Disparate Rates of Molecular Evolution in Cospeciating Hosts and Parasites

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DNA sequences for the gene encoding mitochondrial cytochrome oxidase I in a group of rodents (pocket gophers) and their ectoparasites (chewing lice) provide evidence for cospeciation and reveal different rates of molecular evolution in the hosts and their parasites. The overall rate of nucleotide substitution (both silent and replacement changes) is approximately three times higher in lice, and the rate of synonymous substitution (based on analysis of fourfold degenerate sites) is approximately an order of magnitude greater in lice. The difference in synonymous substitution rate between lice and gophers correlates with a difference of similar magnitude in generation times.

Chewing lice of the genera Geomydoecus and Thomomysdoecus are obligate ectoparasites of pocket gophers (Fig. 1). Because the entire life cycle of these lice occurs exclusively in the fur of the host, and because different host species rarely interact, each species of louse is normally restricted to a single host species (1). As a result, there is close correspondence between gopher taxonomic boundaries and louse taxonomic boundaries (2). When viewed over large geographic and temporal scales, this restricted distributional pattern of chewing lice on pocket gophers has resulted in phylogenetic histories of lice and gophers that are remarkably similar (3–5).

Although well-documented cases of host-parasite cospeciation are rare (3, 6), they are of interest because they permit comparative study of organisms with a long history of parallel evolution. The temporal component of parallel phylogenesis (in which lineages of hosts and their parasites speciate repeatedly at approximately the same time) permits examination of relative rates of evolution in the two groups by comparison of the amount of change each has undergone during their parallel histories. Because the life histories of hosts and their parasites are often profoundly different, studies of molecular evolution in host-parasite assemblages can help answer a broad spectrum of questions relating to the possible effects of generation time, metabolic rate, and other life history parameters on rates of mutation and evolutionary change.

We examined DNA sequence variation in 14 species of pocket gophers and their chewing lice (7) to test for cospeciation and to investigate rates of molecular evolution in this host-parasite assemblage. We sequenced and compared homologous regions of the gene encoding the mitochondrial cytochrome c oxidase subunit I (COI) in both groups (8). Of the 379 nucleotides sequenced for each taxon, 134 positions were variable in pocket gophers and 178 positions were variable in chewing lice (Table 1).

The cospeciation hypothesis predicts that the branching structure of the host and parasite phylogenies will be similar to a degree beyond that expected by chance. This prediction can be evaluated statistically (3, 4). For any particular host-parasite assemblage, confidence in the test of cospeciation can be no stronger than confidence in the phylogenies under comparison. Thus, it is essential that the host and parasite phylogenies accurately estimate the evolutionary history of each group. There are many methods for estimating phylogenies from sequence data (9), each of which uses a different model of nucleotide evolution and potentially yields a phylogenetic hypothesis (a tree) that differs from that estimated with other methods (10). To consider the effects of different evolutionary models on our estimates of phylogeny, we applied multiple methods of analysis (11, 12) to our sequence data. In cases where different methods yielded different results, we retained all host and parasite trees for topological comparison in order to determine whether the inference of cospeciation is warranted and, if so, whether the inference is sensitive to the method of analysis.

All analyses of the pocket gopher sequence data (using different models of DNA sequence evolution) yielded trees that were very similar in overall branching structure. For example, phylogenetic analysis (11) of the COI sequence data for pocket gophers yielded two most-parsimonious trees of equal length (1423 steps). One of these trees (Fig. 2A) was topologically identical to the tree generated by a maximum-likelihood analysis of the same data (12). The other most-parsimonious tree showed only minor differences (13) from the tree shown in Fig. 2A. The general structure of the gopher parsimony tree (Fig. 2A) also was supported by Fitch-Margoliash (Fig. 2B) and neighbor-joining analyses of genetic distances (12). Differences among the trees generated by the parsimony, maximum-likelihood, Fitch-Margoliash, and neighbor-joining analyses of the pocket gopher data were judged nonsignificant by a likelihood ratio test (15). Accordingly, all four trees were retained for topological comparison with the parasite trees. The basic structure of these trees and, in particular, relations within the genera Orthogeomys and Geomys, also are supported by inde-

![Fig. 1. Chewing lice (Geomydoecus texanus, inset) are wingless insects that are obligate ectoparasites of pocket gophers (Thomomys bottae is shown here). The entire life cycle of the chewing lice occurs in the fur of these fossorial rodents.](image)

<table>
<thead>
<tr>
<th>Percent of sequence difference (± 1 SD)*</th>
<th>Gophers</th>
<th>Lice</th>
</tr>
</thead>
<tbody>
<tr>
<td>First position transitions</td>
<td>1.43 (0.49)</td>
<td>2.09 (0.62)</td>
</tr>
<tr>
<td>First position transversions</td>
<td>0.00 (0.25)</td>
<td>0.46 (0.34)</td>
</tr>
<tr>
<td>Second position transitions</td>
<td>0.24 (0.18)</td>
<td>0.38 (0.37)</td>
</tr>
<tr>
<td>Second position transversions</td>
<td>0.00 (0.00)</td>
<td>0.16 (0.17)</td>
</tr>
<tr>
<td>Third position transitions</td>
<td>8.74 (1.65)</td>
<td>9.59 (1.51)</td>
</tr>
<tr>
<td>Third position transversions</td>
<td>5.01 (1.67)</td>
<td>7.68 (1.99)</td>
</tr>
<tr>
<td>Total difference</td>
<td>15.64 (3.20)</td>
<td>20.75 (2.31)</td>
</tr>
<tr>
<td>Silent nucleotide differences</td>
<td>14.75 (3.09)</td>
<td>17.66 (2.32)</td>
</tr>
<tr>
<td>Replacement nucleotide differences</td>
<td>0.89 (0.71)</td>
<td>2.67 (1.05)</td>
</tr>
<tr>
<td>Amino acid differences</td>
<td>2.40 (1.83)</td>
<td>6.85 (2.62)</td>
</tr>
</tbody>
</table>

*Mean and standard deviation based on all pairwise comparisons.
dependent phylogenetic studies based on morphology, allozymes, comparative immunology, karyology, and nucleotide sequence data (3, 5, 16-18).

All analyses of the chewing louse sequence data likewise yielded trees with similar branching structures. Phylogenetic analysis of the louse COI data yielded three most-parsimonious trees of equal length (4208 steps). One of these trees (Fig. 2A) was topologically identical to the tree generated by a maximum-likelihood analysis of the same data. The two remaining parsimony trees showed only minor differences (involving one species in each case) from the tree in Fig. 2A (19). The Fitch-Margoliash analysis (Fig. 2B) and the neighbor-joining analysis (20) yielded louse trees very similar to those generated by the parsimony analysis. Differences among the trees generated by the parsimony, maximum-likelihood, Fitch-Margoliash, and neighbor-joining analyses of the louse data were judged nonsignificant by a likelihood ratio test (15). Accordingly, all five louse trees were retained for topological comparison with the host trees. The basic structure of the louse trees and, in particular, relations among lice hosted by species of Orthogeomys and Geomys, also are supported by independent phylogenetic studies of allozymes (3, 5, 21).

The COMPONENT program (22) determined if the fit between observed parasite and host trees was significantly better than the fit between the parasite tree and trees drawn at random from the set of all possible host trees (4). For each of 20 pairwise comparisons (four host trees and five parasite trees), the observed degree of fit between the gopher and louse trees was significantly better (P < 0.01) than the fit between the louse tree and 10,000 randomized gopher trees (23). These results, which are robust to the method of phylogenetic inference and to the evolutionary models used, falsify the null hypothesis of chance similarity between the host and parasite trees. Although this evidence is consistent with the hypothesis of cospeciation, the concordant phylogenies might instead result from dispersal, extinction, or incomplete sampling of closely related taxa (4). However, only the cospeciation hypothesis predicts temporal congruence of host and parasite speciation events, which (given roughly time-dependent molecular change in each group) would result in a significant relation between measures of molecular differentiation in the host and parasite trees. We demonstrate below that our molecular data are consistent with this prediction. This finding, which requires no assumptions about rate similarity between hosts and parasites (3), corroborates independent evidence for cospeciation in several genera of pocket gophers (Orthogeomys, Geomys, and Thomomys) and their lice (3-5).

Given evidence for cospeciation, it is possible to test the null hypothesis that pocket gophers and chewing lice have undergone equivalent amounts of genetic differentiation during their parallel histories. It is appropriate that this test be restricted to hosts and parasites that have cospeciated, because time since divergence can be assumed to be equal only for host-parasite pairs that show cospeciation (9 host-parasite pairs in Fig. 2A and 10 host-parasite pairs in Fig. 2B) (24). We first compared maximum-likelihood branch length matrices for cospeciating gophers and lice using Mantel's test (25), which showed a highly significant (P < 0.01) association between genetic distances in corresponding hosts and parasites. This test demonstrates that evolutionary rates in gophers and lice are significantly correlated, regardless of tree structure. To test for equality of rates between gophers and lice, we compared maximum-likelihood branch lengths for all possible combinations of cospeciating taxa (24, 26). In all cases, Wilcoxon sign-rank tests showed that louse branches were significantly longer than gopher branches (P < 0.003 in each case). Given this significant difference, we used Model II regression.
analysis (through the origin) and determined that the slopes of the regressions (Fig. 3A) ranged from 2.60 to 2.83 (with a mean of 2.74). This indicates that the overall rate of nucleotide substitution in lice is approximately three times higher than in gophers (27).

To estimate rates of synonymous substitution in gophers and lice, we restricted our analysis of the COI sequences to fourfold degenerate sites (sites at which all base substitutions are silent). We focused on the largest group of closely related species (Orthogeomys species and their lice) because these species are sufficiently closely related to ensure that corrections for multiple mutations are effective (28). The numbers of variable fourfold degenerate sites in gophers and lice were approximately equal (67 and 69, respectively). We used a maximum-likelihood model of evolution to infer branch lengths based solely on substitutions at these sites (24). The model included corrections for observed transitional bias (a maximum 4:1 bias in gophers; 10:1 bias in lice) and for significantly different nucleotide compositional biases in the two data sets (P < 0.05) (29). These corrections are necessary to estimate evolutionary rates (28), and spurious results should not occur simply because of differences in the number of characters compared or differences in mutational dynamics (and resultant saturation levels) in the two groups being compared. In theory, rates of synonymous substitution are proportional to mutation rates (30), but our estimates cannot be considered direct measures of mutation rates because we have not controlled for possible constraints on the translational apparatus, such as codon bias and secondary structure of mRNAs.

If nucleotide substitutions at fourfold degenerate sites are selectively neutral, then change at these sites should fit a molecular clock model (30). Accordingly, we tested all possible combinations of cospeciating gophers (Orthogeomys only) and their lice (24) for significant departure from clocklike behavior, using the log-likelihood ratio test (12). In all cases, the data were consistent with molecular-clock assumptions, which indicates that substitutions within gophers and within lice accumulate in a roughly time-dependent fashion. Wilcoxon sign-rank tests showed that louse branches were significantly longer than gopher branches in four of the six possible comparisons (P < 0.05 in each case). We used Model II regression analysis (through the origin) to quantify the relation between gopher and louse branch lengths. Slopes of the regressions (Fig. 3B) ranged from 9.68 to 11.83 (with a mean of 11.04), which indicates that the estimated rate of silent substitution for this gene region is approximately an order of magnitude greater in chewing lice than in pocket gophers. Evidence for a higher rate of substitution in lice appears to be independent of the evolutionary model employed, although the magnitude of the rate difference is sensitive to certain parameters of the model (31).

Viewed together, the analysis of all nucleotide substitutions (Fig. 3A) and the analysis of substitutions at fourfold degenerate sites (Fig. 3B) provide insight into the dynamics of molecular evolution for this gene region in the species studied. The analysis of all substitutions indicates that the overall rate of evolutionary change is approximately three times greater in chewing lice than in their hosts (Fig. 3A). Likewise, the means of all pairwise replacement differences for nucleotides and amino acids are approximately three times greater in lice than in gophers (Table 1). In contrast, the analysis of nucleotide substitutions at fourfold degenerate sites indicates that rates of silent substitution in this gene region are roughly 11 times greater in lice than in gophers (Fig. 3B). The fact that this 11-fold rate difference is not evident when all substitutions are considered is probably the result of selective constraints on replacement substitutions. High levels of functional constraint on the COI enzyme have been reported in other organisms (28).

The 11-fold difference in rates of synonymous substitution in Orthogeomys gophers and their lice (Fig. 3B) cannot be explained by transition bias or nucleotide frequency bias. Because silent substitutions at the fourfold degenerate sites show clocklike behavior, it is likely that they are neutral or nearly neutral (30). Several possible mechanisms could account for this rate difference, including mutation rate differences caused by possible differences in gene order that affect vulnerability to mutation (32), differences in metabolic rate or general metabolic physiology, generation-time differences, or other factors correlated with body size (33). Alternatively, this rate difference could be caused by mechanisms that are independent of mutation rate, such as codon bias and other constraints on the translational apparatus, or differences in DNA repair efficiency. It is perhaps important that this 11-fold rate difference is accompanied by a similar difference in generation time between gophers and lice (approximately 1 year in gophers and 40 days in lice) (34). If the observed rate difference results from an underlying difference in mutation rate, then generation time may explain this difference. However, mutation rates are more likely to be influenced directly by nucleotide generation time than by organismal generation time (33). As such, our study suggests that each organismal generation is equivalent to equal numbers of nucleotide generations in pocket gophers and chewing lice. If the 11-fold rate difference reflects a similar difference in mutation rate, then these findings are consistent with the neutral theory of molecular evolution (30), because once the data are corrected for the difference in generation time, they suggest equal rates of mutation per generation in distantly related groups of animals.

REFERENCES AND NOTES

Pocket gophers were trapped, killed, and immediately brushed to recover lice. Gopher tissues and lice were stored at −70°C. DNA extractions from gophers followed the phenol-chloroform technique (D. M. Hills, A. Larson, S. K. Davis, E. A. Zimmer, in Molecular Systematics). We used one 0.5-ml Eppendorf tube, and 10 μl of 1× TE buffer, and 1 μl of proteinase K (5 mg/ml) at 37°C for 1 h. DNA extractions from lice followed the phenol-chloroform technique (D. M. Page, Personal Communication). 

Within or between lice and gophers, contamination is not suspected. Gopher and louse tissues will be stored at −70°C until samples are sufficient for DNA extractions.

Two sets of control reactions were conducted, 10 for pocket gophers and 10 for lice, using the same conditions as used above.


11. We used the PAUP program (Phylogenetic Analysis Using Parsimony) to perform phylogenetic analyses of the sequence data. Of the 134 variable sites in pocket gophers (178 in lice), 113 were phylogenetically informative (142 in lice). To compensate for the effects of multiple mutations at a site, we used the model of DNA substitution described by Goldman and Goldman (1995).

We used the model of DNA substitution described by Goldman and Goldman (1995). The slope of this relationship is affected very little by differences in nucleotide composition being surveyed (25), and the non-parametric Wilcoxon sign-rank test shows that there are significantly larger numbers for gopher and lice branches (26). When the regression analyses were not constrained through the origin, none of the y-interpretations was significantly different from zero.

12. We used Model II regression analysis (reduced major axis model), which does not permit conventional tests of significance [R. R. Sokal and F. J. Rohlf, Biometry (W. H. Freeman, San Francisco, 1969)]. However, the non-parametric Mantel's test documents a significant relation between genetic distances in gophers and lice (25), and the non-parametric Wilcoxon sign-rank test shows that louse branches are significantly longer than gopher branches. When the regression analyses were not constrained through the origin, none of the y-interpretations was significantly different from zero.

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