species or "species-level" phylotypes currently listed in the web-accessible HOMD database (www.homd.org) (58), 15 correspond to oral phylogroup 1, and 5 correspond to phylogroup 2. The vast majority of phylogroup 2 taxa commonly identified in the oral cavity (e.g., via 16S rRNA gene amplicon sequencing-based approaches) correspond to *T. denticola* (HOT 584), with *T. putidum* (HOT 743) or other phylotypes encountered much less frequently (see, for example, references 1, 32, 33, and 40). There is a large body of evidence linking *T. denticola* with periodontal disease, with many putative pathological mechanisms having been identified (see, for example, references 10, 11, 34, 35, and 60). However, our current knowledge of the respective distributions of phylogroup 1 treponeme taxa within the oral cavity is far less well understood. This is greatly complicated by the lack of formal species descriptions for previously isolated/cultivated phylogroup 1 phylotypes and strains. Thus, many of the ca. 200- to 500-bp 16S rRNA gene reads commonly generated from next-generation DNA sequencing analyses cannot be accurately assigned to specific treponeme species (or putative species). This prevents us from obtaining a more detailed picture of the "*T. vincentii*-like" and "*T. medium*-like" taxa present within specific oral niches or infected clinical sites, greatly hampering our understanding of disease etiology. The four-gene multi-locus genetic analysis described here was primarily aimed at addressing this important issue. An additional objective was to analyze the phylogenetic differences between *T. denticola* and *T. putidum* strains, which share many phenotypic characteristics and have high levels of 16S rRNA gene sequence similarity (27).

In our previous seven-gene MLSA of human oral *T. denticola* strains (56), our results indicated that the *flaA*, *recA*, and *pyrH* genes exhibited the highest levels of gene sequence diversity. Consequently, we selected these three genes for the phylogenetic analysis of a large and comprehensive collection of oral treponeme strains belonging to phylogroups 1 ($n = 23$) and 2 ($n = 48$). Taxonomy was assigned based on 16S rRNA gene phylogeny (Fig. 1). To facilitate comparisons with previous studies, we directly correlated the results from our phylogenetic analyses with both the HOMD taxonomic framework, as well as the oral treponeme taxonomic framework originally established by Paster and coworkers (1, 32, 40, 61). Our results supported the division of the ($n = 23$) "*T. vincentii*-like" and "*T. medium*-like" phylogroup 1 treponeme strains into five "species-level" groupings: *T. vincentii* (HOT 029), *T. sinensis* (*Treponema* sp. IA; HOT 231), *Treponema* sp. IC (HOT 231), *T. medium* (HOT 667), and *Treponema* sp. IB (HOT 667). This phylogeny-based taxonomic assignment was still strongly supported when 16S rRNA data from relevant as-yet-uncultivated oral taxa were added (Fig. 2).

Our data strongly support the long-held (though not yet officially recognized) designation of *T. vincentii* as a distinct "species" of oral treponeme, since in both phylogenetic (Fig. 1 to 4) and sequence similarity-based (Fig. 5) analyses the component strains ($n = 11$) consistently grouped together. The gene lengths (Table 3) and nucleotide compositions (Table 4) were also highly conserved in component *T. vincentii* strains and were different from those of the other four "species-level" groups. It may be noted that Correia et al. previously reported the 16S rRNA gene sequences of the *T. vincentii* OMZ 858, 860, 861, and 862 strains as part of their genetic analysis of the subtilisin operon in oral treponemes (62). Importantly, our data clearly indicate that the Ritz A (OMZ 305) strain, which was originally classified as being *T. vincentii* (63), does not belong within this species group. It belongs within the *Treponema* sp. IB group. It should be noted that the Ritz A strain has previously been included in a number of investigations as a representative *T. vincentii* strain (e.g., see references 64 to 67). Consequently, any previous "species-specific" generalizations involving the Ritz A strain should be carefully reappraised.

Our data are also consistent with the taxonomic position of *T. medium* as a distinct species. However, it should be noted that there is a paucity of *T. medium* strains

reported in the literature. To the best of our knowledge, the properties of only one *T. medium* strain (ATCC 700293; ex. G7201) have been reported (22, 23). Thus, in the absence of data from additional strains, the precise nature of the relationship between *T. medium* and *Treponema* sp. IB taxa (ATCC 700767 = OMZ 806, Ritz A = OMZ 305, and OMZ 805) remains somewhat ill defined. As noted above, *T. sinensis* (*Treponema* sp. IA) has been proposed to constitute a distinct putative "species" of oral treponeme (Wyss, unpublished). With the exception of the recent publication of the genome sequence of the OMZ 838 (ATCC 700772) strain (44), there is a dearth of genetic or biological information about this proposed species. The properties of the *Treponema* sp. IC strains have previously been reported. Riviere et al. previously noted that the *Treponema* sp. IC strain OMZ 804 (ATCC 700766) could not be amplified by either "*T. vincentii*-specific" or "*T. medium*-specific" primer sets. In addition, the results from these authors' arbitrarily primed PCR analysis of genomic DNA indicated that the OMZ 804 strain was distinct from the *T. vincentii* ATCC 33580, *T. vincentii* 802, *T. medium* G7201, and *Treponema* sp. IB OMZ 805 strains (68). These observations are consistent with our MLSA.

A wide range of MLSA or MLST studies have previously utilized *recA* and/or *pyrH* genes to delineate species (subspecies) boundaries within diverse bacterial taxa, such as *Vibrio* spp. (69), *Streptococcus* spp. (70), and *Achromobacter* spp. (71). Of note, the *pyrH* gene had the highest resolution for discriminating the diversity of *Vibrio cholerae* and *Vibrio mimicus* species (72), and the *recA* gene was most effective for differentiating *Achromobacter* taxa (71). Genes encoding components of the flagellum have previously been included in a number of MLSA and (multilocus) bacterial typing systems, e.g., in *Campylobacter* spp. (73) and *Clostridium difficile* (74). The *flaB2* gene has previously been used to discriminate treponemes associated with animal hoof/foot infections (38).

Clegg et al. (50) recently designed and employed an MLST system based on seven housekeeping genes for the discrimination and phylogenetic analysis of 121 treponeme strains isolated from digital dermatitis (DD) lesions of cloven-hoofed (farm) animals. These researchers used a PCR-based strategy to analyze ca. 500- to 600-bp fragments of the *groEL*, *recA*, *glpK*, *adk*, *gdh*, *pyrG*, and *rplB* genes and included data from the genome sequenced *T. sinensis* OMZ 838 and *T. medium* ATCC 700293 strains for references. These authors noted that both of these human oral strains were highly distinct from all the (nonoral) animal strains analyzed. To further probe this issue, we directly compared our human oral treponeme *recA* gene data with corresponding *recA* gene data from the 121 animal (nonoral) treponeme isolates reported by Clegg et al. via an ML phylogenetic analysis of the entire data set. The resultant ML tree is shown in Fig. S6 in the supplemental material. This clearly indicated that the human and animal treponemes had no direct phylogenetic overlap, with the very notable exception of the *Treponema* sp. IB Ritz A (OMZ 305) strain. This single human oral strain clustered along with 31 phylogroup I DD strains of uncertain standing in taxonomy, which corresponded to the *recA* "allele 1" defined in the study by Clegg et al. (50). However, it should be noted that this represents a single gene locus of this strain, which may not be wholly representative of the phylogenic origins of the rest of its genome. The implications of this phylogenetic relationship remain to be determined.

Regions of the FlaB and/or FlaA (flagellin) proteins of phylogroup 1 and 2 treponeme strains may be surface exposed, thereby becoming antigenic, and may be glycosylated (64, 67, 68, 75, 76). This phenotypic property is responsible for the ability of several strains of *T. denticola*, *T. putidum*, *T. medium*, *T. vincentii*, and "*T. vincentii*-like" species to cross-react with monoclonal antibodies (e.g., H9-2) raised against *T. pallidum*. This led to the definition of the term pathogen-related oral spirochete (PROS), a term that was discontinued due to its somewhat confusing and poorly defined nature (68). Many of the strains we analyzed here were previously identified as "PROS-positive" strains (27, 64, 67, 68).

Since the (antigenic) FlaA protein may become intimately associated with the host tissues, it may be hypothesized that the *flaA* gene could be under different selective pressures compared to genes encoding intracellular "housekeeping" proteins, such as

RecA and PyrH. However, our findings here do not support this hypothesis. The overall topologies (branching patterns) of the ML trees constructed from the *flaA* (Fig. 3), *recA* (see Fig. S1A in the supplemental material), and *pyrH* (Fig. S1B) single gene data sets were all highly congruent with one another. Although there were differences in the relative numbers of polymorphic sites within these three protein-coding genes, all exhibited a strong stabilizing selection (Table 4). This is consistent with our previous findings for *T. denticola* strains (56). There was no evidence of genetic recombination for the *flaA* and *pyrH* genes. However, one possible recombination site was identified in the *recA* gene of the phylogroup 2 strains (Val-8), which is where a polymorphic site is located (see Fig. S3 in the supplemental material). Based on the functions and predicted tertiary structure of the RecA protein (53), the biological reasons underlying this variation remain obscure.

The results from the ML phylogenetic analysis of the concatenated *flaA-recA-pyrH* data sets clearly separated *T. putidum* from *T. denticola* (Fig. 4), with the *T. denticola* ATCC 700768 (OMZ 830) strain being a notable outlier. This is consistent with a previous report (27) which stated that this strain had a notably different phenotype from the other *T. denticola* and *T. putidum* strains analyzed. However, the phylogenetic distinction between *T. putidum* and *T. denticola* strains is not always clear-cut for the individual *recA* and *pyrH* genes (see Fig. S1 in the supplemental material), suggesting that these two species may share a certain amount of overlap in their genome compositions. It should also be noted that several of the *T. putidum* and *T. denticola* strains studied here were originally isolated from ANUG lesions in Chinese individuals (27, 59), as opposed to periodontitis lesions (see Table S1 in the supplemental material). It remains to be seen whether there are any significant genomic differences in treponeme taxa that inhabit ANUG versus periodontitis lesions or play etiological roles in these two oral infectious diseases.

We were curious to investigate whether there were any correlations between the phylogenies of the concatenated *flaA-recA-pyrH* gene sequences and the geographical origins of these clinical treponeme isolates. Based on the phylogenetic branching patterns (which may be visualized by the respective distributions of the country flags in Fig. 4), we tentatively speculate that there may be some genomic similarities for certain sets of oral treponeme strains isolated from the same geographical region. For example, several of the *T. putidum* strains isolated from Switzerland (ATCC 700334 and OMZ 844) and China (OMZ 848, OMZ 835, and OMZ 846) cluster together. The two Swiss *Treponema* sp. IB strains (OMZ 805 and ATCC 700767) cluster together. The four *T. sinensis* strains, all isolated in China, share high levels of phylogenetic similarity. Also, the two Chinese *T. vincentii* strains OMZ 861 and 863 cluster closely together. However, there is also evidence to support the hypothesis that there are treponeme strain lineages that may have a "global" distribution, as evidenced by phylogenetically closely related strains being isolated from geographically distinct locations. For example, the *T. vincentii* ATCC 35580 (USA) and ATCC 700774 (China) strains cluster together, as do the *T. vincentii* OMZ 801 (Switzerland), OMZ 802 (Switzerland), and OMZ 862 (China) strains. These speculative conclusions are consistent with the findings from our previous seven-gene MLSA analysis of 20 *T. denticola* isolates (56). However, we are cautious with these correlations, since although these three respective protein-coding genes are widely separated on the chromosome (37, 44), they only represent a very small snapshot of the entire genome composition.

Conclusions. Taken together, the results from our multilocus phylogenetic and sequence-similarity-based analyses of oral treponeme strains clearly indicate that the 16S rRNA, *flaA*, *recA*, and *pyrH* genes can be used to effectively characterize and discriminate phylogroup 1 and 2 taxa spanning multiple species. Our data confirm the taxonomic positions of *T. vincentii*, *T. medium*, and *T. putidum* and defines three new "species-level" phylotypes: *T. sinensis* (*Treponema* sp. IA), *Treponema* sp. IB, and *Treponema* sp. IC. We envisage that results from future whole-genome-based analyses and systematic polyphasic taxonomic studies will support the oral treponeme "species"

definitions proposed here. Our MLSA-based approach may be easily applied for the systematic characterization and phylogenetic analysis of treponemes from other phylogroups, as well as those from other ecological systems.

MATERIALS AND METHODS

Strain culture. Details of the oral treponeme strains used in this study are summarized in Table 1 and see Table S1 in the supplemental material. Strains of *Treponema denticola*, *Treponema putidum*, *Treponema vincentii*, and *Treponema medium*, as well as other *Treponema* strains of uncertain taxonomic standing, were either purchased from the ATCC or were kindly provided by Chris Wyss, Georgios Belibasakis, and R. Gmür (University of Zurich, Switzerland); E. Peter Greenberg (University of Washington, USA); and Barry McBride (University of British Columbia, Canada). All isolates were stored at −70°C and were cultivated anaerobically in TYGVS medium supplemented with thiamine pyrophosphate (Sigma-Aldrich, USA), volatile fatty acids (Sigma-Aldrich, USA), and 10% rabbit serum (Gibco, USA) as described previously (22, 77). Strains were incubated anaerobically (Thermo Scientific Forma anaerobic system; gas mix: 85% nitrogen, 10% hydrogen, 5% carbon dioxide) at 37°C for 5 to 7 days until active growth became apparent. The cells were harvested by centrifugation (14,000 rpm; 5 min) and washed with 5 ml of phosphate-buffered saline prior to genomic DNA extraction using a QIAamp DNA mini-extraction kit (Qiagen, Germany) according to the manufacturer's Gram-negative protocol.

Primer design and PCR gene amplification. All primer sets were designed using Omiga 2.0 (Oxford Molecular) and are listed in Table 2. For phylogroup 1 strains, the respective sets of PCR primers for amplifying the *flaA*, *recA*, and *pyrH* genes were designed based on the sequences of the corresponding genes present in the genomes of *T. vincentii* ATCC 35580 (accession no. PRJNA34095), *T. vincentii* F0403 (accession no. PRJNA169493), and *T. medium* ATCC 700293 (accession no. PRJNA169490), as well as preliminary genome sequence data for *Treponema* sp. IB OMZ 305 (Y. Chan et al., unpublished data). See Table S2 in the supplemental material for additional details. For phylogroup 2 strains, PCR primers targeting the *flaA* (TDE1712), *recA* (TDE0872), and *pyrH* (TDE2085) genes were designed based on the genome sequence of the type strain *Treponema denticola* ATCC 35405 (37). Respective "touchdown" PCRs were performed on a Veriti 96-Well Fast thermal cycler (Applied Biosystems, USA). PCRs (50 μl) contained 10 μl of 5× Go *Taq* Flexi buffer (Promega, USA), 5 μl of 7.5 mM MgCl$_2$ (Invitrogen, USA), 2 μl of deoxynucleoside triphosphates (2.5 mM each; Invitrogen), 2 μl (10 μM) of forward and reverse primers (Integrated and Technologies, USA), 1 μl of purified genomic DNA (ca. 50 ng/μl), 1 μl of GoTaq DNA polymerase (5 U/μl; Promega), and 27 μl of sterile water. The PCR thermal cycling program consisted of the following: (i) an initial denaturation (95°C, 2 min); (ii) six cycles of denaturation (95°C, 30 s), annealing (temperatures as indicated in the T_m column in Table 2, 30 s) decreasing by ca. 0.5 to 1°C every cycle, and extension (72°C, 90 s); (iii) 27 cycles of denaturation (95°C, 30 s), annealing (lowest temperature of the range indicated in Table 2, 30 s), and extension (72°C, 90 s); and (iv) a final extension (72°C, 8 min). The PCR products were examined by using 1% agarose gel electrophoresis in Tris-borate-EDTA buffer and stained with ethidium bromide.

Clone library construction. PCR products were gel purified using a QIAquick gel extraction kit (Qiagen) according to the manufacturer's instructions. The purified PCR products were cloned into pCR2.1-TOPO vectors by using a TA cloning kit (Invitrogen). Ligation mixtures were transformed into *Escherichia coli* DH10B competent cells and plated on Luria-Bertani (LB) agar plates supplemented with kanamycin (50 μg/ml) and X-Gal (5-bromo-4-chloro-indolyl-β-D-galactopyranoside; 20 μg/ml). Plates were incubated overnight at 37°C for blue-white screening. Five to six white colonies from each plate were picked and inoculated in LB medium. Plasmid DNA was extracted using the QIAprep spin miniprep kit (Qiagen) and commercially sequenced in both directions using the M13 universal forward and reverse primers.

Phylogenetic analysis. Sequence data were edited and assembled using OMIGA 2.0 (78) and MEGA 7.0.14 (79). Multiple sequence alignments were performed using MUSCLE (80) and manually edited using BioEdit v.7.1.3 (81). The ranges of intraspecific and interspecific sequence similarities for each gene (*flaA*, *recA*, *pyrH*, and 16S rRNA) among *T. putidum*, *T. denticola*, and *Treponema* phylogroup 1 strains were calculated using the sequence identity matrix implemented in BioEdit and plotted in R using the default boxplot code. The G+C content and the numbers and locations of polymorphic sites were determined using DnaSP5 (82). The aligned sequences of the three genes were concatenated (*flaA-recA-pyrH*) using SeaView (83).

A maximum-likelihood (ML) approach was utilized to analyze the individual (single-gene) and the concatenated (two- or three-gene) sequence data sets. The best-fit substitution model and gamma rate heterogeneity for the individual gene and concatenated gene data sets were determined using Akaike's information criterion implemented in jModelTest (57). ML trees for single gene and multiple genes concatenation were generated using the Genetic Algorithm for Rapid Likelihood Inference (GARLI) (84) and Phylogenetic Analysis Using Parsimony (PAUP) (85), with branch support calculated from 1,000 bootstrap replicates, and Bayesian posterior probabilities were calculated using MrBayes v3.4 (86) on a maximum clade credibility tree topology selected by SumTrees using DendroPy 4.1.0 (87).

Detection of recombination and natural selection. A codon-based approach implemented in DataMonkey (88) was used to analyze selection pressures. Genetic Algorithm Recombination Detection (GARD) was used to identify putative recombination breakpoints within genes. Single-likelihood ancestor counting was used to calculate the average global nonsynonymous (d_N) and synonymous (d_S) nucleotide substitution rate ratios ($\omega = d_N/d_S$), as well as to test the selection of variable codon sites based on the most appropriate nucleotide substitution model and tree topology, with a critical P value of 0.05.

SUPPLEMENTAL MATERIAL

Supplemental material for this article may be found at https://doi.org/10.1128/AEM.02499-16.

TEXT S1, PDF file, 2 MB.

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REFERENCES

1. Dewhirst FE, Chen T, Izard J, Paster BJ, Tanner AC, Yu WH, Lakshmanan A, Wade WG. 2010. The human oral microbiome. J Bacteriol 192:5002–5017. https://doi.org/10.1128/JB.00542-10.
2. Johnson RC. 1977. The spirochetes. Annu Rev Microbiol 31:89–106. https://doi.org/10.1146/annurev.mi.31.100177.000513.
3. Charon NW, Goldstein SF. 2002. Genetics of motility and chemotaxis of a fascinating group of bacteria: the spirochetes. Annu Rev Genet 36:47–73. https://doi.org/10.1146/annurev.genet.36.041602.134359.
4. Fenno JC, McBride BC. 1998. Virulence factors of oral treponemes. Anaerobe 4:1–17. https://doi.org/10.1006/anae.1997.0131.
5. Rosebury T. 1962. The indigenous spirochetes, p 186–221. *In* Rosebury T (ed), Microorganisms indigenous to man. McGraw-Hill, New York, NY.
6. Listgarten MA. 1976. Structure of the microbial flora associated with periodontal health and disease in man: a light and electron microscopic study. J Periodontol 47:1–18. https://doi.org/10.1902/jop.1976.47.1.1.
7. Loesche WJ. 1988. The role of spirochetes in periodontal disease. Adv Dent Res 2:275–283.
8. Socransky SS, Haffajee AD, Cugini MA, Smith C, Kent RL, Jr. 1998. Microbial complexes in subgingival plaque. J Clin Periodontol 25:134–144. https://doi.org/10.1111/j.1600-051X.1998.tb02419.x.
9. Chan EC, McLaughlin R. 2000. Taxonomy and virulence of oral spirochetes. Oral Microbiol Immunol 15:1–9. https://doi.org/10.1034/j.1399-302x.2000.150101.x.
10. Sela MN. 2001. Role of *Treponema denticola* in periodontal diseases. Crit Rev Oral Biol Med 12:399–413. https://doi.org/10.1177/10454411010120050301.
11. Ellen RP, Galimanas VB. 2005. Spirochetes at the forefront of periodontal infections. Periodontol 2000 38:13–32. https://doi.org/10.1111/j.1600-0757.2005.00108.x.
12. Perez-Chaparro PJ, Goncalves C, Figueiredo LC, Faveri M, Lobao E, Tamashiro N, Duarte P, Feres M. 2014. Newly identified pathogens associated with periodontitis: a systematic review. J Dent Res 93:846–858. https://doi.org/10.1177/0022034514542468.
13. Sakamoto M, Siqueira JF, Jr, Rocas IN, Benno Y. 2009. Diversity of spirochetes in endodontic infections. J Clin Microbiol 47:1352–1357. https://doi.org/10.1128/JCM.02016-08.
14. Maruyama N, Maruyama F, Takeuchi Y, Aikawa C, Izumi Y, Nakagawa I. 2014. Intraindividual variation in core microbiota in peri-implantitis and periodontitis. Sci Rep 4:6602. https://doi.org/10.1038/srep06602.
15. Leite FR, Nascimento GG, Demarco FF, Gomes BP, Pucci CR, Martinho FC. 2015. Prevalence of *Treponema* species detected in endodontic infections: systematic review and meta-regression analysis. J Endod 41:579–587. https://doi.org/10.1016/j.joen.2015.01.020.
16. Belibasakis GN, Mir-Mari J, Sahrmann P, Sanz-Martin I, Schmidlin PR, Jung RE. 2016. Clinical association of *Spirochaetes* and *Synergistetes* with peri-implantitis. Clin Oral Implants Res 27:656–661. https://doi.org/10.1111/clr.12690.
17. Zhuang LF, Watt RM, Mattheos N, Si MS, Lai HC, Lang NP. 2016. Periodontal and peri-implant microbiota in patients with healthy and inflamed periodontal and peri-implant tissues. Clin Oral Implants Res 27:13–21. https://doi.org/10.1111/clr.12508.
18. Chan EC, Siboo R, Keng T, Psarra N, Hurley R, Cheng SL, Iugovaz I. 1993. *Treponema denticola* (ex Brumpt 1925) sp. nov., nom. rev., and identification of new spirochete isolates from periodontal pockets. Int J Syst Bacteriol 43:196–203. https://doi.org/10.1099/00207713-43-2-196.
19. Smibert RM, Burmeister JA. 1983. *Treponema pectinovorum* sp. nov. isolated from humans with periodontitis. Int J Syst Bacteriol 33:852–856.
20. Smibert RM, Johnson JL, Ranney RR. 1984. *Treponema socranskii* sp. nov., *Treponema socranskii* subsp. *socranskii* subsp. nov., *Treponema socranskii* subsp. *buccale* subsp. nov, and *Treponema socranskii* subsp. *paredis* subsp. nov. isolated from the human periodontia. Int J Syst Bacteriol 34:457–462.
21. Wyss C, Choi BK, Schupbach P, Guggenheim B, Gobel UB. 1996. *Treponema maltophilum* sp. nov., a small oral spirochete isolated from human periodontal lesions. Int J Syst Bacteriol 46:745–752. https://doi.org/10.1099/00207713-46-3-745.
22. Umemoto T, Nakazawa F, Hoshino E, Okada K, Fukunaga M, Namikawa I. 1997. *Treponema medium* sp. nov., isolated from human subgingival dental plaque. Int J Syst Bacteriol 47:67–72. https://doi.org/10.1099/00207713-47-1-67.
23. Nakazawa F, Hoshino E, Fukunaga M, Jinno T, Asai Y, Yamamoto H, Ogawa T. 2003. Amended biochemical characteristics and phylogenetic position of *Treponema medium*. Oral Microbiol Immunol 18:127–130. https://doi.org/10.1034/j.1399-302X.2003.00015.x.
24. Wyss C, Choi BK, Schupbach P, Guggenheim B, Gobel UB. 1997. *Treponema amylovorum* sp. nov., a saccharolytic spirochete of medium size isolated from an advanced human periodontal lesion. Int J Syst Bacteriol 47:842–845. https://doi.org/10.1099/00207713-47-3-842.
25. Wyss C, Choi BK, Schupbach P, Moter A, Guggenheim B, Gobel UB. 1999. *Treponema lecithinolyticum* sp. nov., a small saccharolytic spirochaete

with phospholipase A and C activities associated with periodontal diseases. Int J Syst Bacteriol 49(Pt 4):1329–1339. https://doi.org/10.1099/00207713-49-4-1329.

26. Wyss C, Dewhirst FE, Gmur R, Thurnheer T, Xue Y, Schupbach P, Guggenheim B, Paster BJ. 2001. *Treponema parvum* sp. nov., a small, glucuronic, or galacturonic acid-dependent oral spirochaete from lesions of human periodontitis and acute necrotizing ulcerative gingivitis. Int J Syst Evol Microbiol 51:955–962. https://doi.org/10.1099/00207713-51-3-955.

27. Wyss C, Moter A, Choi BK, Dewhirst FE, Xue Y, Schupbach P, Gobel UB, Paster BJ, Guggenheim B. 2004. *Treponema putidum* sp. nov., a medium-sized proteolytic spirochaete isolated from lesions of human periodontitis and acute necrotizing ulcerative gingivitis. Int J Syst Evol Microbiol 54:1117–1122. https://doi.org/10.1099/ijs.0.02806-0.

28. Klein HS. 1946. What role do *Treponema vincentii* play in certain diseases of the gingiva? Acta Odontol Scand 7:92–96. https://doi.org/10.3109/00016354609040426.

29. Hampp EG, Scott DB, Wyckoff RW. 1948. Morphologic characteristics of certain cultured strains of oral spirochetes and treponema pallidum as revealed by the electron microscope. J Bacteriol 56:755–769.

30. Smibert RM. 1984. Genus III. *Treponema* Schaudinn 1905, 1728 AL, p 49–57. *In* Krieg NR, Holt JG (ed), Bergey's manual of systematic bacteriology, vol 1. Williams & Wilkins, Baltimore, MD.

31. Olsen I, Paster BJ, Dewhirst FE. 2000. Taxonomy of spirochetes. Anaerobe 6:39–57. https://doi.org/10.1006/anae.1999.0319.

32. Dewhirst FE, Tamer MA, Ericson RE, Lau CN, Levanos VA, Boches SK, Galvin JL, Paster BJ. 2000. The diversity of periodontal spirochetes by 16S rRNA analysis. Oral Microbiol Immunol 15:196–202. https://doi.org/10.1034/j.1399-302x.2000.150308.x.

33. You M, Mo S, Leung WK, Watt RM. 2013. Comparative analysis of oral treponemes associated with periodontal health and disease. BMC Infect Dis 13:174. https://doi.org/10.1186/1471-2334-13-174.

34. Ishihara K. 2010. Virulence factors of *Treponema denticola*. Periodontol 2000 54:117–135. https://doi.org/10.1111/j.1600-0757.2009.00345.x.

35. Dashper SG, Seers CA, Tan KH, Reynolds EC. 2011. Virulence factors of the oral spirochete *Treponema denticola*. J Dent Res 90:691–703. https://doi.org/10.1177/0022034510385242.

36. Rocas IN, Siqueira JF, Jr. 2005. Occurrence of two newly named oral treponemes—*Treponema parvum* and *Treponema putidum*—in primary endodontic infections. Oral Microbiol Immunol 20:372–375. https://doi.org/10.1111/j.1399-302X.2005.00238.x.

37. Seshadri R, Myers GS, Tettelin H, Eisen JA, Heidelberg JF, Dodson RJ, Davidsen TM, DeBoy RT, Fouts DE, Haft DH, Selengut J, Ren Q, Brinkac LM, Madupu R, Kolonay J, Durkin SA, Daugherty SC, Shetty J, Shvartsbeyn A, Gebregeorgis E, Geer K, Tsegaye G, Malek J, Ayodeji B, Shatsman S, McLeod MP, Smajs D, Howell JK, Pal S, Amin A, Vashisth P, McNeill TZ, Xiang Q, Sodergren E, Baca E, Weinstock GM, Norris SJ, Fraser CM, Paulsen IT. 2004. Comparison of the genome of the oral pathogen *Treponema denticola* with other spirochete genomes. Proc Natl Acad Sci U S A 101:5646–5651. https://doi.org/10.1073/pnas.0307639101.

38. Evans NJ, Brown JM, Demirkan I, Murray RD, Vink WD, Blowey RW, Hart CA, Carter S. 2008. Three unique groups of spirochetes isolated from digital dermatitis lesions in UK cattle. Vet Microbiol 130:141–150. https://doi.org/10.1016/j.vetmic.2007.12.019.

39. Klitgaard K, Boye M, Capion N, Jensen TK. 2008. Evidence of multiple *Treponema* phylotypes involved in bovine digital dermatitis as shown by 16S rRNA gene analysis and fluorescence *in situ* hybridization. J Clin Microbiol 46:3012–3020. https://doi.org/10.1128/JCM.00670-08.

40. Paster BJ, Boches SK, Galvin JL, Ericson RE, Lau CN, Levanos VA, Sahasrabudhe A, Dewhirst FE. 2001. Bacterial diversity in human subgingival plaque. J Bacteriol 183:3770–3783. https://doi.org/10.1128/JB.183.12.3770-3783.2001.

41. Griffen AL, Beall CJ, Campbell JH, Firestone ND, Kumar PS, Yang ZK, Podar M, Leys EJ. 2012. Distinct and complex bacterial profiles in human periodontitis and health revealed by 16S pyrosequencing. ISME J 6:1176–1185. https://doi.org/10.1038/ismej.2011.191.

42. Mason MR, Nagaraja HN, Camerlengo T, Joshi V, Kumar PS. 2013. Deep sequencing identifies ethnicity-specific bacterial signatures in the oral microbiome. PLoS One 8:e77287. https://doi.org/10.1371/journal.pone.0077287.

43. Lacap-Bugler DC, Jiang J, Huo YB, Chan Y, Leung FC, Watt RM. 2014. Complete genome sequence of the oral spirochete bacterium *Treponema putidum* strain OMZ 758T (ATCC 700334T). Genome Announc 2:e01076-14. https://doi.org/10.1128/genomeA.01076-14.

44. Chan Y, Ma AP, Lacap-Bugler DC, Huo YB, Keung Leung W, Leung FC, Watt RM. 2014. Complete genome sequence for *Treponema* sp. OMZ 838 (ATCC 700772, DSM 16789), isolated from a necrotizing ulcerative gingivitis lesion. Genome Announc 2:e01333-14. https://doi.org/10.1128/genomeA.01333-14.

45. Group NHW, Peterson J, Garges S, Giovanni M, McInnes P, Wang L, Schloss JA, Bonazzi V, McEwen JE, Wetterstrand KA, Deal C, Baker CC, Di Francesco V, Howcroft TK, Karp RW, Lunsford RD, Wellington CR, Belachew T, Wright M, Giblin C, David H, Mills M, Salomon R, Mullins C, Akolkar B, Begg L, Davis C, Grandison L, Humble M, Khalsa J, Little AR, Peavy H, Pontzer C, Portnoy M, Sayre MH, Starke-Reed P, Zakhari S, Read J, Watson B, Guyer M. 2009. The NIH human microbiome project. Genome Res 19:2317–2323. https://doi.org/10.1101/gr.096651.109.

46. Gomez-Diaz E, Boulinier T, Sertour N, Cornet M, Ferquel E, McCoy KD. 2011. Genetic structure of marine *Borrelia garinii* and population admixture with the terrestrial cycle of Lyme borreliosis. Environ Microbiol 13:2453–2467. https://doi.org/10.1111/j.1462-2920.2011.02515.x.

47. Margos G, Gatewood AG, Aanensen DM, Hanincova K, Terekhova D, Vollmer SA, Cornet M, Piesman J, Donaghy M, Bormane A, Hurn MA, Feil EJ, Fish D, Casjens S, Wormser GP, Schwartz I, Kurtenbach K. 2008. MLST of housekeeping genes captures geographic population structure and suggests a European origin of *Borrelia burgdorferi*. Proc Natl Acad Sci U S A 105:8730–8735. https://doi.org/10.1073/pnas.0800323105.

48. Rasback T, Johansson KE, Jansson DS, Fellstrom C, Alikhani MY, La T, Dunn DS, Hampson DJ. 2007. Development of a multilocus sequence typing scheme for intestinal spirochaetes within the genus *Brachyspira*. Microbiology 153:4074–4087. https://doi.org/10.1099/mic.0.2007/008540-0.

49. Ahmed A, Thaipadungpanit J, Boonsilp S, Wuthiekanun V, Nalam K, Spratt BG, Aanensen DM, Smythe LD, Ahmed N, Feil EJ, Hartskeerl RA, Peacock SJ. 2011. Comparison of two multilocus sequence based genotyping schemes for *Leptospira* species. PLoS Negl Trop Dis 5:e1374. https://doi.org/10.1371/journal.pntd.0001374.

50. Clegg SR, Carter SD, Birtles RJ, Brown JM, Hart CA, Evans NJ. 2016. Multilocus sequence typing of pathogenic treponemes isolated from cloven hoofed animals and their comparison to human isolates. Appl Environ Microbiol 82:4523–4536. https://doi.org/10.1128/AEM.00025-16.

51. Karlsson F, Svartstrom O, Belak K, Fellstrom C, Pringle M. 2013. Occurrence of *Treponema* spp. in porcine skin ulcers and gingiva. Vet Microbiol 165:402–409. https://doi.org/10.1016/j.vetmic.2013.03.031.

52. Stamm LV, Bergen HL, Walker RL. 2002. Molecular typing of papillomatous digital dermatitis-associated *Treponema* isolates based on analysis of 16S-23S ribosomal DNA intergenic spacer regions. J Clin Microbiol 40:3463–3469. https://doi.org/10.1128/JCM.40.9.3463-3469.2002.

53. Cox MM. 2007. Motoring along with the bacterial *RecA* protein. Nat Rev Mol Cell Biol 8:127–138. https://doi.org/10.1038/nrm2099.

54. Serina L, Blondin C, Krin E, Sismeiro O, Danchin A, Sakamoto H, Gilles AM, Barzu O. 1995. *Escherichia coli* UMP-kinase, a member of the aspartokinase family, is a hexamer regulated by guanine nucleotides and UTP. Biochemistry 34:5066–5074. https://doi.org/10.1021/bi00015a018.

55. Limberger RJ. 2004. The periplasmic flagellum of spirochetes. J Mol Microbiol Biotechnol 7:30–40. https://doi.org/10.1159/000077867.

56. Mo S, You M, Su YC, Lacap-Bugler DC, Huo YB, Smith GJ, Leung WK, Watt RM. 2013. Multilocus sequence analysis of *Treponema denticola* strains of diverse origin. BMC Microbiol 13:24. https://doi.org/10.1186/1471-2180-13-24.

57. Posada D. 2008. jModelTest: phylogenetic model averaging. Mol Biol Evol 25:1253–1256. https://doi.org/10.1093/molbev/msn083.

58. Chen T, Yu WH, Izard J, Baranova OV, Lakshmanan A, Dewhirst FE. 2010. The Human Oral Microbiome Database: a web accessible resource for investigating oral microbe taxonomic and genomic information. Database (Oxford) 2010:baq013. https://doi.org/10.1093/database/baq013.

59. Gmur R, Wyss C, Xue Y, Thurnheer T, Guggenheim B. 2004. Gingival crevice microbiota from Chinese patients with gingivitis or necrotizing ulcerative gingivitis. Eur J Oral Sci 112:33–41. https://doi.org/10.1111/j.0909-8836.2004.00103.x.

60. Fenno JC. 2012. *Treponema denticola* interactions with host proteins. J Oral Microbiol 2012:4. https://doi.org/10.3402/jom.v4i0.9929.

61. Choi BK, Paster BJ, Dewhirst FE, Gobel UB. 1994. Diversity of cultivable and uncultivable oral spirochetes from a patient with severe destructive periodontitis. Infect Immun 62:1889–1895.

62. Correia FF, Plummer AR, Ellen RP, Wyss C, Boches SK, Galvin JL, Paster BJ, Dewhirst FE. 2003. Two paralogous families of a two-gene subtilisin operon are widely distributed in oral treponemes. J Bacteriol 185:6860–6869. https://doi.org/10.1128/JB.185.23.6860-6869.2003.

63. Reijntjens FM, Mikx FH, Wolters-Lutgerhorst JM, Maltha JC. 1986. Adherence of oral treponemes and their effect on morphological damage and detachment of epithelial cells in vitro. Infect Immun 51:642–647.

64. Choi BK, Wyss C, Gobel UB. 1996. Phylogenetic analysis of pathogen-related oral spirochetes. J Clin Microbiol 34:1922–1925.

65. Heuner K, Meltzer U, Choi BK, Gobel UB. 2001. Outer sheath associated proteins of the oral spirochete Treponema maltophilum. FEMS Microbiol Lett 197:187–193. https://doi.org/10.1016/S0378-1097(01)00104-5.

66. Heuner K, Bergmann I, Heckenbach K, Gobel UB. 2001. Proteolytic activity among various oral Treponema species and cloning of a prtP-like gene of Treponema socranskii subsp. socranskii. FEMS Microbiol Lett 201:169–176. https://doi.org/10.1016/S0378-1097(01)00264-6.

67. Wyss C. 1998. Flagellins, but not endoflagellar sheath proteins, of Treponema pallidum and of pathogen-related oral spirochetes are glycosylated. Infect Immun 66:5751–5754.

68. Riviere GR, Smith KS, Willis SG, Riviere KH. 1999. Phenotypic and genotypic heterogeneity among cultivable pathogen-related oral spirochetes and Treponema vincentii. J Clin Microbiol 37:3676–3680.

69. Thompson FL, Gevers D, Thompson CC, Dawyndt P, Naser S, Hoste B, Munn CB, Swings J. 2005. Phylogeny and molecular identification of vibrios on the basis of multilocus sequence analysis. Appl Environ Microbiol 71:5107–5115. https://doi.org/10.1128/AEM.71.9.5107-5115.2005.

70. Yu J, Sun Z, Liu W, Xi X, Song Y, Xu H, Lv Q, Bao Q, Menghe B, Sun T. 2015. Multilocus sequence typing of Streptococcus thermophilus from naturally fermented dairy foods in China and Mongolia. BMC Microbiol 15:236. https://doi.org/10.1186/s12866-015-0551-0.

71. Gomila M, Prince-Manzano C, Svensson-Stadler L, Busquets A, Erhard M, Martinez DL, Lalucat J, Moore ER. 2014. Genotypic and phenotypic applications for the differentiation and species-level identification of Achromobacter for clinical diagnoses. PLoS One 9:e114356. https://doi.org/10.1371/journal.pone.0114356.

72. Thompson CC, Thompson FL, Vicente AC. 2008. Identification of Vibrio cholerae and Vibrio mimicus by multilocus sequence analysis (MLSA). Int J Syst Evol Microbiol 58:617–621. https://doi.org/10.1099/ijs.0.65461-0.

73. Korczak BM, Zurfluh M, Emler S, Kuhn-Oertli J, Kuhnert P. 2009. Multiplex strategy for multilocus sequence typing, fla typing, and genetic determination of antimicrobial resistance of Campylobacter jejuni and Campylobacter coli isolates collected in Switzerland. J Clin Microbiol 47:1996–2007. https://doi.org/10.1128/JCM.00237-09.

74. Lemee L, Bourgeois I, Ruffin E, Collignon A, Lemeland JF, Pons JL. 2005. Multilocus sequence analysis and comparative evolution of virulence-associated genes and housekeeping genes of Clostridium difficile. Microbiology 151:3171–3180. https://doi.org/10.1099/mic.0.28155-0.

75. Cockayne A, Sanger R, Ivic A, Strugnell RA, MacDougall JH, Russell RR, Penn CW. 1989. Antigenic and structural analysis of Treponema denticola. J Gen Microbiol 135:3209–3218.

76. Ruby JD, Li H, Kuramitsu H, Norris SJ, Goldstein SF, Buttle KF, Charon NW. 1997. Relationship of Treponema denticola periplasmic flagella to irregular cell morphology. J Bacteriol 179:1628–1635. https://doi.org/10.1128/jb.179.5.1628-1635.1997.

77. Fenno JC. 2005. Laboratory maintenance of Treponema denticola. Curr Protoc Microbiol Chapter 12:Unit 12B 11.

78. Kramer JA. 2001. Omiga: a PC-based sequence analysis tool. Mol Biotechnol 19:97–106. https://doi.org/10.1385/MB:19:1:097.

79. Kumar S, Nei M, Dudley J, Tamura K. 2008. MEGA: a biologist-centric software for evolutionary analysis of DNA and protein sequences. Brief Bioinform 9:299–306. https://doi.org/10.1093/bib/bbn017.

80. Edgar RC. 2004. MUSCLE: multiple sequence alignment with high accuracy and high throughput. Nucleic Acids Res 32:1792–1797. https://doi.org/10.1093/nar/gkh340.

81. Hall TA. 1999. BioEdit: a user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT. Nucleic Acids Symp Ser 41:95–98.

82. Librado P, Rozas J. 2009. DnaSP v5: a software for comprehensive analysis of DNA polymorphism data. Bioinformatics 25:1451–1452. https://doi.org/10.1093/bioinformatics/btp187.

83. Galtier N, Gouy M, Gautier C. 1996. SEAVIEW and PHYLO_WIN: two graphic tools for sequence alignment and molecular phylogeny. Comput Appl Biosci 12:543–548.

84. Zwickl DJ. 2006. Genetic algorithm approaches for the phylogenetic analysis of large biological sequence datasets under the maximum likelihood criterion. PhD thesis. University of Texas, Austin, TX.

85. Swofford DL. 2002. PAUP* phylogenetic analysis using parsimony (* and other methods), v4. Sinauer Associates, Sunderland, MA.

86. Huelsenbeck JP, Ronquist F. 2001. MRBAYES: Bayesian inference of phylogenetic trees. Bioinformatics 17:754–755. https://doi.org/10.1093/bioinformatics/17.8.754.

87. Sukumaran J, Holder MT. 2010. DendroPy: a Python library for phylogenetic computing. Bioinformatics 26:1569–1571. https://doi.org/10.1093/bioinformatics/btq228.

88. Pond SL, Frost SD. 2005. Datamonkey: rapid detection of selective pressure on individual sites of codon alignments. Bioinformatics 21:2531–2533. https://doi.org/10.1093/bioinformatics/bti320.