Comparative Genomics of a Plant-Parasitic Nematode Endosymbiont Suggest a Role in Nutritional Symbiosis

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Abstract

Bacterial mutualists can modulate the biochemical capacity of animals. Highly coevolved nutritional mutualists do this by synthesizing nutrients missing from the host’s diet. Genomics tools have advanced the study of these partnerships. Here we examined the endosymbiont Xiphinematobacter (phylum Verrucomicrobia) from the dagger nematode Xiphinema americanum, a migratory ectoparasite of numerous crops that also vectors nepovirus. Previously, this endosymbiont was identified in the gut, ovaries, and eggs, but its role was unknown. We explored the potential role of this symbiont using fluorescence in situ hybridization, genome sequencing, and comparative functional genomics. We report the first genome of an intracellular Verrucomicrobium and the first exclusively intracellular non-Wolbachia nematode symbiont. Results revealed that Xiphinematobacter had a small 0.916-Mb genome with only 817 predicted proteins, resembling genomes of other mutualist endosymbionts. Compared with free-living relatives, conserved proteins were shorter on average, and there was large-scale loss of regulatory pathways. Despite massive gene loss, more genes were retained for biosynthesis of amino acids predicted to be essential to the host. Gene ontology enrichment tests showed enrichment for biosynthesis of arginine, histidine, and aromatic amino acids, as well as thiamine and coenzyme A, diverging from the profiles of relatives Akkermansia muciniphila (in the human colon), Methylacidiphilum infernorum, and the mutualist Wolbachia from filarial nematodes. Together, these features and the location in the gut suggest that Xiphinematobacter functions as a nutritional mutualist, supplementing essential nutrients that are depleted in the nematode diet. This pattern points to evolutionary convergence with endosymbionts found in sap-feeding insects.

Key words: comparative genomics, nutritional symbiosis, Verrucomicrobia, Wolbachia, Akkermansia, Xiphinematobacter.

Introduction

Microbial mutualists are increasingly understood to be widespread in animal species, probably because they expand the biochemical repertoire of the hosts (Douglas 2009; Gerardo and Wilson 2011; Ferrari and Vavre 2011; Hussa and Goodrich-Blair 2013). Thus, their biological importance and biochemical integration can be significant in the adaptation of organisms and a major force in the evolution of biological systems (Dethlefsen et al. 2007; Ellers et al. 2012; Wernegreen 2012; McFall-Ngai et al. 2013). For example, mitochondria and plastids contributed major innovations in early eukaryotes, and highly coevolved obligate symbioses shift the flow of carbon, nitrogen, and organics, by providing photosynthesis to nonphotosynthetic organisms (e.g., in lichens and corals) or by assimilating elements (e.g., nitrogen-fixing bacteria in legumes) or breaking down organic compounds (e.g., cellulose digesting microbes in herbivore guts). Bacteria-animal endosymbioses have arisen at least a dozen times from at least five bacterial phyla, often serving in biosynthesis of nutrients missing in the host diet (Toft and Andersson 2010; Moran and Bennett 2014). These endosymbioses are common in the sap- and blood-feeding insects, but may occur more broadly among invertebrates that are pests of plants or parasites with specialized diets (Gottlieb et al. 2008, 2012; Douglas 2009; Bright and Bulgheresi 2010). So far, it has been challenging to identify and characterize these associations due to difficulty culturing and manipulating the microbes; however,
Nematodes have diverse ecological roles and recently have been shown to harbor varying communities of microbial symbionts (De Ley 2006; Murfin et al. 2012; Baquiran et al. 2013; Cheng et al. 2013). Plant-parasitic nematodes cause about $100$ billion in global annual agricultural damage, and also contribute to terrestrial carbon flow through the rhizosphere (Neher 2001, 2010; Piškiewicz et al. 2007; Jones et al. 2013). Plant-parasitic nematodes have evolved from free-living nematodes at least three times (Van Megen et al. 2009; Haegeman et al. 2011). During these transitions from an ancestral diet generally feeding on bacteria to a plant-based diet, some nematodes met the challenge of the new food source through horizontal gene transfers, for example, cellulases in the Tylenchida (Danchin et al. 2010; Haegeman et al. 2011; Paganini et al. 2012). In the Tylenchida, as well as in other invertebrates, these horizontally transferred genes are thought to have arisen from past symbioses that have since been lost (Hotopp et al. 2007; Husnik et al. 2013; Koutsouvolos et al. 2014). In nematodes, mutualistic endosymbiotic associations with Wolbachia appear to have played a role in the transition to a new diet for filarial nematodes in mammal hosts, for example, Brugia malayi, the cause of lymphatic filariasis, and possibly historically for strongyloidian parasites in cattle, for example, Dictyocaulus viviparus (McNulty et al. 2010; Comandatore et al. 2013; Koutsouvolos et al. 2014; Zug and Hammerstein 2014).

Here we examine an endosymbiont of the dagger nematode, Xiphinema americanum species complex (hereafter, X. americanum), so named for its long protruding spear-like mouthpart, or odontostyle used to penetrate host-plant roots. Xiphinema americanum is a large species-complex comprising about 36 named species forming several major clades (Lamberti and Ciancio 1993; Zasada et al. 2014). These species are migratory ectoparasites of plant roots and serious pests of hundreds of plants, including corn, soybeans, fruits, grapevines, tomato, tobacco, and coffee (http://www.ipm.ucdavis.edu/NEMABASE/, last accessed January 1, 2014). Much of their damage is caused by transmission of nepoviruses (single-stranded RNA plant-viruses) (Taylor and Brown 1997). Xiphinema americanum harbor intracellular bacterial endosymbionts with an unknown role: Candidatus Xiphinematobacter americanum, Candidatus Xiphinematobacter rivesi, and Candidatus Xiphinematobacter brevicolli (Vandekerckhove et al. 2000); hereafter referred to collectively as Xiphinematobacter. Previous authors have suggested that Xiphinematobacter may cause parthenogenesis (Coomans and Claey s 1998; Coomans and Willems 1998; Luc et al. 1998), based on exclusive association with species in the X. americanum species-complex which almost always use thelytokous parthenogenesis rather than sexual reproduction, but they also occur in the gut where they could play a nutritional role (Coomans et al. 2000; Vandekerckhove et al. 2000, 2002).

Our comparative genomics study centers around Xiphinematobacter, which belongs to the Verrucomicrobia, a recently described bacterial phylum whose closest relatives are the Planctomycetes and Chlamydiae (Schlesner et al. 2006). These species have wide-ranging morphologies and metabolisms (Sangwan et al. 2004; Schlesner et al. 2006; Hou et al. 2008; Van Passel et al. 2011; Wertz et al. 2012; Herlemann et al. 2013). This group was reported to be abundant, making up 11–23% of soil bacteria (Bergmann et al. 2011). Members with host associations are quite diverse. Although Xiphinematobacter is obligately intracellular (Coomans and Claey s 1998; Coomans and Willems 1998; Coomans et al. 2000; Vandekerckhove et al. 2000), other Verrucomicrobia range from free-living, to extracellular in the host lumen (e.g., Akkermansia muciniphila—a mucin-degrader in the human colon inversely associated with obesity; Derrien et al. 2004; Van Passel and et al. 2011), to intranuclear (e.g., Candidatus Nucleococcus trichonymphae—in the nuclei of protists in termite guts; Sato et al. 2013). This diversity of host-associations and the availability of several complete genomes from Verrucomicrobia allowed us to compare genetic patterns among free-living and host-associated relatives to explore the potential role of the endosymbiont Xiphinematobacter in X. americanum.

Our study presents fluorescence in situ hybridization (FISH) microscopy analysis coupled with the complete genome of the endosymbiont Xiphinematobacter from the nematode X. americanum, along with a comparative functional genomics analysis to illuminate the symbiont’s role. Our findings are novel in that this is the first report of the complete genome sequence from a non-Wolbachia exclusively intracellular endosymbiont in a nematode and the first genome from an intracellular Verrucomicrobi um. Together, our results support a nutritional mutualist role for this endosymbiont much like that found in distantly related endosymbionts from sap-feeding insects. Such findings could have enormous implications for understanding the role of this symbiont in host-plant specificity of these nematodes (Hansen and Moran 2014).

Materials and Methods

Nematode Collection

Nematodes identified morphologically as X. americanum originally collected from grape (Vitis vinifera) in Idaho, USA were cultured in the greenhouse on sorghum-sudangrass (Sorghum sudanense) at the USDA-ARS in Corvallis, OR. Nematodes were extracted from culture soil using a combination of decant-sieving and sugar centrifugation (Ingham 1994). Approximately 1,000 individuals comprising mostly adult females and juveniles were collected from the extracted soil samples for genomic library preparations and another 30
individuals of mixed stages, and also individual eggs containing embryos of various stages, were collected for FISH microscopic study. Because these long-lived nematodes cannot be easily grown as single-maternal lineages, our pooling strategy of combining many nematodes for sequencing can include multiple genotypes or strains.

FISH and Confocal Microscopy

FISH was performed largely following the high-stringency protocol of Vandekerckhove et al. (2002). Mixed stages, including juveniles, females, and eggs were surface sterilized in 100 μl 0.1% wt/vol benzalkonium chloride for 1 min, then washed twice with 100 μl of 0.85% wt/vol NaCl for 2 min and permeabilized by fixation in 100 μl of 1:1 vol/vol glacial acetic acid and 100% ethanol for 10 min, washing twice in 100 μl of 100% ethanol for 5 min. Samples were then treated with a 10-min soak in 100 μl of 1:1 vol/vol 100% methanol and phosphate-buffered saline solution with Tween (PBT; 150 mM NaCl, 10 mM Na₂HPO₄, 0.1% wt/vol Tween 20, with HCl to adjust to pH 7.4). Specimens were then fixed in 100 μl of 1% wt/vol formaldehyde and PBT for 30 min, followed by two washes in 100 μl of PBT for 2 min. Hybridization was performed for 3 h at 46°C using 90 μl of prewarmed hybridization buffer (20 mM Tris–HCl pH 7.4, 0.02% wt/vol sodium dodecyl sulfate [SDS], 0.9 M NaCl, 5 mM ethylenediaminetetraacetic acid [EDTA], 60% vol/vol formamide) and 10 μl of the probe at 10 μM in TE (10 mM Tris–HCl, 1 mM EDTA, pH 7.4). The FISH probe 5'-ATTG633N/TGC TGC CAC CCG TAG GTG T-3' modified to accommodate an ATTO fluorophore by adding a T to the 5'-end. After hybridization, specimens were washed twice at 48°C for 30 min in 100 μl of prewarmed hybridization wash buffer (20 mM Tris–HCl, 0.02% wt/vol SDS, 0.008 M NaCl, 5 mM EDTA). These conditions were previously shown to ensure high-specificity (Vandekerckhove et al. 2002). Finally, specimens were mounted on slides in 8 μl of VECTASHIELD with DAPI (Vector Laboratories, Burlingame, CA) and viewed on a Zeiss LSM510 META with Axiovert 200 motorized microscope with version 3.2 LSM software at the Center for Genome Research and Bioinformatics (CGRB; Oregon State University, Corvallis, OR). Negative controls for FISH were prepared as above using 1) the reverse compliment of the probe, 2) no probe during hybridization, and 3) Caenorhabditis briggsae instead of Xiphinema americanum.

DNA Library Preparation and Sequencing

DNA from 1,000 X. americanum was prepared using Qiagen DNeasy Blood & Tissue Kit (Valencia, CA) following an initial grinding step using a motorized micropestle for 2 min to disrupt the cuticles. Genomic library preparation was performed using the Illumina TruSeq DNA Sample Preparation Kit (San Diego, CA) following the manufacturer’s instructions, with initial shearing using a Diagenode Bioruptor Pico (Denville, NJ) for 50 s, to obtain peak library fragment sizes of approximately 600–700 bp. Following adapter ligation, fragmented ligated targets about 650–750 bp were gel-excised. Paired-end sequencing was performed using the Illumina MiSeq system for 301 cycles at the CGRB.

Xiphinematabacter Genome Assembly and Polymerase Chain Reaction Finishing

Raw reads were inspected for quality drop off, and then trimmed accordingly using a custom perl script. Reads were then quality filtered using FASTX-Toolkit v.0.014 (http://hannonlab.cshl.edu/fastx_toolkit/) and the genome assembly was performed using Velvet v.1.2.10 (Zerbino and Birney 2008) with parameters such as kmer size, coverage cutoff and average coverage optimized to select for the endosymbiont by looking for the largest contig sizes and greatest total contig lengths matching genomes from phylum Verrucomicrobia by BLAST+ v.2.2.29 (NCBI; National Center for Biotechnology Information) searches. This produced two large scaffolds 930,828 and 64,662 bp with an approximately 100-bp overlap, with numerous stretches of Ns, and several shorter scaffolds with lower read-depth coverage that were 99% similar to regions within the larger scaffold. GapFiller v.1.11 (Boetzer and Pirovano 2012) was used to help close gaps with “Ns.” The resulting linear scaffolds were further inspected using bwa and SAMtools (Li et al. 2009; Li and Durbin 2009) mapping all reads to the assembly and inspecting the .bam file using the tablet v.1.12.03.26 genome viewer (Mille et al. 2010) to look for regions of uneven coverage, Ns, or unpaired reads suggestive of assembly errors. Because the 16S rRNA gene was found in two separate contigs at 99% similarity, BLAST (Basic Local Alignment Search Tool) searches were performed for several other genes and this showed the same pattern, suggesting the presence of two strains of Xiphinematabacter. Thus, systematic assembly errors (duplicated regions due to a second low-coverage strain) were removed manually as follows. Mapping was performed to show distinctly different coverage depth between duplicates on either side of Ns, suggestive of artifacts resulting from two strains (supplementary fig. S1, Supplementary Material online). To assemble the high-coverage strain, the lower-coverage duplicates were removed, GapFiller was run again, then finally reads were mapped back to the contigs and the final assembly was inspected in tablet to check for coverage discrepancies, duplicates, Ns, and unpaired reads. Final genome-finishing to close the circular genome and confirm the overlap of the two scaffolds was performed using polymerase chain reaction (PCR) primers (supplementary table S1, Supplementary Material online) and sequencing was done using BigDye Terminator v. 3.1 Cycle Sequencing Kit (Applied Biosystems) using an ABI Prism 3730 Genetic
Analyzer at the CGRB. Although the focus in this study was the more abundant strain, we also assembled and analyzed the less abundant strain as follows. De novo genome assembly was performed optimizing for lower coverage in velvet. The resulting Verrucomicrobial contigs were ordered in Mauve 2.3.1 multiple sequence aligner (Darling et al. 2010) using the abundant strain as a reference to enable an analysis of gene order differences. Because of the difficulty obtaining a complete, contiguous de novo assembly for the second strain, strain divergence was analyzed by a mapping approach. Filtered reads were mapped to the finished genome of the common strain using bwa and SAMtools, then single nucleotide polymorphisms (SNPs) and indels were called using the Genome Analysis Toolkit GATK v.3.3-0 (DePristo et al. 2011) pipeline. Gene content from the strains was compared by generating a variant genotype from the .vcf using vcftools (Danecek et al. 2011) and aligning this to the reference. Distribution of SNPs with respect to coding positions was calculated using KsKs-calculator v.1.2 (Zhang et al. 2006). To determine whether both strains were present in single nematodes, single-nematode DNA preparations were performed as described in Zasada et al. (2014), followed by PCR (see supplementary table S1, Supplementary Material online) and BigDye sequencing (described above).

Gene Annotation and Functional Category Assignment

The Prokka package v1.10 (Seemann 2014) was used to perform complete genome annotation for Xiphinema tabaticter and the other bacteria listed in table 2. Briefly, Prokka employs BioPerl, Prodigal for ab initio gene prediction, HMMER3 for protein family profiles, BLAST+ for comparative annotation, RNAmmer/Barrnap for rRNAs, Aragorn for tRNAs, Infernal for ncRNAs, and SignalP for signal peptide prediction. For outgroup bacteria, gene lists resulting from these annotations were performed as described in Caspi et al. (2014), followed by PCR (see supplementary table S1, Supplementary Material online) and BigDye sequencing (described above).

Orthologous Gene Comparisons and Phylogenomic Analysis

From the 16 verrucomicrobial species listed in table 2, a set of single-copy orthologous genes were chosen based on BLAST matches and PROKKA and these were translated and aligned in Geneious v.5.4.4 (created by Biomatters). Thereafter, maximum-likelihood trees were reconstructed using RAxML-HPC2 v.8.0.24 (Stamatakis 2006) run on XSEDE (CIPRES Science Gateway V 3.1 http://www.phylo.org/sub_sections/portal/) using the PROTCATDAYHOF substitution model and empirical amino acid frequencies with likelihood evaluation under the GAMMA model and free model parameters estimated by RAxML with fast-bootstrapping (1,000 replicates).

Gene Enrichment Tests and Comparative Genomics

Gene set enrichment comparisons were performed to examine patterns that may be associated with differential gene loss or retention due to the environment, thus we chose three target verrucomicrobial species: Xiphinema tabaticter, A. muciniphila, and Methylacidiphilum infernorum. These species originated from three distinct environments, the first two species being host-associated in very different hosts (plant-parasitic nematode vs. human intestine), whereas the third is free-living in extreme thermophilic/acidophilic
environments. These species also have the smallest genomes (table 2). We used an outgroup gene set comprised a set of overlapping, nonredundant genes shared among three free-living Verrucomicrobia, which occur on different branches of the tree: Ch. flavus, O. terrae, and Pedosphaera parvula. This shared gene set from widely diverged free-living Verrucomicrobia was used in enrichment tests against each target gene set. Gene enrichment tests for Wolbachia involved a comparison of two strains: The target gene set from the obligate mutualist Wolbachia strain wOo from a filarial nematode and from the reproductive manipulator Wolbachia...
strain wPip from a mosquito. Functional enrichment tests were performed using the one-sided Fisher exact P value, testing the proportion of genes in a GO category for the target species (e.g., Xiphinematobacter) relative to the expected proportion of genes in that category, comprised the total gene set from the target species and the gene set from the shared outgroups. Fisher exact P values were generated using the GoMiner software (Zeeberg et al. 2003) with multiple testing correction. GoMiner correction for multiple testing (false discovery rate or FDR) resamples the P-value distribution based on the number of genes in a category, and is quite overconservative (high rate of type II error) for categories with small numbers of genes (Zeeberg et al. 2003; and see supplementary material online). It also overestimates GO categories (i.e., it annotates many functions even for pathways, processes, or cellular components that do not exist in the test organism); thus, FDR is also somewhat overconservative globally. For these reasons, we report both FDR-corrected and uncorrected P values.

Results

Xiphinematobacter Localization by FISH

FISH results (fig. 1A–J) showed that the FISH probe was localized specifically to bacterial cells within the nematode gut wall, ovarian sheath, eggs, and developing embryos. The DAPI stain colocalized with the probe consistently, highlighting bacterial cells of two forms corresponding to their location: Rod-shaped, larger cells, about 4–7 μm long × 1.0 μm diameter, within cells of the gut (fig. 1G–J), and smaller, densely packed rod-shaped to coccoid cells, about 1.9–2.1 μm long × 0.7–0.9 μm diameter within the ovaries (fig. 1B–D). The longer appearance of bacterial cells in the gut may be partially due to cell division with daughter cells often not fully

Table 2

Habitat and Genomic Features of Endosymbiont Xiphinematobacter Compared with Other Verrucomicrobia and Outgroup Bacteria Available in GenBank

| Species | Accessiona | Habitat | Genome Size | Proportion Coding | %GC | Proteins | tRNA Operons | tRNAs | Ortholog | Length |
|---------|------------|---------|-------------|-------------------|-----|----------|-------------|-------|-----------|--------|
| Xiphinematobacter americani | CP012665 | Endosymbiotic, in plant-parasitic nematodes | 915,884 | 0.84 | 47.7 | 817 | 1 | 45 | 25,047 |
| Akkermansia muciniphila | NC_010655.1 | Human colon, beneficial | 2,664,102 | 0.89 | 55.8 | 2,182 | 3 | 54 | 25,578 |
| Rubitalea marina | NZ_ARP000000000.1 | Marine, associated with sponge | 3,013,001 | 0.91 | 51.5 | 2,655 | 2 | 43 | 25,321 |
| Diplosphaera coliterrimut | ABEA000000000.3 | Termite gut, culturable | 5,671,497 | 0.87 | 60.9 | 5,023 | 1 | 68 | 25,433 |
| Verrucomicrobia bacterium DG | NZ_AB500000000.1 | Marine, associated with dinoflagellate | 5,769,153 | 0.90 | 54.3 | 4,684 | 1 | 45 | 25,231 |
| Methylacidiphilum infernorum | NC_010794.1 | Free-living, extreme acidophile/thermophile | 2,287,145 | 0.89 | 45.5 | 2,101 | 1 | 46 | 25,272 |
| Verrucomicrobi um sp. 3C | NZ_ARAS000000000.1 | Free-living, lakes | 2,772,066 | 0.87 | 60.9 | 2,727 | 1 | 48 | 25,304 |
| Coralimargarita akajimensis | NC_014008.1 | Free-living, near corals | 3,750,771 | 0.90 | 53.6 | 3,138 | 2 | 47 | 25,198 |
| Verrucomicrobi um bacterium SC | NZ_ARTV000000000.1 | Free-living, marine | 3,949,105 | 0.87 | 47.7 | 3,272 | 2 | 28 | 25,521 |
| Opitutus terrae | NC_010571.1 | Free-living, rice paddy soil | 5,957,605 | 0.89 | 65.6 | 4,669 | 1 | 72 | 25,410 |
| Opitutaceae bacterium | NZ_AHKS000000000.2 | Free-living, termite associated | 7,067,882 | 0.88 | 62.1 | 5,899 | 1 | 71 | 25,765 |
| Pedosphaera parvula | NZ_ABOX000000000.2 | Free-living, pasture soil | 7,414,222 | 0.89 | 52.6 | 6,411 | 2 | 60 | 25,194 |
| Chthoniobacter flavus | NZ_ABVL000000000.1 | Free-living, soil | 7,848,700 | 0.88 | 61.1 | 5,667 | 2 | 64 | 25,383 |
| Verrucomicrobi um spinosum | NZ_ABI201000001.1 | Free-living, aquatic/si l/Feces | 8,220,857 | 0.87 | 60.3 | 6,502 | 4 | 67 | 25,646 |
| Parachlamydia acanthamoebae | NC_015702.1 | Lives in acanthamoebae, human pneumonia | 3,072,383 | 0.89 | 39.0 | 2,569 | 5 | 40 | 25,359 |
| Lentisphaera araneosa | NZ_ABCK000000000.1 | Free-living, marine | 6,023,180 | 0.89 | 40.9 | 4,903 | 6 | 42 | 25,431 |
| Wolbachia sp. wPip | NC_010981.1 | Endosymbiotic, reproductive parasite of insects | 1,482,455 | 0.89 | 53.2 | 1,423 | 1 | 34 | NA |
| Wolbachia sp. wOo | NC_018267.1 | Endosymbiotic, mutualist of filarial nematodes | 957,990 | 0.70 | 32.1 | 881 | 1 | 32 | NA |

Note.—Species details: Verrucomicrobial strains are A. muciniphila ATCC BAA-835, R. marina DSM 17716, D. coliterrimut TAN2, V. bacterium DG1235 ASM15559v1, M. infernorum VA, V. bacterium SCGCA AAA16404 ASM38371v1, O. terrae PB90-1, O. bacterium TAV1 ASM24348v3, P. parvula Ellin514, Ch. flavus Ellin428, V. spinosum DSM 4136=KCC 18804. Outgroup strains are Phylum Chlamydialia P. acanthamoebae UV-7, Phylum Lentisphaerae L. araneosa HTCC2155, Wolbachia sp. wPip endosymbiont of Culex quinquefasciatus Pel, Wolbachia sp. wOo endosymbiont of Onchocerca ochengi ASM30688v1.

*RefSeq Accession or International Nucleotide Sequence Database Collaboration (WGS).*
separated by cytoplasmic constriction or by new cells remaining close together. Three-dimensional rotation using the Zeiss confocal microscope z-stack feature allowed us to confirm the absence of these cells in the lumen of the gut. In eggs containing early and late embryos (fig. 1E and F), the probe localized to small rod-shaped or coccolid cells about 4 μm long × 0.7 μm in diameter. In later embryos with more defined first-stage juvenile features, the probe localized to focal areas consistent with regions that may develop into the gut. Negative controls (probe with C. briggsae, and reverse-complemented probe, or no probe with X. americanum) produced only very weak, diffuse fluorescence localized to the cuticle and strong autofluorescence of the odontostyle and sometimes amorphous and uneven-shaped specs outside the nematodes, similar to that seen in figure 1F.

Full Genome of Endosymbiont Xiphinematobacter Sequenced at High Coverage

We generated a complete, circular genome for the endosymbiont Xiphinematobacter. The Illumina MiSeq results and assembly details are shown in table 1. Initial assemblies produced closest BLAST matches for bacterial 16S rRNA to Candidatus Xiphinematobacter rivesi (98% similarity), Candidatus Xiphinematobacter americani (96%), and Candidatus Xiphinematobacter brevicoli (94%). The finished endosymbiont genome was 915,884 bp long and sequenced at high coverage (approximately 1,290× read depth). It revealed 47.7% GC content, 817 predicted proteins (147 of these annotated as “hypothetical protein”), 45 tRNAs, and one copy of each typical rRNA gene. There were 4 predicted pseudogenes and 33 predicted signal peptides (supplementary table S2, Supplementary Material online). There was little repetitive DNA, except for two tandem repeat regions (9 repeats of 75 bp at position 60,350; 12 repeats of 15 bp at position 914,875), both causing assembly breaks that had to be closed by PCR.

The data revealed two slightly diverged strains of Xiphinematobacter at 99.4% sequence similarity, with the abundant strain at approximately 1,050× and the less abundant strain at approximately 240×. De novo assemblies of the strains did not reveal any difference in gene order (supplementary fig. S3, Supplementary Material online). Between strains there were 5,676 SNP differences and one 5-bp deletion, with no change in gene content and no predicted additional pseudogenes. Distribution of SNPs was relatively even across the genome (supplementary table S4 and fig. S2, Supplementary Material online). The rate of nonsynonymous substitutions compared with synonymous substitutions (Ka/Ks) between strains was generally less than 1 (supplementary fig. S3, Supplementary Material online), with a mean of 0.27 across all genes. Genes for essential amino acid biosynthesis pathways had a mean Ka/Ks of 0.21 (see supplementary fig. S3, Supplementary Material online). Sequencing of a variable region from 18 individual nematodes (see supplementary table S1, Supplementary Material online), including 6 SNPs that distinguish the strains, revealed 15 individuals matching the abundant strain and 3 individuals matching the less abundant strain, with no signs of secondary peaks in the sequence trances at the variant positions.

Verrucomicrobia and Outgroups Show Correlations in Genome Streamlining

Following genome annotation of the predominant Xiphinematobacter strain in the sample (deposited in NCBI GenBank under accession number CP012665S), genomes were compared and show that the endosymbiont Xiphinematobacter has the smallest genome of any Verrucomicrobia, with the fewest proteins (table 2). Among Verrucomicrobia and outgroups listed in table 2, there was a positive relationship between number of proteins and genome size, and the length of noncoding sequence and genome size (supplementary fig. S4, Supplementary Material online), with the endosymbiont Xiphinematobacter having the most reduced genome size, protein number, and noncoding length, even compared with the endosymbiotic nematode mutualist Wolbachia wOo. Results also showed slight positive relationships with genome size for number of tRNAs, average length of proteins, and lengths of 81 conserved orthologous genes (the set used in phylogenomic tree reconstruction) (supplementary fig. S4, Supplementary Material online), with Xiphinematobacter displaying the shortest orthologous gene length. In contrast, average intergenic space did not show a positive relationship with genome size (supplementary fig. S4, Supplementary Material online) and Xiphinematobacter and Wolbachia wOo had larger predicted intergenic spaces than other species. There was no obvious clustering among host-associated or free-living Verrucomicrobia for any genomic feature.

Phylogenomic Tree Supports Mixed Pattern of Host-Association

From all annotated genes for the 14 Verrucomicrobia and 2 outgroup clades shown in table 2, 81 predicted single-copy orthologs were found (see list in supplementary table S5, Supplementary Material online). Nucleotide sequence alignment was difficult except between close relatives, so phylogenetic reconstruction was performed using translated amino acid sequences that were predicted to have fewer saturated sites. The alignment is shown in supplementary table S6, Supplementary Material online. The resulting maximum-likelihood phylogeny (fig. 2) was well supported by bootstrap at all nodes. Intracellular host-associated taxa had slightly longer branches than their most closely related free-living taxa. Free-living and host-associated species occurred in a mixed pattern, suggesting independent origins of host-association. Verrucomicrobia formed several clades consistent
with previous phylogenetic studies comprising more species but fewer loci (Sangwan et al. 2004; Schlesner et al. 2006). Clades include one basal with soil/marine free-living species, one with both termite-associated and marine-host associated species (subdivision 4 of Hugenholtz et al. 1998), a third clade with the nematode endosymbiont Xiphinematobacter and the sister-species Ch. flavus (subdivision 2, or “Spartobacteria” of Sangwan et al. 2004), and a sister clade with human- and sponge-associated species (subdivision 1, or “Verrucomicrobiae” of Sangwan et al. 2004).

**Genome Content and Architecture**

Xiphinematobacter had a greater proportion of genes well-annotated categories compared with its closest relative with an available genome, Ch. flavus, which had a larger proportion of genes with no assignment (no homologs, listed “hypothetical protein” or “general function prediction only”) (see fig. 3A). The COG categories that were most increased in proportion in Xiphinematobacter compared with Ch. flavus were translation, ribosomal structure and biogenesis, amino acid transport and metabolism, and cell wall/membrane biogenesis. The COG categories least increased compared with Ch. flavus were transcription, signal transduction mechanisms, and cell motility. Gene order (synteny) was poorly conserved between Xiphinematobacter and the five other Verrucomicrobial species with finished (contiguous) genomes (supplementary fig. S5, Supplementary Material online). Further analysis of conserved synteny revealed only 27 blocks with conserved gene order (fig. 3B) between free-living outgroups Ch. flavus, O. terrae, and P. parvula. From these blocks, comprising 131 genes, 7/27 synteny blocks were absent in Xiphinematobacter and 13/27 blocks, comprising 42 genes, were completely conserved (fig. 3B). These most highly conserved synteny blocks consisted of a wide range of well-characterized genes clustered largely by function (e.g., ribosomal structural proteins grouped in block 3, replication genes gyrB, gyrA in block 5, energy production genes in block 7 atpD, atpG, atpA, etc. [supplementary table S3, Supplementary Material online]), suggestive of conserved operons.

**Pathway and Functional Enrichment (COG and GO)**

GO category enrichment, here meaning statistical over-representation of a GO term in one genome (e.g., Xiphinematobacter) compared with outgroups computed in GoMiner, differed among species (fig. 4; detailed results in supplementary table S7, Supplementary Material online). Although overall amino acid and cofactor biosynthesis was enriched for all three Verrucomicrobia in this study, specific groups of amino acid and cofactor biosynthesis pathways
enriched differently, as shown in figure 5. In particular, Xiphinematobacter alone showed enrichment for arginine biosynthesis genes, as well as aromatic amino acid biosynthesis (phenylalanine, tryptophan, and tyrosine). Akkermansia muciniphila alone showed enrichment for serine and lysine biosynthesis, and general sulfur and branched chain amino acid biosynthesis. Xiphinematobacter and A. muciniphila were also both enriched for histidine biosynthesis. Xiphinematobacter alone was enriched for coenzyme A, fatty acids, lipids, and isoprenoids/terpenoids biosynthesis, and also heme biosynthesis.

Because Xiphinematobacter is abundant in the gut of the nematode, we performed a comparison to look at potential nutrient supplementation capacity of the symbiont. This comparison looked at predicted essential amino acids and vitamins/cofactors thought to be required in the diet versus predicted nonessential amino acids thought to be readily synthesized de novo by the nematode, based on studies from related nematodes (see Chitwood 1998 and references therein). We found that Xiphinematobacter had a larger relative number of essential amino acid genes retained compared with nonessential amino acid biosynthesis genes relative to the other target species (A. muciniphila, M. infernorum, and Wolbachia wOo).
(see fig. 6), when the number of genes in each category was normalized for the genome size reduction in a species relative to the outgroups. The result in figure 6 represents 10 essential amino acid biosynthesis pathways comprising about 130 genes, 11 nonessential amino acid pathways comprising about 50 genes, and 8 vitamins/cofactors or coenzymes pathways comprising 56 genes (details in supplementary table S7, Supplementary Material online).

A simplified reconstruction of the retained pathways for biosynthesis of amino acids and vitamins/cofactors in Xiphinematobacter shows the retention of most steps in essential amino acid biosynthesis, with the exception of methionine (fig. 7). Conversely, most steps for de novo synthesis of nonessential amino acids and vitamins/cofactors are missing, with the exception of iron–sulfur cluster and lipoate (fig. 7). Very few amino acid or vitamin/cofactor transport genes were present in Xiphinematobacter. These included the branched-chain amino acid import genes \( \text{livF} \) and \( \text{livH} \) (but not \( \text{livG} \), \( \text{livM} \), \( \text{livI} \), and \( \text{livK} \)), the serine/alanine uptake gene \( \text{cycA} \), and the biotin carboxyl carrier protein \( \text{accB} \).

A few nonbiosynthetic processes were also enriched in Xiphinematobacter; for example, it alone was enriched for terms related to glycolysis/ATP synthesis-coupled proton transport. It was also uniquely enriched for small GTPase-mediated signal transduction, nucleoside/nucleotide interconversion, ribonucleoprotein complex assembly, protein folding/maturation/processing/transport, regulation of cell shape, and defense response to bacterium. Xiphinematobacter also shared with \( \text{A. muciniphilia} \) enrichment for terms related to DNA repair, response to DNA damage stimulus) and translation (ribosome biogenesis, translational initiation, tRNA processing). Xiphinematobacter shared with \( \text{M. infernorum} \) enrichment for amino acid activation, translational elongation, and tRNA aminoacylation (see full enrichment results in supplementary table S7, Supplementary Material online).

**Incomplete Pathways and Lost or Pseudogenized Genes**

The free-living outgroups shared 296 genes that were absent in Xiphinematobacter. Among these genes missing in Xiphinematobacter, the most common function is regulation (see detailed list in supplementary table S7, Supplementary Material online). For example, 30 of 51 significantly enriched GO terms in the outgroups describe regulation or negative regulation of general biological, metabolic, biosynthetic processes, gene expression and transcription, nitrogen compound metabolism, RNA metabolism, transcription, and nucleotide metabolism. Xiphinematobacter also showed significant enrichment for loss of signaling, signal transmission, signal transduction, molybdopterin cofactor biosynthesis and metabolism, prosthetic group metabolism, pteridine-containing compound metabolism and biosynthesis, peptidyl-histidine phosphorylation/modification, peptidyl-amino acid modification, RNA biosynthesis, transcription, and locomotion/chemotaxis. It also appears that almost all genes involved in mismatch repair, locomotion/chemotaxis, and glutamate and molybdopterin biosynthesis have been lost. Compared with \( \text{Ch. flavus} \), Xiphinematobacter lacks all six genes with predicted cellulase activity. There were four predicted pseudogenes in Xiphinematobacter. Among these were thiazole
synthase (involved in thiamine synthesis), spore protein SP21 (stress response), and UDP-glucose 4-epimerase (involved in galactose metabolism).

**Discussion**

We examined the endosymbiont *Xiphinematobacter* in the plant-parasitic nematode *X. americanum*, showing with FISH microscopy that these bacteria reside in the gut, ovaries, eggs, and embryo gut primordia. We present its complete, annotated genome—the first reported for an exclusively intracellular nematode endosymbiont outside the Genus *Wolbachia*.

Comparative genomic analyses show extreme genome reduction and gene set enrichment for several biological functions consistent with this endosymbiont playing a role in nutrition of the host. Most notably, we observed enrichment for animal-essential amino acid biosynthesis, which is consistent with its location in the gut and its host nematode’s likely primary diet of phloem, which is generally depleted in amino acids. We explore how this pattern is widespread among unrelated obligate mutualists in sap-feeding insects, and how this endosymbiosis differs from the mutualisms of *Wolbachia* in filarial nematodes and *A. muciniphilia* in the human colon.

**Key Features Point to Nutritional Mutualism**

Our data shed new light on the potential role of *Xiphinematobacter* in its host nematode. Our FISH results at high-stringency confirm features shown previously at lower-stringency (Vandekerckhove et al. 2002) and provide additional clarity on the location, size, and shape of *Xiphinematobacter* cells in adults and developing embryos. Based on previous transmission electron microscopic (TEM) evidence of intracellularity in the ovary and oocytes.

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**Fig. 5.**—Biosynthetic processes enriched in *Xiphinematobacter*, *A. muciniphilia*, and *M. infernorum*, compared with a gene set shared between free-living outgroup species *Ch. flavus*, *O. terrae*, and *Pedosphaera parvula*. Similar figures for metabolic/catabolic processes and other processes are in supplementary figure S6, Supplementary Material online.
Coomans and Claeys 1998; Coomans et al. 2000; Vandekerckhove et al. 2000) several authors suggested *Xiphinematobacter*'s primary role may be to cause thelytokous parthenogenesis in the nematode (Coomans and Claeys 1998; Coomans and Willems 1998; Luc et al. 1998). However, if this were the case, *Xiphinematobacter* could be classified as a reproductive manipulator like most strains of the very distantly related endosymbiont, *Wolbachia*. Our data and previous studies show that like *Wolbachia*, *Xiphinematobacter* has a well-established mechanism for vertical transmission (Vandekerckhove et al. 2002; Werren et al. 2008; Zug and Hammerstein 2014), but unlike reproductive-manipulator strains of *Wolbachia*, it is more localized to specific tissues in its host, with 100% prevalence in all individuals at all stages and at high abundance in the host (Vandekerckhove et al. 2000, 2002). For example, our FISH results confirmed that the symbiont was confined to the ovaries, eggs, and gut wall cells, where the bacteria were actively dividing and abundant. These features are more typical of specialized mutualists, including the mutualist *Wolbachia* strains in nematodes (wBm, wOo, etc.) and insects (wCle) (Foster et al. 2005; Hosokawa et al. 2010; Lefoulon et al. 2012), where the symbiont is required for host survival. Furthermore, if the primary role of *Xiphinematobacter* were to induce parthenogenesis, we must ask why many other species of *Xiphinema* such as *X. index* and *X. pachtaicum*, which also reproduce by parthenogenesis, have not been shown to host the endosymbiont *Xiphinematobacter* (Coomans and Claeys 1998; Coomans et al. 2000). Another topic of interest in our FISH data is the difference in cell shape of *Xiphinematobacter* in the gut versus the ovaries. Our single-nematode sequence results do not support two populations or genotypes, but instead suggest that the single genotype can have two distinct morphologies. It is possible that determination of symbiont shape is under host control, as is seen in other intracellular endosymbionts (Kondorosi et al. 2013), and that differences in cell shape correspond to different functions in these host tissues, but these questions would need to be investigated with further experiments.

Genomic analyses offer more insight into the role of *Xiphinematobacter* in its host nematode, *X. americanum*. Its genome size (0.916 Mb) and number of protein-coding genes (817) are in the range typical for mutualists. For example, genomes of obligate mutualist *Wolbachia* strains from filarial nematodes (including wOo) range from 0.958 to 1.1 Mb, with 647–805 predicted proteins, whereas reproductive parasite *Wolbachia* strains range from 1.3 to 1.6 Mb with 1,010–1,270 proteins (Wu et al. 2004; Foster et al. 2005; Klasson et al. 2005).
We also note that Xiphinematobacter’s genome is smaller than that from the obligate mutualist *Wolbachia* wCle in the bedbug *Cimex lectularius* (1.25 Mb, with 1,256 genes) (Nikoh et al. 2014). Furthermore, *Xiphinematobacter* falls within the range of most obligate mutualists (genome size < 1.0 Mb) rather than that of facultative symbionts (> 1.25 Mb) compared with an array of intracellular symbionts from animals (Moran and Bennett 2014). Although several bacteria with genomes less than 1 Mb are pathogens, notably *Mycoplasma/Phytoplasma* at 0.6 Mb, the smallest known genomes, ranging from 0.11 to 0.54 Mb, belong to mutualists, with the majority of species less than 1.0 Mb being endosymbiotic mutualists (NCBI GenBank; April 2015). Furthermore, this extreme genome reduction in mutualists appears to have arisen numerous times, occurring in at least 22 genera from numerous phyla. This pattern could arise from extreme population bottleneck during long-term coevolution.
with strict vertical transmission, combined with a ratchet effect decreasing the gene set to only those few functions/products or processes that cannot be supplied by the host. Our comparison of genomic features among Verrucomicrobia also fit this pattern, showing much larger genomes and more proteins in species that are host-associated but not obligate mutualists, such as \textit{A. muciniphila} (in human colon), \textit{Diplospheara coltermitum} (in termite gut), and \textit{Verrucomicrobiae bacterium DG} (dinoflagellate-associated).

Massive gene loss due to drift is universal in obligate endosymbionts, and can highlight processes that are not necessary in the host environment (e.g., motility). For example, our results suggest that \textit{Xiphinematobacter} has lost many genes for locomotion and taxis/chemotaxis—reflecting an exclusively endosymbiotic lifestyle. Gene loss can also rule-out potential symbiont roles. For example, in \textit{Xiphinematobacter} some functions appear to be completely lost, for example, molybdopterin cofactor and glutamate amino acid biosyntheses, and cellulose degradation. Gene loss can show other changes as well. For example, \textit{Xiphinematobacter} has lost many regulation functions, including negative regulation for biosynthesis of amino acids and vitamins. This is typical for mutualists whose primary role is to synthesize these essential nutrients, and evidence suggests that the host typically takes over the regulation and transport of these products (Dale and Moran 2006; Bennett and Moran 2013).

Comparative Genomics Suggest Symbiont Role Pathways

Gene set comparisons showed enrichment for several biological processes that illuminate the possible role of \textit{Xiphinematobacter}. Although direct experimental tests of the bacteria’s role are not possible at this time, due to the difficulty in growing \textit{X. americanum} under laboratory conditions, our comparative approach was similar to that used elsewhere (Touchon et al. 2009; Frese et al. 2011; Kjeldsen et al. 2012; Santos-Garcia, Latorre et al. 2014). The basis of our approach was that although theory predicts random mutations cause pseudogenization and subsequent gene loss during bottlenecks, purifying selection will result in enrichment for core housekeeping functions (Herbeck et al. 2003; Touchon et al. 2009). More importantly, within the context of core function enrichment, purifying selection should also enrich for other essential genes and pathways specific to the symbiont’s role in proportion to their influence on fitness (McCutcheon et al. 2009; Williams and Wermegreen 2012; Brown et al. 2014). Our COG comparison with \textit{Ch. flavus}, the closest relative of \textit{Xiphinematobacter} with an available genome, largely fit the first expectation, with the extremely reduced genome of \textit{Xiphinematobacter} having a much lower proportion of poorly annotated genes than \textit{Ch. flavus}—we presume that the genes having no hits to current databases do not serve universally conserved core functions. Furthermore, broad COG categories that had the most and least proportional increase in \textit{Xiphinematobacter} compared with \textit{Ch. flavus} generally represent functions that are most and least universal in bacteria, respectively (e.g., translation, ribosomal structure and biogenesis, cell wall/membrane biogenesis increased most, whereas signal transduction mechanisms, and cell motility increased least). Conversely, our COG comparison suggested that genes involved in transcription were not as well retained as genes involved in amino acid transport and metabolism. This result may reflect the relaxed need for transcription products/processes in the rich environment of the host cell, and the increased need to maintain amino acid transport and metabolism above other core functions, pointing to a possible role in the symbiont. This pattern has been seen in other mutualists (Hansen and Moran 2014; Santos-Garcia, Rollat-Farnier et al. 2014).

Although COG categories show only broad functions, our GO function tests and nutritional pathway reconstruction, provided more specific evidence that \textit{Xiphinematobacter} may function in nutritional supplementation. The basis of these tests was a comparison of distantly related species whose genomes appear to have been reduced under different conditions: Endosymbiosis (\textit{Xiphinematobacter}), extracellular host-association (\textit{A. muciniphila}), and acidophilic/thermophilic conditions (\textit{M. infernorum}). The tests partially controlled for differences in ancestral metabolism by comparing changed genes only against genes shared among distantly related free-living Verrucomicrobia. The most important result was the enrichment of biosynthesis pathway genes for the amino acid arginine and aromatic amino acids (phenylalanine, tryptophan, and tyrosine) in \textit{Xiphinematobacter} and the increased retention of amino acid biosynthesis genes considered essential in animals, including nematodes, compared with amino acid biosynthesis genes considered nonessential (i.e., that can generally be synthesized de novo). These biosynthetic pathways were not enriched in \textit{A. muciniphila} or \textit{M. infernorum}, nor in the mutualist Wolbachia strain wOo from nematodes.

Free-living bacteria usually synthesize all the common amino acids, whereas intracellular pathogens usually lose the ability to synthesize all amino acids (both essential and nonessential for their hosts) over time (Payne and Loomis 2006). This is due to the high transcriptional and translational cost of these biosynthetic pathways, and Muller’s ratchet under relaxed need for the products, which can be supplied by the host cell. In contrast, obligate mutualists that supply essential amino acids to their animal hosts (e.g., \textit{Buchnera}, \textit{Ishikawaella}, \textit{Sulcia}, \textit{Hodgkinia}, \textit{Carsonella}, \textit{Portiera}, \textit{Evansia}, \textit{Nasuia}, \textit{Zinderia}, etc.) tend to retain these pathways even under conditions of massive genome reduction (Shigenobu et al. 2000; McCutcheon and Moran 2007; Brownlie et al. 2009; Douglas 2009; MacDonald et al. 2011; Nikoh et al. 2011; Santos-Garcia et al. 2012, Santos-Garcia, Latorre et al. 2014, Santos-Garcia, Rollat-Farnier et al. 2014). It is thought that the hosts maintain these symbionts for their
ability to supply amino acids or vitamins/cofactors that the hosts cannot de novo synthesize or obtain from their specialized plant sap diets (Sandström and Pettersson 1994). Although we do not explicitly know the metabolic capacity of X. americanum, we know that related plant-parasitic nematodes are unable to de novo synthesize the ten essential amino acids and other essential cofactors described for insects and mammals (Barrett 1991; Chitwood 1998). Unlike bacteria-feeding nematodes, which would have ample supply of these nutrients, X. americanum has a specialized piercing and sucking feeding structure, the odontostyle that provides a limited liquid diet. Although there are few detailed records of feeding in the X. americanum species complex, several observations suggest the diet involves phloem (Cohn 1970; Lamberti and Ciancio 1993). For this group, feed access exclusively along roots, with the odontostyle often penetrating the stele (or vascular bundle) where the nematode remains in one spot for many hours to days “drinking” using 90 per minute contractions of the esophageal bulb (Cohn 1970), without eliciting a visible host response. This feeding method differs from that of other nematodes related to Xiphinema spp. including Longidorus spp. and more distantly related Tylenchids, many of which involve modifications of root cortex cells and a notable host response. Access to the vascular bundle (xylem and phloem sieve elements) may be related to the success of X. americanum in transmitting nepoviruses, which are abundant in phloem (Kommineni et al. 1998) and presumably move through these tissues.

Interestingly, we found several genes for amino acid or vitamin/cofactor transport/import in Xiphinema species complex, several observations suggest the diet involves phloem (Cohn 1970; Lamberti and Ciancio 1993). For this group, feed access exclusively along roots, with the odontostyle often penetrating the stele (or vascular bundle) where the nematode remains in one spot for many hours to days “drinking” using 90 per minute contractions of the esophageal bulb (Cohn 1970), without eliciting a visible host response. This feeding method differs from that of other nematodes related to Xiphinema spp. including Longidorus spp. and more distantly related Tylenchids, many of which involve modifications of root cortex cells and a notable host response. Access to the vascular bundle (xylem and phloem sieve elements) may be related to the success of X. americanum in transmitting nepoviruses, which are abundant in phloem (Kommineni et al. 1998) and presumably move through these tissues.

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purifying selection (e.g., Ka/Ks) on these remaining genes in broken pathways by comparison with other species of *Xiphinematobacter*.

The enrichment of coenzyme biosynthesis and amino acid activation in *Xiphinematobacter* are consistent with a role in diet supplementation, as many coenzymes, cofactors, and vitamins are known to be limiting in plant-based diets (Sandström and Pettersson 1994); however, the free-living methanotrophic, thermophilic, acidophile (Hou et al. 2008) *M. infernorum* is also enriched for these. Thus, despite many differences in enrichment profiles for *Xiphinematobacter* and *M. infernorum*, these similarities may be of interest. For example, it has been suggested that *M. infernorum* may have numerous past horizontal gene transfers from the proteobacteria facilitating its lifestyle (Hou et al. 2008), but another possibility is that it descended from ancestors that were symbionts. Indeed, loss of vitamin biosynthesis appears to be widespread (Helliwell et al. 2013).

**Evidence for Functional Convergence with Endosymbionts of Sap-Feeding Insects**

Our comparative genomic results suggest that *Akkermansia, Methylacidiiphilum, Wolbachia* and *Xiphinematobacter* have different functional profiles, with functional enrichment in *Xiphinematobacter* resembling that found in endosymbionts from sap-feeding insects (Bennett and Moran 2013; Hansen and Moran 2014). The differences between *Xiphinematobacter* and *A. muciniphila* suggest several potential functions for *A. muciniphila* that could be explored, particularly, biosynthesis of amino acids serine and lysine and biosynthesis of cobalamin (vitamin B12). It was not surprising to find *M. infernorum* alone was enriched for terms related to inorganic ion transport and energy production, given its free-living status and habitat in geothermal fields. For several reasons, it is also not surprising that the profile of *Xiphinematobacter* differed from that of *Wolbachia* in filarial nematodes. Obviously their food sources are quite different. Additionally, *Wolbachia* has descended from alphaproteobacteria and appears to have had a very long ancestry as a strictly intracellular symbiont (Weinert et al. 2009; Rodríguez-Ezepeleta and Embley 2012; Nikoh et al. 2014), whereas *Xiphinematobacter* derives from Verrucomicrobial lineages that appear to be more recently adapted from free-living ancestors (Vandekerckhove et al. 2000). In future, more detailed comparisons of gene set enrichment among strains of *Wolbachia* could shed light on the evolution of functional roles in this group, but given the very large evolutionary distance and host differences between *Xiphinematobacter* and *Wolbachia*, we predict limited overlap. Of perhaps greater interest is a future analysis of *Wolbachia* species from plant-parasitic nematodes (Haegeman et al. 2009), for which we might expect some gene set convergence with *Xiphinematobacter*, if they function as nutritional mutualists. However, at present genomes are not available from this group.

Our study adds to the growing list of bacterial phyla that appear to have independently converged on nutritional supplementation in their hosts (McCutchcheon and Moran 2010; Toft and Andersson 2010; Nikoh et al. 2014). Although nutritional supplementation can take on various forms, here the functional profile of *Xiphinematobacter* most closely matched that from bacterial mutualists in phloem-feeding insects (e.g., *Buchnera*) (Hansen and Moran 2014). We suggest that the common selective force on these endosymbionts relates to the need to supplement limiting essential amino acids in the plant-fluid restricted diet. Of course, this restricted diet is a result of the specialized mouthparts for piercing and sucking (odontostyle in *Xiphinema* nematodes or stylet in Hemipteran insects). In Hemipterans, the sap-feeding through stylet arose perhaps 270 Ma (see Bennett and Moran 2013 and references therein), along with a dependence on obligate bacterial mutualists to supplement nutrients in the sap-diet. In the Longidorid nematodes, the odontostyle and the occurrence of the endosymbiont *Xiphinematobacter* arose perhaps 50–100 Ma (Vandekerckhove et al. 2000). This more recent history of endosymbiosis could explain some genomic features observed in *Xiphinematobacter*, such as intermediate %GC reduction, intermediate tRNA gene number compared with obligate mutualists from Hemiptera. These features could also result from weaker selection due to less strict dependence on phloem in the diet of *X. americanum*; however, details of the feeding mode and diet of *X. americanum* need to be better characterized. Taxonomic challenges across the broad *X. americanum* species-complex (Lamberti and Ciancio 1993; Zasada et al. 2014) and incomplete study of the occurrence of *Xiphinematobacter* in these hosts make it difficult to correlate feeding mode and symbiont for this group. The early appearance of the endosymbiont in gut primordia of first-stage juveniles before hatching also raises the question of nutrient supplementation variance during the nematode lifespan.

**Nutritional Mutualists in Nematodes: Widespread or Rare?**

It is not clear how widespread nutritional mutualism is among nematodes, but our study of *Xiphinematobacter* tends to support previous results showing that among known nematode-bacterial symbioses, diet specialization may be a predictor. For example, several extracellular ectosymbionts, gut lumen, or other organ mutualists have been described in nematodes (e.g., *Photorhabdus, Xenorhabdus*, and various microbiome inhabitants) (Burnell and Stock 2000; Bayer et al. 2009; Baquiran et al. 2013; Cheng et al. 2013), all of which are associated with some sort of nutrient provisioning. *Photorhabdus* and *Xenorhabdus*, bacterial symbionts of
entomopathogenic nematodes, have quite specialized diet and associations with their hosts, but unlike *Xiphinematobacter*, have obligate stages outside the nematode cells and retain much larger genomes (Chaston et al. 2011). Several exclusively intracellular endosymbionts are known, such as *Wolbachia* strains in parasitic filarial nematodes (Foster et al. 2005; Lefoulon et al. 2012; Landmann et al. 2014) and the plant-parasitic nematode *Radopholus similis* (Haegeman et al. 2009), and *Wolbachia* genetic remnant suggestive of a possible past endosymbiosis in parasitic strongyloidean nematodes (Koutsovoulos et al. 2014). Others include *Cardinium* strains in the plant-parasitic nematodes *Globodera* and *Heterodera* (Noel and Atibalentja 2006), *Comamonas* sp. in parasitic spiruridean nematodes (Gottlieb et al. 2012), and an undescribed bacteria in the nematode *Noctuidonema* that are ectoparasites of insects (Marti et al. 1995). We speculate that within the *X. americanum* species-complex, members which depend most on phloem might depend more on this bacterial partner, whereas species within or outside of the *X. americanum* group that do not feed on phloem may not need this symbiont at all. Given the often overlooked diversity of nematodes themselves (De Ley 2006), we speculate that there may be many other important nutritional mutualist endosymbionts to be discovered in the Nematoda.

Conclusions

Using a comparative approach we analyzed the first genome from an exclusively intracellular nematode endosymbiont, other than *Wolbachia*, and showed evidence that the Verrucomicrobial endosymbiont *Xiphinematobacter* likely serves as a nutritional mutualist for its host *X. americanum*. Specific evidence includes location in the gut and gut primordia of the embryo, massive genome reduction that mirrors that found in obligate intracellular mutualists, and enrichment for retention of essential amino acid and vitamin biosynthesis pathways. Explicit demonstration of this role awaits experimental testing with and without the symbiont. Although such manipulative experiments are not feasible at present given the difficulty of growing these nematodes in the laboratory, our results illuminate promising directions for future work and management of the plant-parasitic nematode *X. americanum* species-complex. For example, these findings suggest candidate limiting nutrient pathways that may explain nematode specialization or pathogenicity on various plants, and suggest alternative nonnematicidal targets for control. This study is novel in presenting the first genome from an endosymbiotic Verrucomicrobia, which showed perhaps unexpected similarity to genomes from endosymbionts of strictly sap-feeding Hemiptera—a pattern of convergent strategies in symbiont potentially resulting from convergence in feeding mode. Moreover, our findings highlight how much is still to be learned about the broader diversity, abundance, and functional relationships of nematode bacterial symbionts.

**Supplementary Material**

Supplementary figures S1–56 and tables S1–S7 are available at *Genome Biology and Evolution* online (http://www.gbe.oxfordjournals.org).

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