

The Genome Sequence of *Mannheimia haemolytica* A1: Insights into Virulence, Natural Competence, and *Pasteurellaceae* Phylogeny†

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The draft genome sequence of *Mannheimia haemolytica* A1, the causative agent of bovine respiratory disease complex (BRDC), is presented. Strain ATCC BAA-410, isolated from the lung of a calf with BRDC, was the DNA source. The annotated genome includes 2,839 coding sequences, 1,966 of which were assigned a function and 436 of which are unique to *M. haemolytica*. Through genome annotation many features of interest were identified, including bacteriophages and genes related to virulence, natural competence, and transcriptional regulation. In addition to previously described virulence factors, *M. haemolytica* encodes adhesins, including the filamentous hemagglutinin FhaB and two trimeric autotransporter adhesins. Two dual-function immunoglobulin-protease/adhesins are also present, as is a third immunoglobulin protease. Genes related to iron acquisition and drug resistance were identified and are likely important for survival in the host and virulence. Analysis of the genome indicates that *M. haemolytica* is naturally competent, as genes for natural competence and DNA uptake signal sequences (USS) are present. Comparison of competence loci and USS in other species in the family *Pasteurellaceae* indicates that *M. haemolytica*, *Actinobacillus pleuropneumoniae*, and *Haemophilus ducreyi* form a lineage distinct from other *Pasteurellaceae*. This observation was supported by a phylogenetic analysis using sequences of predicted housekeeping genes.

Mannheimia haemolytica serotype A1 is the principle bacterial pathogen associated with bovine respiratory disease complex, also known as bovine shipping fever (25, 31). *M. haemolytica* resides in the upper respiratory tracts of healthy ruminants, although in immunocompromised animals, such as those with a preexisting viral infection, *M. haemolytica* can descend into the lungs, leading to pneumonia. The mortality and morbidity associated with this disease cause substantial losses to the cattle industry (25, 31). Hence, much research on *M. haemolytica* is directed at understanding its virulence and designing vaccines to protect cattle (31).

M. haemolytica is a member of the family *Pasteurellaceae*, which is classified among the γ -proteobacteria and includes human and animal pathogens of the genera *Mannheimia*, *Pasteurella*, *Haemophilus*, *Actinobacillus*, and *Histophilus* (31). *M. haemolytica* (formerly *Pasteurella haemolytica*) is classified in the genus *Mannheimia* based upon 16S rRNA sequence phylogeny and DNA-DNA hybridizations (3). The family *Pasteurellaceae* includes several members whose genomes have been

sequenced: *Haemophilus influenzae*, *Pasteurella multocida*, *Mannheimia succiniciproducens*, *Actinobacillus pleuropneumoniae*, *Histophilus somni*, *Haemophilus ducreyi*, and *Actinobacillus actinomycetemcomitans*.

The primary virulence factor of *M. haemolytica* is considered the leukotoxin. It is a calcium-dependent toxin that is a member of the RTX family of toxins. Cytolytic at low concentrations and apoptotic at high concentrations, the leukotoxin provokes an inflammatory response that can lead to intense edema and necrosis in the lungs of infected cattle (36). Despite the importance of the leukotoxin, leukotoxin-defective strains are only partially attenuated, suggesting that other virulence factors are important in pathogenesis (31). Furthermore, because *M. haemolytica* undergoes a niche change from commensal to pathogenic, the control of the expression of its virulence factors is also of significant interest.

M. haemolytica BAA-410, which was isolated from a calf with bovine respiratory disease complex, was sequenced to draft coverage. Annotation and analysis of the genome provided an opportunity to discover new features potentially related to virulence. It also permitted identification of possible transcriptional regulatory networks and a natural competence system. The genome sequence also allowed comparisons to other sequenced *Pasteurellaceae* genomes and an evaluation of *M. haemolytica*'s place within the *Pasteurellaceae* lineage.

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† Supplemental material for this article may be found at <http://jb.asm.org/>.

TABLE 1. *M. haemolytica* genome general features

Feature	Value
Total length of contigs (bp).....	2,569,125
Coverage (fold).....	8
No. of contigs.....	152
No. of scaffolds.....	103
No. of gaps.....	148
G+C content (%).....	41
No. of tRNAs.....	42
No. of CDS.....	2,839
No. (%) of CDS with assigned function.....	1,966 (69)
No. (%) of <i>Pasteurellaceae</i> conserved hypothetical proteins.....	113 (4)
No. (%) of CDS unique to <i>M. haemolytica</i>	436 (15)
No. (%) of CDS broken at contig ends.....	162 (5.7)
No. (%) of pseudogenes ^a	72 (3)
Average CDS size(bp).....	833
Coding density (%).....	92

^a Given that this is a draft sequence, some pseudogenes may be the result of sequencing errors.

MATERIALS AND METHODS

Bacterial growth and DNA isolation. *M. haemolytica* strain BAA-410 was selected for sequencing because it is virulent in cattle and is the parent of strain SH1217, which is used for genetic studies (23). SH1217 was created by repeated passage of BAA-410 in the presence of acridine orange to render the strain streptomycin sensitive, and SH1217 has been used to make chromosomal mutations (47). Template DNA was harvested from BAA-410 grown in brain heart infusion broth at 37°C with shaking. Cells from overnight cultures were lysed using lysozyme and Triton X-100, and chromosomal DNA was isolated by ultracentrifugation in a CsCl gradient (62).

Library construction and sequencing. Library construction, DNA sequencing, and assembly were performed as previously described (48). A cosmid library was also created for end sequencing and scaffolding. BAA-410 DNA was partially digested with Sau3A. Digested DNA was size fractionated by agarose gel electrophoresis, and 30- to 40-kb fragments were ligated into pJG2560, a pBeloBAC11-derived vector with a *lac*-inducible P1 lytic replicon (J. Gioia, G. M. Weinstock, and S. K. Highlander, unpublished). Cosmids were packaged using the Gigapack III XL packaging kit (Stratagene, La Jolla, CA) according to the manufacturer's instructions. The ends of the ca. 35-kb bacterial artificial chromosome inserts were sequenced from primers flanking the insertion site in pJG2560.

Sequence assembly. A total of 39,949 reads were assembled after using phred for base calling (21, 22) and the Atlas assembly system (30). The reads were assembled into 152 contigs of >1 kb, totaling 2,569,125 bases (Table 1). Read pairs were used to assemble the contigs into 103 scaffolds. The scaffolds were arbitrarily ordered into one artificial superscaffold, using Ns to bridge the gaps.

Genome annotation. The superscaffold was used for gene identification and annotation. Glimmer (17) and GeneMark (45) were used to predict protein-coding sequences (CDS), and several databases were used for comparison of sequences. GenBank nr and CDD databases (70) were used for all CDS, and specialized databases such as Expasy ENZYME (27), the Transporter Classification Database (60), PSORTb (59), TIGR Transporter BLAST Search (<http://tigrblast.tigr.org/er-BLAST/index.cgi?project=transporter>), MEROPS the Peptidase Database (56), SignalP (7), LipoP (37), and Helix-Turn-Helix Predictor (19) were used when applicable. Sequences of tRNAs were identified using tRNAscan-SE (44). All CDS were annotated manually by two annotators, and discrepancies were resolved to reach a consensus annotation. Annotation was done using previously described conventions (48). The authors believe that a labor-intensive manual evaluation of each CDS is more accurate than automated annotation, as effort is devoted to assigning accurate definitions to each CDS and extant errors within databases are more likely to be avoided.

Phylogenetic tree construction. Sequences for tree construction were obtained from this work, NCBI (<http://www.ncbi.nlm.nih.gov/>), and the *A. actinomycetemcomitans* genome sequencing project (<http://www.genome.ou.edu/act.html>). Fifty housekeeping genes common to all nine genomes were selected for analysis. Genes were selected based upon use in previous phylogenetic studies (11, 73). Sequences were aligned using the European Bioinformatics Institute ClustalW (10) server with default parameters to produce alignments in PHYLIP format.

The sequences of each gene were aligned individually to confirm alignments before concatenation. Tree construction was done using the SEQBOOT, DNAPARS, CONSENSE, RETREE, and DNAML programs of PHYLIP (24). Phylogendron (28) was used to display the trees. The genes used were *pykA*, *pgk*, *atpA*, *atpB*, *atpD*, *atpF*, *atpG*, *atpH*, *holB*, *dnaE*, *dnaG*, *uvrB*, *uvrC*, *rpoA*, *rpoB*, *infB*, *rluA*, *truA*, *truB*, *truC*, *dnaJ*, *groEL*, *rplA*, *rplF*, *rplK*, *rplJ*, *rplL*, *rplO*, *rplP*, *rplQ*, *rplR*, *rplW*, *rplC*, *rplD*, *rpsB*, *rpsD*, *rpsC*, *rpsF*, *rpsG*, *rpsH*, *rpsI*, *rpsJ*, *rpsK*, *rpsN*, *rpsO*, *rpsP*, *rpsQ*, *rpsR*, *rpsS*, and *rpsT*.

Project accession numbers. This Whole Genome Shotgun project has been deposited at GenBank under project accession no. AASA00000000. The version described in this paper is the first version, accession no. AASA01000000.

RESULTS AND DISCUSSION

Draft genome sequence. Sequencing of the *M. haemolytica* BAA-410 genome was slated only to draft coverage, and thus the quality of the draft product was evaluated (Table 1). The draft genome sequence has 152 contigs, linked into 103 scaffolds, spanning 2.57 Mb. There are 148 gaps in the sequence (46 captured gaps within scaffolds and 102 gaps between scaffolds), amounting to one gap per 17.3 kb of sequence. This degree of contiguity is adequate for gene prediction, and 2,839 predicted CDS and 42 tRNAs were annotated. The average contig length is 16.9 kb, containing 18.7 CDS, and the average scaffold length is 24.9 kb, containing 27.6 CDS. Blastn analysis of the sequence against itself indicates that a maximum of 35 gaps (24%) are associated with repeated sequences at contig ends. Therefore, other factors besides repeated sequences, such as cloning bias, may contribute to the gaps. More than half of the contig ends are within coding sequences, and the gaps within the assembled sequence disrupt 162 CDS, all of which are labeled "incomplete." Most CDS (69%) have an assigned function or definition, although 436 are hypothetical proteins unique to *M. haemolytica*. Additionally, the draft genome encodes 113 conserved hypothetical proteins that have orthologs only in the family *Pasteurellaceae*. Additional features of the genome are listed in Table 1.

The quality of the draft *M. haemolytica* BAA-410 sequence was addressed by a comparison to previously sequenced genes. All 91 previously sequenced *M. haemolytica* A1 genes or gene fragments in GenBank are present in the draft genome of strain BAA-410, indicating that the data are comprehensive. The aggregate DNA sequence identity between the previously determined sequences and those from BAA-410 is 99.2%. Nevertheless, the draft nature of the genome means that some features are missing because they lie in nonsequenced gaps. For example, tRNAs for tyrosine, asparagine, and phenylalanine are not found in the draft sequence, and the rRNA operons are all incomplete. Additionally, it is not known if the 162 CDS broken at contig ends are actually intact genes.

Genome content. A Blastx analysis of every *M. haemolytica* CDS allowed a general comparison of *M. haemolytica* to other organisms. The source organism of the best match of each BLAST report was recorded for every CDS (Fig. 1a). For over 40% of CDS the best match was to a predicted *A. pleuropneumoniae* protein; this value was far greater than that for any other species. However, when the analysis was extended beyond the best match, it became apparent that the number of *M. haemolytica* CDS with *A. pleuropneumoniae* orthologs is not substantially greater than the number of orthologs in related *Pasteurellaceae* species (Fig. 1b). Slightly more than half of all *M. haemolytica* CDS have orthologs in the other sequenced

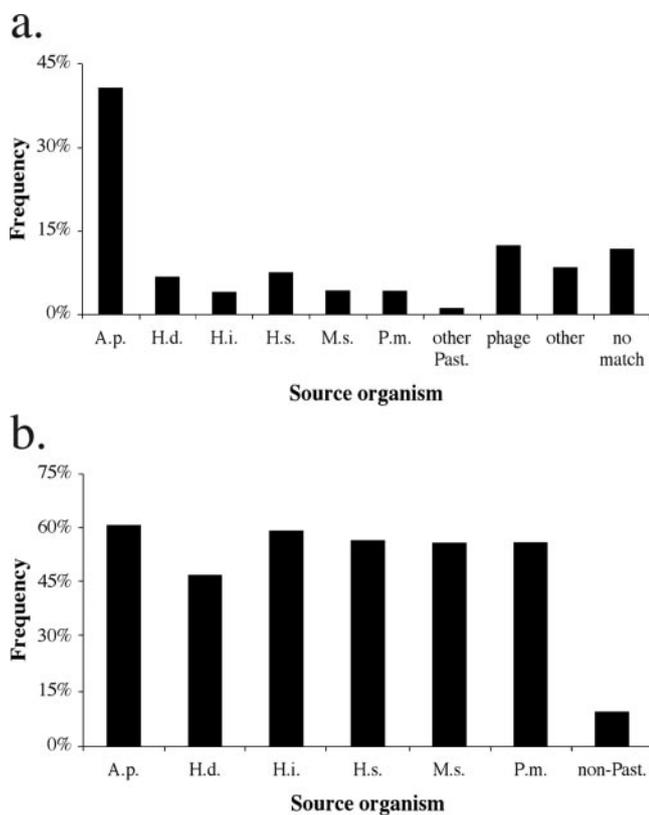


FIG. 1. Distribution of *M. haemolytica* CDS orthologs. The Blast reports of all *M. haemolytica* CDS were analyzed with respect to source organisms of alignments. a. Percentages of *M. haemolytica* CDS with best match to specific source organisms or classes. b. Percentages of CDS with any alignment to specific source organisms. High-scoring pairs with expect values of $>e^{-5}$ were not considered. Abbreviations: A.p., *A. pleuropneumoniae*; H.d., *H. ducreyi*; H.i., *H. influenzae*; H.s., *H. somni*; M.s., *M. succiniciproducens*; P.m., *P. multocida*; other Past., other *Pasteurellaceae* species; non-Past., only non-*Pasteurellaceae* organisms.

Pasteurellaceae genomes, with the exception of *H. ducreyi*. Only 9.3% of *M. haemolytica* CDS have only non-*Pasteurellaceae* orthologs.

Although the number of *M. haemolytica* CDS with *A. pleuropneumoniae* orthologs is not remarkable with respect to other source organisms analyzed here (Fig. 1b), there is a clear distinction between *A. pleuropneumoniae* and other bacteria when only the best match is considered (Fig. 1a). These observations indicate that there is widespread gene conservation among the *Pasteurellaceae* but that on an amino acid sequence level, *M. haemolytica* is closely related to *A. pleuropneumoniae*. The similarity between *M. haemolytica* and *A. pleuropneumoniae* is expected, as they occupy similar niches, although in different hosts. Both cause acute pneumonia associated with massive edema and necrosis, and they use similar virulence factors, including leukotoxin and iron acquisition proteins (8, 35). The similarities between these genomes are discussed in further detail below.

The data in Fig. 1a also revealed that 8.4% of *M. haemolytica* CDS match best to predicted proteins from 110 non-*Pasteurellaceae* species. Among these 237 CDS, the largest group consists of 27 CDS with top hits to *Escherichia coli* proteins.

Another 15 have best matches to *Neisseria meningitidis* proteins (see Table S1 in the supplemental material). Among these are several putative virulence factors, including catalase (MHA_0814), the iron receptor protein Irp (MHA_1629), two immunoglobulin A (IgA)-specific metalloendopeptidase/possible adhesin proteins (MHA_0563 and MHA_2800), a possible adhesin-associated protein (MHA_2262), and two predicted hemoglobin receptor proteins (MHA_1639 and MHA_2261). All of these except MHA_2262 have orthologs in other *Pasteurellaceae* species. The similarity of virulence factor proteins in *M. haemolytica* and the β -proteobacterium *N. meningitidis* suggests that the two share common mechanisms of pathogenesis. This is not surprising considering that both colonize the upper respiratory tract. There are two reasons to consider these similarities the result of convergent evolution rather than horizontal gene transfer. The orthologs described here share only moderate identity on the amino acid level and virtually no similarity on the nucleotide level, except for catalase. Additionally, with the exception of hemoglobin receptor HmBR2 and the adhesin-associated protein, the CDS are neither clustered nor colinear.

Bacteriophages. A substantial fraction (12.3%) of *M. haemolytica* genes are bacteriophage-related (Fig. 1a). There are at least two intact prophages in the genome. Two additional large regions (>20 kb) truncated by contig ends may also be prophages.

Strain BAA-410 contains an intact P2-like phage similar to ϕ MhaA1-PHL101 of strain PHL101 (33). Both phages are integrated within a valine tRNA gene (MHA_t0001), located between the bis(5'-nucleosyl)-tetrphosphatase (MHA_0390) and glyceraldehyde-3-phosphate dehydrogenase (MHA_0442) genes. ϕ MhaA1-PHL101 is a 34.5-kb inducible bacteriophage that encodes 50 CDS. ϕ MhaA1-BAA410 and ϕ MhaA1-PHL101 are very similar and differ only in 22 single-base-pair substitutions, most of which lie within the variable tail fiber gene (MHA_0423), and a 75-bp insertion. The 75-bp insertion lies within a hypothetical CDS (MHA_0419) containing a repeated TTGC tetrad. In ϕ MhaA1-BAA410 this tetrad is repeated 19 more times than in ϕ MhaA1-PHL101. Though this gene appears to be subject to phase variation by slipped mispairing, the relevance is unclear because the protein has no known function.

The *M. haemolytica* genome contains two Mu-like bacteriophages, ϕ MhaMu1 and ϕ MhaMu2 (Fig. 2a), which are similar to the enteric bacteriophage Mu and to the *H. influenzae* bacteriophage FluMu. Mu is a 36.7-kb prophage consisting of a 5' early region containing regulatory genes and a 3' late region containing mostly structural genes (50). The early region is highly conserved, containing transcriptional regulatory genes *c* and *ner* and transposase genes *a* and *b*. Genes encoding these regulatory proteins were identified in both ϕ MhaMu1 and ϕ MhaMu2 (Fig. 2a). Both prophages encode several other Mu orthologs, but there is greater mosaicism within the structural proteins, which is common among other Mu-like bacteriophages (50). The 36-kb ϕ MhaMu1 prophage sequence is complete, contains 54 CDS (MHA_1966 to MHA_2019), and is integrated into a pseudogene of an immunoglobulin metalloendopeptidase (MHA_2020). ϕ MhaMu2 is present on a 30-kb fragment encoding 46 CDS (MHA_0901 to MHA_0946), and it is integrated downstream of a possible nucleoside triphos-

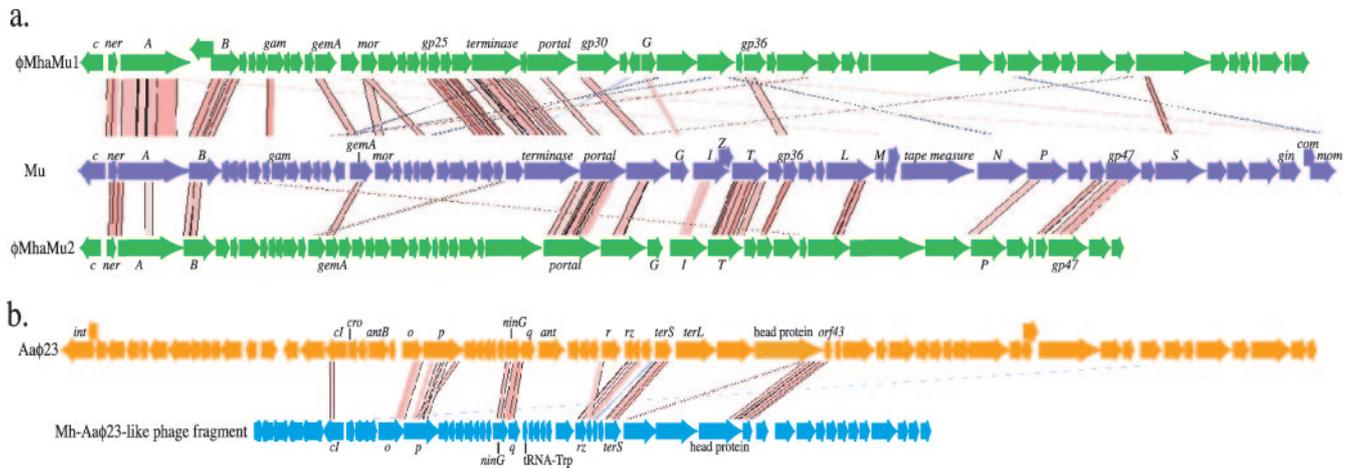


FIG. 2. Bacteriophage maps. The Artemis comparison tool (9) was used to plot Tblastx matches of *M. haemolytica* prophage sequences to Mu and Aa ϕ 23. Red and pink lines indicate similar regions; darker lines represent higher-quality matches. a. Comparison of ϕ MhaMu1 and ϕ MhaMu2 to Mu. b. Comparison of the Aa ϕ 23-like prophage to Aa ϕ 23.

phage-binding transposition protein. ϕ MhaMu2 appears to be incomplete, since its terminal gene encodes a product similar to tail protein S and is located at a contig end. ϕ MhaMu1 and ϕ MhaMu2 share very little nucleotide similarity (81% identity over only 1,100 bp), although many of the predicted proteins share sequence similarity.

A fourth bacteriophage fragment, similar to *A. actinomyces-temcomitans* λ -like Aa ϕ 23, was detected in the genome. Aa ϕ 23, which contains 66 CDS on its 43-kb sequence (58), is not associated with virulence but can transduce antibiotic resistance genes (71). A 22.5-kb scaffold of the *M. haemolytica* genome containing 49 CDS (MHA_2429 to MHA_2477) includes several orthologs of Aa ϕ 23 proteins (Fig. 2b). Compared to the Aa ϕ 23 sequence, the *M. haemolytica* sequence is missing a ca. 5-kb region (9 CDS) at the 5' end and ca. 10 kb (11 CDS) at the 3' end. If *M. haemolytica* contains a complete Aa ϕ 23-like phage, the remaining fragments must be on other contigs. The first gene of Aa ϕ 23 is *int* (58); there are several integrases annotated in the *M. haemolytica* genome that could be candidates. The 3' end of Aa ϕ 23 encodes tail proteins. The scaffold containing the Aa ϕ 23-like sequence ends with a CDS resembling λ protein M, while a second scaffold encodes orthologs of λ tail proteins L, K, I, and J (MHA_0358 to MHA_0362), which are downstream of M in λ . This scaffold may be part of the *M. haemolytica* Aa ϕ 23-like prophage. Unlike Aa ϕ 23, the Aa ϕ 23-like sequence in *M. haemolytica* carries a tRNA^{Trp} gene. A second tRNA^{Trp} gene is found elsewhere on the *M. haemolytica* chromosome. The two sequences are each 76 nucleotides long but share only 89% identity over a 37-bp span. Despite this divergence, analysis with tRNAscan-SE indicates that both sequences encode cloverleaf tRNA structures with CCA anticodons. As there is only one tryptophan anticodon, it is unclear what advantage a second tRNA^{Trp} might provide.

Virulence factors. *M. haemolytica* produces a number of virulence factors that have been the subject of much research. All previously known virulence factor genes have been located in the draft genome, and these have been reviewed previously (31). The *M. haemolytica* leukotoxin is perhaps the most significant virulence factor. The leukotoxin gene *lktA* and associ-

ated genes *lktC*, *lktB*, and *lktD* are known to have a highly mosaic structure among different *M. haemolytica* strains (15). The leukotoxin locus of strain BAA-410 carries alleles *lktC1.1*, *lktA1.1*, *lktB1.1*, and *lktD1.1* (MHA_0253 to MHA_0256), which are common among serotype A1 strains. *M. haemolytica* A1 produces a capsule whose role in virulence may include adherence and resistance to serum-mediated killing and phagocytosis (31, 42). The capsule consists of disaccharide repeats of *N*-acetylmannosaminuronic acid and *N*-acetylmannosamine (42). The 12 genes (MHA_0519 to MHA_0530) in the capsule locus of strain BAA-410 share 99% or greater identity with the sequence previously reported by Lo et al. (42). Lipopolysaccharide (LPS) is a component of the gram-negative bacterial cell wall and is associated with virulence. *M. haemolytica* LPS induces an inflammatory cytokine response and expression of the β_2 -integrin LFA-1 leukotoxin receptor in the host (31, 40). *M. haemolytica* serotypes are clonal with respect to LPS type, and the variation occurs primarily in the lipid A core/oligosaccharide region rather than within the O antigen (16). Serotype A1 was previously shown to produce an O-antigen consisting of repeated trisaccharides of D-galactose-*N*-acetyl-D-galactosamine-D-galactose (31). A total of 38 genes functioning in the synthesis of LPS components, including several genes common to enterobacterial common antigen biosynthesis, and related genes located within LPS gene clusters are listed in Table S2 in the supplemental material. Also included are genes for O-antigen assembly of mannose moieties and epimerases that presumably convert mannose to galactose.

Bacterial adhesins function in colonization by binding to receptor molecules on host cell surfaces. Many adhesins are pili, and the type IV pilus locus *pilABCD* (MHA_0662 to MHA_0665) was annotated in *M. haemolytica*. Type IV pili are known to function in DNA uptake, adhesion, and motility in *H. influenzae*, *P. aeruginosa*, and *Neisseria* species (5) and may perform these functions in *M. haemolytica*. Several predicted nonpilus adhesion proteins and additional proteins that could modify host mucosal surfaces are also present in *M. haemolytica*.

Many pathogens express a filamentous hemagglutinin that functions in adhesion to host mucosa (14, 64). In *Bordetella*

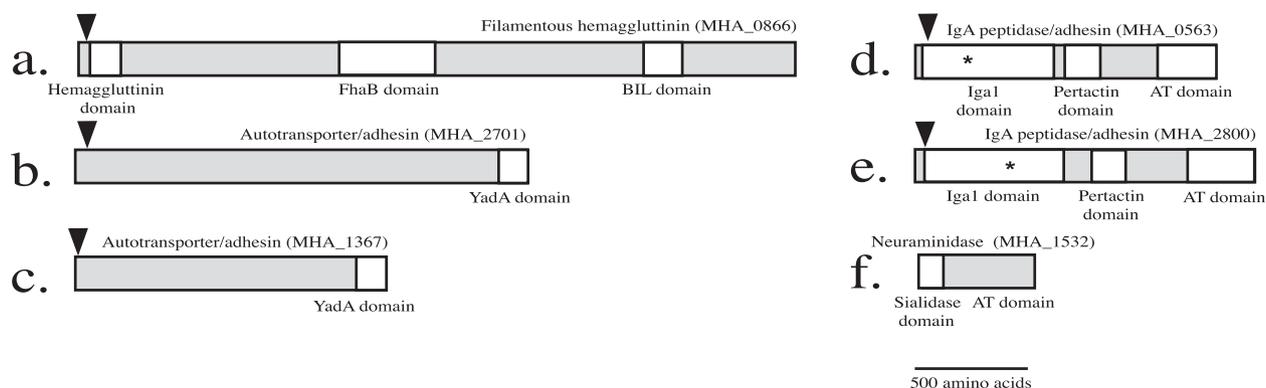


FIG. 3. Domain maps of predicted colonization proteins. a. Filamentous hemagglutinin MHA_0866. b. autotransporter/adhesin MHA_2701. c. autotransporter/adhesin MHA_1367. d. IgA peptidase/adhesin MHA_0563. e. IgA peptidase/adhesin MHA_2800. f. neuraminidase MHA_1532 (incomplete CDS). The sketches are to scale. Domains are labeled below each sketch. Triangle, signal sequence cleavage site. Asterisk, IgA protease active serine residue.

pertussis, the filamentous hemagglutinin gene, *fhaB*, encodes a 3,591-amino-acid preprotein that is found both on the cell surface and in the extracellular milieu. In *B. pertussis*, *fhaB* lies in a cluster with *fhaC*, which encodes an outer membrane transporter specific for FhaB (64). *M. haemolytica* encodes a 3,215-amino-acid FhaB ortholog (MHA_0866) (Fig. 3a) with moderate amino acid similarity to *B. pertussis* FhaB (40% over 1,587 amino acids) and FhaB orthologs in *N. meningitidis*, *A. pleuropneumoniae*, *M. succiniciproducens*, and *Pseudomonas syringae*. *M. haemolytica* *fhaB* is adjacent to an *fhaC* ortholog (MHA_0867), so it likely uses the two-partner secretion pathway. Unlike *B. pertussis* FhaB, the *M. haemolytica* ortholog does not contain an integrin-binding RGD motif. If the *M. haemolytica* FhaB functions as an adhesin, it must have a different binding physiology. A second physical feature distinguishing *M. haemolytica* FhaB from *B. pertussis* FhaB is the presence of a bacterial intein-like (BIL) domain within the carboxy terminus of *M. haemolytica* FhaB. BIL domains are similar to protein-splicing domains found in eukaryotic proteins such as Hedgehog and Hedgehog-like proteins (1). An active BIL domain may allow the protein to undergo autoproteolysis. The cleavage and release of the BIL domain may be advantageous by allowing variability in receptor recognition or receptor release. Since cleavage of the BIL domain changes the structure of FhaB, it may also interfere with the host immune response.

M. haemolytica also encodes a protein (MHA_2262) similar to an adhesin complex protein found only in *N. meningitidis* and the periodontal pathogen *Eikenella corrodens*. The *E. corrodens* protein is believed to be associated with an adhesin protein and located near the carbohydrate recognition domain, but its function is unknown (4).

Nontypeable *H. influenzae* produces HMW, an adhesin that requires accessory proteins HMWB and HMWC for maturation. HMWB is an outer membrane protein that translocates HMW across the outer membrane (65), while HMWC functions in glycosylation of HMW (29). Neither HMW nor HMWB orthologs were found in *M. haemolytica*, but an HMWC ortholog was annotated (MHA_0708). It is unknown what adhesin *M. haemolytica* HMWC glycosylates.

The serotype A1-specific antigen (Ssa1) is also thought to

function as an adhesin (43). The amino acid sequence of Ssa1 from BAA-410 (MHA_2492) is identical to that of the previously sequenced Ssa1, except for the carboxy-terminal 14 amino acids (43). The sequence contains an amino-terminal signal sequence and carboxy-terminal autotransporter β domain. An internal serine protease domain is also present, but no domain typical of adhesins was identified.

Autotransporter proteins can be involved in adhesion to host mucosal surfaces. *M. haemolytica* encodes two proteins, MHA_2701 and MHA_1367, resembling the autotransporter adhesins of *H. influenzae* and *N. meningitidis* (13). Both predicted proteins contain amino-terminal signal sequence cleavage sites for inner membrane translocation and carboxy-terminal translocator domains for outer membrane pore formation (63). MHA_2701 and MHA_1367 contain ATP-binding sequences and carboxy-terminal YadA-like domains typical of the trimeric subfamily of autotransporters (Fig. 3b and c). This subfamily, which includes the *Yersinia enterocolitica* YadA and *H. influenzae* Hia adhesins, is distinguished from conventional autotransporters by the formation of trimers in the periplasmic space (13). Trimeric carboxy-terminal domains form a pore through which the passenger domains traverse the outer membrane. This mechanism results in the presentation of homotrimeric adhesin complexes. It is hypothesized that this structure enhances avidity with its multimeric binding sites and resists extracellular proteases by protecting nonbinding regions of the protein within the core of the trimer (13). MHA_2701 is similar to the Hsf-like adhesions of *A. pleuropneumoniae* and *P. multocida*. The MHA_1367 sequence is similar to those of *H. influenzae* Hia and the Hia orthologs of *A. pleuropneumoniae* and *P. multocida*.

M. haemolytica encodes two autotransporters (MHA_0563 and MHA_2800) orthologous to *H. influenzae* and *N. meningitidis* Iga1, an IgA peptidase/adhesin (Fig. 3d and e). The primary function of Iga1 is to cleave host mucosal antibody, supporting colonization by immunoevasion (65). MHA_0563 and MHA_2800 have Iga1 domains and conserved serine residues corresponding to the active sites of *H. influenzae* Iga1 proteases (54). Although these proteins are similar to IgA proteases, they may actually cleave IgG, as this is the secretory antibody of the bovine respiratory tract and IgG protease ac-

tivity has been reported to be present in *M. haemolytica* (31). In addition to an Iga1-like domain, MHA_0563 and MHA_2800 have an internally located, 240-amino-acid domain similar to the *B. pertussis* adhesin pertactin (64). Proteolytic cleavage and release of the Iga1-like domain may expose the pertactin-like domain on the *M. haemolytica* surface, facilitating a function in adhesion. However, MHA_0563 and MHA_2800 lack the RGD motif common to many bacterial adhesins, including pertactin, so this domain may use an alternative motif for molecular interaction with a host receptor. Like FhaB, pertactin is a *B. pertussis* vaccine component (64), making these predicted proteins possible *M. haemolytica* vaccine targets. *M. haemolytica* encodes a third protein with an Iga1 domain and conserved serine active site; however, the CDS (MHA_1965) does not contain an adhesin domain or an autotransporter domain. MHA_1965 does have an amino-terminal signal sequence, and PSORT predicts it localizes to the outer membrane.

Bacteria can cleave host cell glycoproteins with glycoproteases and neuraminidases (or sialidases), modifying cell surfaces to enhance adhesion (61). The neuraminidase and zinc metallo-glycoprotease genes previously described for *M. haemolytica* are also present in the BAA-410 sequence. The *gcp* gene (MHA_1559) encodes an M22 family *O*-sialoglycoprotein endopeptidase that has been associated with enhancement of adhesion to host cells (51). The neuraminidase gene (MHA_1532) is incomplete in the *M. haemolytica* BAA-410 genome, as it is truncated at a contig end (Fig. 3f). The carboxy-terminal 584 amino acids share 55% identity with the 832-amino-acid *P. multocida* ortholog NanH. The sequenced fragment of the *M. haemolytica* neuraminidase contains a carboxy-terminal autotransporter domain and an incomplete amino-terminal sialidase domain. The incomplete sialidase domain contains one aspartic acid box motif. This motif, common among sialidases (12), is found three times in NanH. It is suspected that the unsequenced 5' end of the *M. haemolytica* neuraminidase gene encodes two additional aspartic acid boxes orthologous to those of NanH.

Iron is a vital nutrient for most bacteria, including *M. haemolytica* (32). The role of iron in *M. haemolytica* pathogenesis is unclear, as there are conflicting reports on the role of iron in the transcription and expression of leukotoxin (47, 67). *M. haemolytica* genes encoding iron acquisition proteins and several related iron homeostasis proteins are listed in Table S3 in the supplemental material. Expression of these proteins should allow *M. haemolytica* to acquire iron from host hemoglobin, hemopexin, and transferrin. *M. haemolytica* encodes two hemoglobin receptors, HmbR1 (MHA_1639) and HmbR2 (MHA_2261), that are more similar to *N. meningitidis* HmbR than the hemoglobin receptors of other *Pasteurellaceae*. *M. haemolytica* also has a gene encoding the hemophore HxuA (MHA_1004), indicating that it can acquire iron from hemopexin. The previously described transferrin-binding proteins TbpA (MHA_0196) and TbpB (MHA_0197) were also annotated in strain BAA-410 (18, 52). Other iron-regulated outer membrane proteins may also participate in iron acquisition. Although *M. haemolytica* has no known siderophores, it may use the iron scavengers produced by other bacteria, as it encodes two siderophore receptors. One receptor, which has several *Pasteurellaceae* orthologs, is similar to FhuE

(MHA_2388), the *E. coli* ferric hydroxamate siderophore receptor, while a second ferric hydroxamate siderophore receptor (MHA_1541) is unique among *Pasteurellaceae* species. To complement these TonB-dependent outer membrane receptors, *M. haemolytica* also encodes ATP-binding cassette (ABC) superfamily transporters for transporting heme, hemin, siderophores, and iron across the inner membrane. The number of ABC transporters suggests diversity in substrates, as there are four ferric transporters and four siderophore transporters. *M. haemolytica* also encodes a ferric uptake regulator (Fur; MHA_2790), which is a transcriptional repressor that regulates iron acquisition genes (2). Recent experiments suggest that *M. haemolytica* Fur is atypical, as its transcription is not repressed by iron (J. Gioia and S. K. Highlander, unpublished data).

Resistance to antibiotics such as β -lactams, tetracycline, streptomycin, and sulfanomides is well documented in *M. haemolytica* (31). Although there is increasing control of the practice in some nations, administration of antibiotics in cattle feed still occurs and is likely to contribute to antibiotic resistance. Several antimicrobial resistance genes were found in the BAA-410 genome (see Table S4 in the supplemental material). These include the TetH tetracycline resistance protein (MHA_1158) and its regulator TetR (MHA_1159), a possible Zn- β -lactamase (MHA_2752), and a major facilitator superfamily permease possibly associated with efflux of bicyclomycin (MHA_1575), an antibiotic that targets transcription terminator factor ρ (38). Orthologs of the resistance-nodulation-cell division superfamily multidrug efflux pump AcrAB, as well as the regulatory protein AcrR (MHA_0370 to MHA_0372), are also present (41). A possible MarC family multiple antibiotic resistance transporter (MHA_0052) was also identified. The gene encoding this transporter is upstream of genes encoding an ABC superfamily binding protein and an ATPase. They may function together in antibiotic resistance. Additionally, there are 13 drug metabolite transporter family transporters predicted in the genome, though their substrates are unknown.

Genes encoding resistance to antimicrobial metals are also present. TehA (MHA_0652) and TehB (MHA_2274) function in the efflux of tellurite and several additional antiseptic compounds (68). *M. haemolytica* also encodes a tellurium resistance protein, TerC (MHA_1456). Strain BAA-410 may also be resistant to mercury, since it encodes a mercury transporter, MerT (MHA_2090); two MerP mercury transport periplasmic proteins (MHA_2089 and MHA_2120); and the MerR transcriptional regulator (MHA_2119) (53).

Transcriptional regulation. As an opportunistic pathogen, *M. haemolytica* changes its relationship with its host from commensal to pathogenic. Transcriptional regulation may be central to niche versatility and the production of virulence factors. Based on the annotation, 125 CDS (4.4%) were classified as transcriptional regulators. These include CDS orthologous to transcriptional regulators, CDS encoding helix-turn-helix motifs as predicted using the method of Dodd and Egan (19), and sigma factors. The ratio of percentage of transcriptional regulators to total number of CDS (1.55×10^{-3}) is similar to that in *Pseudomonas aeruginosa* (1.69×10^{-3}), which has the highest proportion of transcriptional regulators described for any bacterial genome (66). In contrast, the ratio for *E. coli* is 1.35×10^{-3} (66). Transcriptional regulators identified are listed in Table S5 in the supplemental material. While it is not possible

to predict the effectors of transcriptional regulators by annotation, there are several proteins of interest for future study. Ten regulators belong to the LysR family, which is associated with various functions such as virulence, nitrogen fixation, and oxidative stress response (72). There are five members of the AraC family, which is associated with virulence, metabolism, and stress response (26). There are two AcrR family transcriptional regulators, which putatively regulate drug efflux genes (46). There are also three members of the MerR family of metal detoxification transporter regulators (53). The ferric uptake regulator (Fur; MHA_2790), associated with virulence in other pathogens (2), is also present in *M. haemolytica*. Finally, the NarPQ two-component regulatory system (MHA_2193 and MHA_1462), though normally associated with nitrite and nitrate metabolism (68), may also be associated with virulence, as NarP was identified in an experiment to select transcriptional regulators of leukotoxin (J. Gioia, A. M. Marciel, L. E. Alvarez, J. M. Criglar, and S. K. Highlander, unpublished data).

M. haemolytica encodes at least six different RNA polymerase sigma factors. These include the major housekeeping sigma factor RpoD (σ^{70} ; MHA_2291), the heat shock sigma factor RpoH (σ^{32} ; MHA_2650), and four RpoE-like alternative sigma factors (MHA_0296, MHA_0739, MHA_1691, and MHA_2095). The alternative sigma factors belong to a subclass of σ^{70} proteins called extracytoplasmic sigma factors that function in response to a variety of conditions, such as periplasmic protein misfolding, heat stress, and nutrient stress (49). The function of the *M. haemolytica* alternative sigma factors remains to be determined. In *E. coli* RpoE is controlled by the RseABC proteins. These proteins sequester RpoE under nonstimulatory conditions to prevent it from transcribing the genes in its regulon (49, 55). Orthologs of RseABC (MHA_2570 to MHA_2572) are present in *M. haemolytica*, suggesting that a similar mechanism of regulation occurs in this organism.

Natural competence. Many bacteria are naturally competent, meaning that they are able to acquire extracellular DNA for nucleic acid supply or gene transfer (20). Although natural competence is well characterized in *H. influenzae*, there are no published reports of natural competence in *M. haemolytica*. The *M. haemolytica* genome contains several features indicating the capacity for natural competence. In *H. influenzae* pilin protein PilA and secretin outer membrane pore protein ComE transport DNA across the outer membrane (20, 57). The *M. haemolytica* genome encodes predicted ComE (MHA_0164), PilA (MHA_0662), and pilus assembly proteins PilB (MHA_0663) and PilC (MHA_0664). The genome also encodes orthologs of proteins that function in the transport of DNA from the periplasm to the cytoplasm, including lipoprotein ComL (MHA_1560), transmembrane protein ComEA (MHA_2354), and periplasmic protein ComF (MHA_1838) (20, 57). Orthologs of cytoplasmic competence proteins DprA (MHA_1048), which functions in transport of DNA across the inner membrane, and ComM (MHA_0963), a protease believed to function in preventing cytoplasmic degradation of DNA, are also present (20, 57), as are competence regulatory proteins CRP (MHA_1000) and Sxy (MHA_1438) (57).

The DNA uptake signal sequence (USS) is a feature of natural competence in bacteria of the *Neisseriaceae* and *Pasteurellaceae* families (6, 69). The cell surface DNA-binding

TABLE 2. Nonamer repeats in *Pasteurellaceae* genomes

Organism	Most common 9-mer	Frequency	Frequency/Mb
<i>H. influenzae</i>	AAGTGC GGT	1,471	803
<i>P. multocida</i>	AAGTGC GGT	927	412
<i>H. somni</i>	AAGTGC GGT	1,345	640
<i>A. actinomycetemcomitans</i>	AAGTGC GGT	1,473	736
<i>M. succiniciproducens</i>	AAGTGC GGT	1,485	642
<i>M. haemolytica</i>	ACAAGC GGT	931	362
<i>A. pleuropneumoniae</i>	ACAAGC GGT	755	329
<i>H. ducreyi</i>	ACAAGC GGT	199	117

proteins of these bacteria bind to their specific USS, facilitating DNA uptake. In *H. influenzae* the USS is an AAGTGC GGT nonamer that is overrepresented in the genome (Table 2). This same nonamer is common among several other *Pasteurellaceae* bacteria (6, 69). Although this *H. influenzae* nonamer is also overrepresented in *M. haemolytica* (98 times), the most common nonamer has the sequence ACAAGC GGT and is present at 931 copies in the draft genome (Table 2). This putative USS does confer a 100-fold increase in uptake when cloned as a dimer onto a plasmid lacking the sequence (M. Dillon and S. K. Highlander, unpublished data).

The *M. haemolytica* USS is also the most common nonamer in *A. pleuropneumoniae* and *H. ducreyi*. Bakkali et al. postulate that USSs are the result of sequence uptake bias, or molecular drive, and that shared USSs among different species indicate a close evolutionary relationship (6). Thus, it can be hypothesized that the divergence of USS among the *Pasteurellaceae* represents different lineages in which *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi* are divergent with respect to the species in which the *H. influenzae* nonamer dominates. The common DNA USS in these organisms also implies the possibility of horizontal gene transfer with one another as the species diverged.

The divergence of *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi* from the *H. influenzae* lineage within the *Pasteurellaceae* is also supported by gene conservation in loci related to competence. In *H. influenzae* the *com* locus consists of the genes *comABCDEFGHI* (Fig. 4). The *comABCDE* gene order is conserved among all *Pasteurellaceae* species except *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi*. These three genomes contain *com* loci with *comA* and *comE* orthologs, but they do not contain orthologs of *comB*, *comC*, and *comD*. Instead, *M. haemolytica* encodes *Pasteurella* conserved hypothetical proteins MHA_0161, MHA_0162, MHA_0163, which are orthologous to AP1013, AP1012, and AP1011, respectively, in *A. pleuropneumoniae*. In *H. ducreyi*, HD0432 and HD0433 are orthologs of MHA_0162 and MHA_0163, respectively, but there is no intact ortholog of MHA_0161. Instead, there are four small hypothetical proteins encoded between *comA* and HD0432. One of these proteins has weak similarity (33% identity over 66 amino acids) to a portion of MHA_0161, so it is possible that *H. ducreyi* had an MHA_0161 ortholog at one time. Thus, a comparison of the *com* loci of these species supports the hypothesis that *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi* are members of a distinct subgroup of the *Pasteurellaceae*. Other features of the *com* locus are consistent

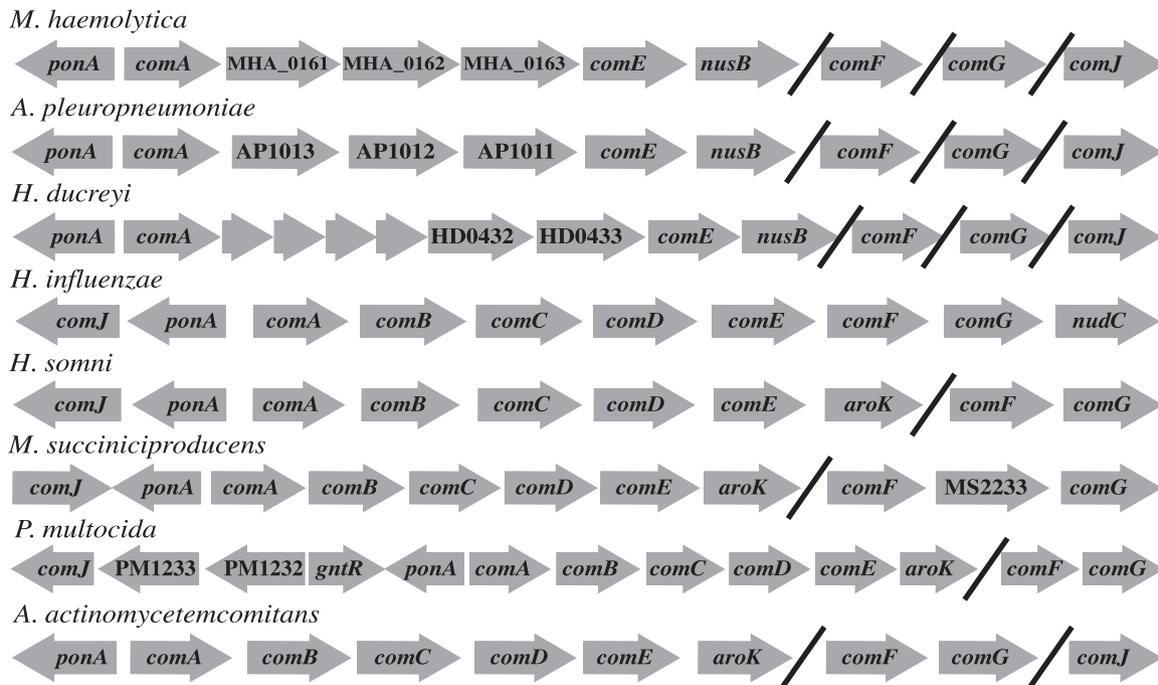


FIG. 4. *Pasteurellaceae* competence loci. The *com* loci and flanking genes of eight *Pasteurellaceae* are sketched (not to scale). Arrows indicate genes and orientation. Hash marks separate noncontiguous sequences. Four small arrows preceding HD0432 represent small hypothetical proteins.

with this point. As shown in Fig. 4, in *H. influenzae* and other *Pasteurellaceae*, *comF* and *comG* are adjacent to one another, and *comJ* is usually located upstream of *comA*. However, these genes are unlinked in *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi*. Additionally, the *com* locus is adjacent to *nusB* in *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi*, whereas it is adjacent to *aroK* or *nudC* in other *Pasteurellaceae*.

A divergence in gene conservation is also observed in the competence regulatory element (CRE) locus (57). In *H. influenzae* the four-gene CRE operon is induced under conditions favorable for natural competence, and mutation of HI0938, the first gene in the locus, prevents DNA uptake (57). Similar CRE operons are found in *M. haemolytica* (MHA_1011 to MHA_1014), *A. pleuropneumoniae*, and *H. ducreyi*, but these organisms have no ortholog to HI0940, the third gene of the locus. Instead, they have a different gene that is conserved among these three species.

***M. haemolytica* phylogeny.** *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi* appear to be closely related based on examination of competence genes and features, but phylogenetic analysis requires a more general approach. Phylogenetic tree construction based upon 16S rRNA gene sequences is a common tool that has been used for classification of the *Pasteurellaceae* (11), including the creation of the genus *Mannheimia* (3). Analysis of 16S rRNA genes of the sequenced *Pasteurellaceae* species is of limited use because the bootstrap values are very low (Fig. 5a). However, the annotated genomes of these organisms allowed the construction of a phylogenetic tree based upon the sequences of 50 highly conserved housekeeping genes (Fig. 5b). Here, *M. haemolytica*, *A. pleuropneumoniae*, and *H. ducreyi* form a group that is divergent from the other *Pasteurellaceae*. Notably, the other *Mannheimia* species,

M. succiniciproducens is found in a cluster with other members of the *Pasteurellaceae* family, distinct from *M. haemolytica*. *M. succiniciproducens* was placed in the genus *Mannheimia* because of phylogenetic analysis of 16S rRNA sequences (34, 39), though the analysis of Lee et al. (39) did not include sequences of *H. ducreyi* and *A. pleuropneumoniae*. Both the 16S rRNA gene tree and the housekeeping gene tree presented here indicate that *M. haemolytica* is more closely related to *A. pleuropneumoniae* and *H. ducreyi* than it is to the other *Pasteurellaceae* included in this analysis. This observation is similar to previously reported analyses using 16S rRNA gene sequences and the sequences of three individual housekeeping genes (11), although *M. succiniciproducens* was not included in those analyses. The data presented here suggest that the taxonomy of the group is not necessarily in agreement with the phylogeny of the group.

The high degree of similarity between *M. haemolytica* and *A. pleuropneumoniae* is not unexpected given the analogous niches of the two bacteria. Both are commensal upper respiratory tract flora that are also opportunistic lower respiratory tract pathogens. Although they infect different host species, they share tissue tropism and similar virulence factors (8, 35). Hence, it is reasonable to hypothesize that these bacteria may be derived from a common *Pasteurellaceae* ancestor. The relationship to *H. ducreyi* is less obvious, as it is a pathogen of the human genital epithelium. Furthermore, the number of *M. haemolytica* CDS with *H. ducreyi* orthologs is the lowest of all *Pasteurellaceae* species examined. The relationships of *H. ducreyi* to *M. haemolytica* and *A. pleuropneumoniae* may reflect a case in which *H. ducreyi* has undergone greater divergence because of its adaptation to a different host species and tissue. Because housekeeping genes are highly conserved, this diver-

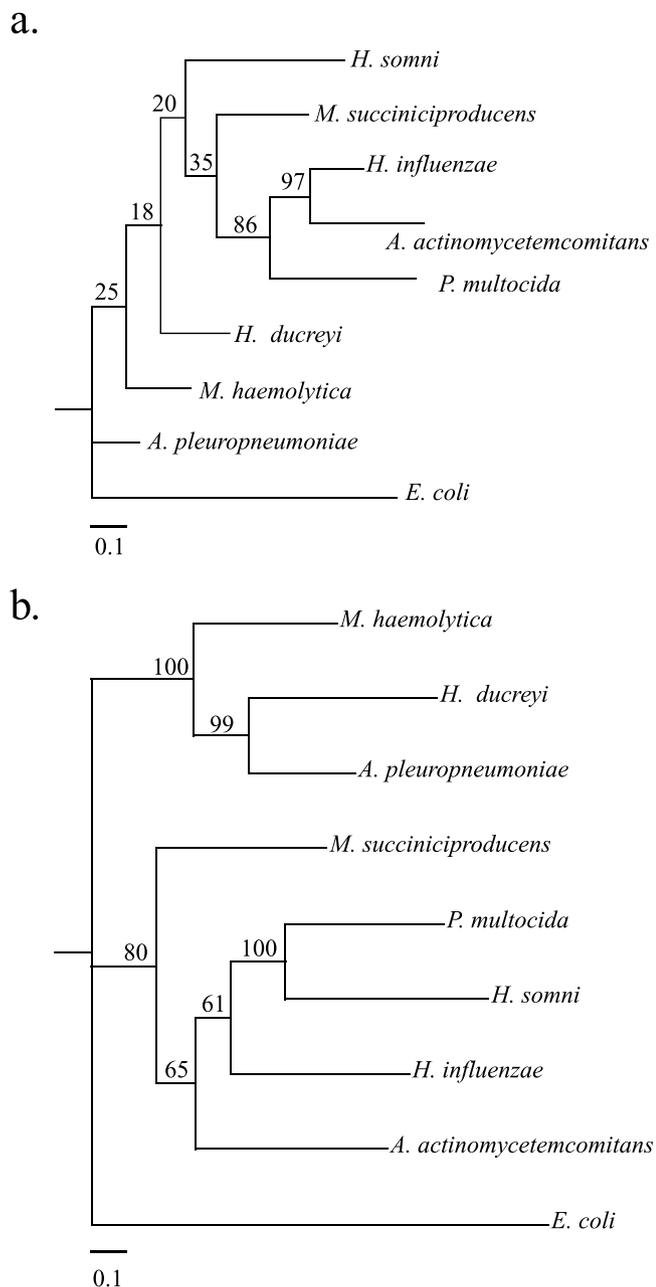


FIG. 5. Phylogenetic trees. PHYLIP (24) was used to make trees, using sequences from eight sequenced *Pasteurellaceae* species. *E. coli* was used as an outgroup. Numbers at nodes represent bootstrap values (out of 100). a. Tree derived from 16S rRNA gene. b. Tree derived from 50 highly conserved housekeeping genes totaling ca. 40 kb.

gence may be slow to appear in an analysis such as the phylogenetic tree presented in Fig. 5b, despite being apparent in a genome-wide examination (Fig. 1b). It is also noteworthy that the DNA USS is present only 199 times in *H. ducreyi*, a far lower frequency than in other *Pasteurellaceae*. Considering the theory of molecular drive, this comparatively low frequency may reflect a lack of interaction with other bacteria sharing the same DNA USS because of diversification in a different niche. It appears that *M. haemolytica* and *M. succiniciproducens* are more closely related to other *Pasteurellaceae* than to each

other, despite being placed in the same genus. This lesser degree of similarity may also be understandable given the difference in niche—*M. succiniciproducens* lives within the rumen of cattle (34). Given the phylogenetic relationships among the species examined here, a reevaluation of the taxonomy of one or more species may be in order.

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