Aligned 18S for Zoraptera (Insecta): Phylogenetic position and molecular evolution

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Received 11 January 2005; revised 6 May 2005

Abstract
The order Zoraptera (angel insects) is one of the least known insect groups, containing only 32 extant species. The phylogenetic position of Zoraptera is poorly understood, but it is generally thought to be closely related to either Paraneoptera (hemipteroid orders: booklice, lice, thrips, and bugs), Dictyoptera (blattoid orders: cockroaches, termites, and mantis), or Embioptera (web spinners). We inferred the phylogenetic position of Zoraptera by analyzing nuclear 18S rDNA sequences, which we aligned according to a secondary structure model. Maximum likelihood and Bayesian analyses both supported a close relationship between Zoraptera and Dictyoptera with relatively high posterior probability. The 18S sequences of Zoraptera exhibited several unusual properties: (1) a dramatically increased substitution rate, which resulted in very long branches; (2) long insertions at helix E23; and (3) modifications of secondary structures at helices 12 and 18.

Keywords: Zoraptera; 18S rDNA; Secondary structure based alignment; Phylogeny; Molecular evolution

1. Introduction
Zoraptera (angel insects) is one of the least diverse and poorly known insect orders. To date, only 38 species (which includes six fossil species) are described, and all extant species are classified under a single genus, Zorotypus (Engel and Grimaldi, 2002). Some other genera have been proposed for extant species (Chao and Chen, 2000; Kukalová-Peck and Peck, 1993), but more the conservative taxonomic system is adopted here, as suggested by Engel and Grimaldi (2000) and New (2000). All species of Zoraptera live under the bark of rotting wood (Smithers, 1991).

Based on morphological characters, the order Zoraptera is thought to be closely related to either Paraneoptera (= hemipteroid orders: bugs, thrips, booklice, and lice: Hennig, 1981; Kristensen, 1975, 1981; Wheeler et al., 2001), Dictyoptera (= blattoid orders: cockroaches, termites, and mantis; Boudreaux, 1979; Kukalová-Peck and Peck, 1993; Smithers, 1991) or Embioptera (= web spinners: Engel and Grimaldi, 2000; Minet and Bourgoin, 1986). Combined morphological and molecular analysis by Wheeler et al. (2001) supported a close relationship between Zoraptera and Dictyoptera. However, separate analysis of molecular data (18S rDNA) placed Zoraptera as the sister taxon of Psocodea (booklice and parasitic lice), conflicting with combined tree (Wheeler et al., 2001).

Separate analyses of 18S data (Wheeler et al., 2001) resulted in tree with a very unconventional placement of some insect orders (e.g., Diplura and Grylloblattodea were imbedded within Holometabola). Wheeler et al. (2001) used direct optimization of morphological and molecular data, which minimizes incongruence between two data partitions. Kjer (2004) pointed out that, when
support from molecular data for nodes is small, conclusions from molecular data by direct optimization would be highly dependent on some combination of (1) morphological data, (2) noise from the homoplastic data, and (3) arbitrarily optimized homology of unalignable data (see also Kjer, 1995 and Simmonds, 2004).

To address the problems of direct optimization, Kjer (2004) conducted phylogenetic analyses of insect orders based on 18S sequences aligned manually according to secondary structure. The resulting tree matched traditional insect classification reasonably well. However, Kjer’s (2004) study lacked a sequence of Zoraptera and thus could not address the phylogenetic position of this order. Part of the reason for the exclusion of Zoraptera by Kjer was that he concluded that the 18S of Zoraptera presented in Wheeler et al. (2001) was either contaminated in part by mite (Acari) DNA sequences, because of a homologous unique sequence shared by the Zoraptera and mites, or that if the zorapteran sequence was not a contaminant, it was highly autapomorphic and problematic.

Thus, a more detailed molecular test of the phylogenetic position of Zoraptera is needed. The 18S rDNA gene has played an important role in resolving the deep phylogeny of insects (Campbell et al., 1995; Johnson et al., 2004; Kjer, 2004; Whiting et al., 1997). However, a correct 18S sequence of Zoraptera may not be available to date. In the present study, we amplified and analyzed the 18S rDNA of Zoraptera using samples collected in the USA, Malaysia, and Vietnam. These sequences of Zoraptera plus additional sequences of Blattodea (cockroaches), Phasmatodea (stick insects), Embioptera, and Paraneoptera were aligned with the 18S data provided by Kjer (2004). We address two questions: (1) is the 18S sequence of Zoraptera used by Wheeler et al. (2001) really a contaminant and (2) what is the closest relative of Zoraptera?

2. Materials and methods

We sequenced four species of Zoraptera, Zorotypus hubbardii from the USA, Z. sp.MY1 and Z. sp.MY2 from Malaysia, and Z. sp.VN from Vietnam (the latter three species are currently being described). Methods of total DNA extraction and 18S amplification and sequencing followed Johnson et al. (2004). Primer sets used were Ns1-Ns2a (Barker et al., 2003), 18Sai-18Sbi (Whiting et al., 1997), and Ns5aP2-Ns8P (Johnson et al., 2004). The 18S sequence of Z. snyderi was obtained from GenBank and was only used to check whether the 18S sequence of the species was contaminant or not. The sequence was not used for phylogenetic analyses because only a short piece of the 18S sequence was available for this species. Additional 18S sequences of Blattodea, Phasmatodea, Embioptera, Psocodea, Thysanoptera, and Hemiptera were obtained from GenBank (Appendix A). These sequences were manually aligned to the data matrix provided by Kjer (2004) according to the secondary structure model presented on his website. When we detected a modification of the secondary structure in the new sequences, the secondary structure of the region was estimated using GeneBee (Brodsky et al., 1995). Except for these additional samples, the taxon set was largely unchanged from Kjer (2004). However, we replaced sequences of Ectopsocidae Gen. sp. and Phthirus pubis with Ectopsocus perkinsi and Pedicinus sp., respectively, because only a short piece of 18S sequence was available for the former two species (Appendix A). Unalignable regions were excluded from the analyses, and the exclusion set followed Kjer (2004). Aligned data is available at http://insect3.agr.hokudai.ac.jp/psoco-web/data/.

Preliminary parsimony (MP) and neighbor-joining (NJ) analyses using PAUP* (Swofford, 2002) placed Zoraptera as the sister taxon of Diptera (flies). Diptera is a holometabolus order (insects with pupal stage) whereas Zoraptera is hemimetabolous (insects without pupal stage), so this result seems unlikely. As mentioned below, the basal branch leading to Zoraptera was very long as was the case for Diptera, and thus this result appeared to be an artifact of long-branch attraction (Felsenstein, 1978). Kjer (2004) also suggested that long-branch attraction was problematic for his MP analysis, with Diptera grouping outside of insect, as the sister taxon of Crustacea. In contrast to MP, the Bayesian tree recovered by Kjer (2004) was more reasonable. Likelihood analysis is thought to be less affected by long-branch attraction (Huelsenbeck, 1997; Huelsenbeck and Hillis, 1993). Therefore, we conducted further phylogenetic analyses using maximum likelihood (ML) in PAUP* (Swofford, 2002) and Bayesian ML in MrBayes (Huelsenbeck and Ronquist, 2001). The simplest model for ML analyses was determined by a hierarchic likelihood ratio test using Modeltest (Posada and Crandall, 1998). The GTR + I + G model was selected (unequal base frequencies: A = 0.2496, C = 0.2210, G = 0.2781, T = 0.2513; six substitution categories: A-C = 1.5445, A-G = 3.5713, A-T = 1.5224, C-G = 0.7884, C-T = 5.0195, G-T = 1; gamma distributions shape parameter = 0.6195; proportion of invariant sites = 0.1861). For ML analysis, the NJ tree was used as a starting tree and TBR branch swapping option was selected. For Bayesian analysis, we ran four chains for 10 million generations, and the tree was sampled every 1000 generations. By analyzing the change in likelihood score during the chain using Tracer (Rambaut and Drummond, 2004), we identified a suitable burn-in of 600,000 generations (Fig. 5). Therefore, the first 600 trees were excluded as burn-in, and we computed a 50% majority consensus tree of the remaining 9400
trees to estimate posterior probabilities of branches in the tree Table 1.

For ML bootstrapping, the NJ tree was used as a starting tree, and the NNI branch swapping option was selected with 100 replicates. TBR branch swapping was not performed because it was computationally infeasible. However, as mentioned above, the tree obtained by NJ method was problematic, and preliminary analysis indicated that NNI branch swapping was not sufficient to escape from long-branch attraction caused by a number of problematic taxa: Diplura + Protura (Entognatha), Zoraptera (“Hemimetabola”), and Diptera (Holometabola) (Fig. 1). Therefore, to avoid long-branch attraction of these distantly related orders, monophyly of Insecta, Neoptera, and Holometabola were given as three constraints for ML bootstrapping. Monophyly of those higher level groups have previously received very strong support from morphological and molecular studies and are not controversial (Kjer, 2004; Kristensen, 1975, 1981; Wheeler et al., 2001). No constraints were given for ML and Bayesian tree searches.

3. Results

3.1. Sequences and data evaluation

We successfully amplified and sequenced the 18S rDNA gene from four species of Zoraptera. As mentioned below, the 18S of Zoraptera had large insertions (E23 sensu Wuyts et al., 2000) and modifications of secondary structure. However, all four Zorotypus 18S sequences obtained here, as well as sequences of Z. hubbardi obtained by Vawter (1991) and Z. snyderi obtained by Wheeler et al. (2001), could be readily aligned according to the secondary structure model for insect 18S (Kjer, 2004). As mentioned by Kjer (2004), our preliminary MP and NJ analyses (trees not shown) indicated that the 18S of Z. hubbardi analyzed by Vawter (1991) was not close to the other Zorotypus sequences, but was imbedded within an odonate (dragonflies) clade composed of the genera Leucorrhinia, Sympernum, and Celithemis (Fig. 1). However, the 18S of Z. snyderi analyzed by Wheeler et al. (2001) was very similar to all the Zorotypus sequences obtained in the present study. For example, using MP and NJ analyses based only on the middle segment of 18S available for Z. snyderi (i.e., no missing data), a sister group relationship between Z. snyderi and Z. hubbardi and monophyly of Zoraptera were always recovered with 100% bootstrap support (trees not shown). The sequence AAAAACTTA CCCCCGC, which appeared in the 18S of Z. snyderi near helix 36 and was considered by Kjer (2004) to be evidence of acarine contamination, was also detected in the newly sequenced samples, although the underlined bases were not A, T, and C but A,T, and A in other zorapterans (Fig. 4). As mentioned by Kjer (2004), when this sequence and the neighboring region was subjected to a BLAST search, the 18S of some Arachnida and Annelida were returned as the top three matches (September 23, 2004: Fig. 4). However, when the middle portion of these 18S sequences were aligned to the data set and analyzed by MP and NJ methods (trees not shown), the arachnid and annelid sequences were distant from Zoraptera and placed near the root of the tree.

In addition to this unusual short fragment, other unique characteristics were observed in the 18S sequences of Zoraptera. For example, helix 18 of Zoraptera could not be aligned to the other insect sequences, although the region was otherwise very conservative throughout insects. Analysis of secondary structure indicated that the shape of helix 18 in Zoraptera differed from that of other insects by having a longer stem and a very small hairpin loop (Fig. 3). Modifications of secondary structures were also identified in helix 12. Although the region was well aligned throughout insects including Zoraptera, the estimated secondary structures of helix 12 in Zoraptera were greatly modified from other insects (Fig. 2). Rather long insertions, ranging about 90–160 bp, were observed between helices E23-2 and E23-8 in Zoraptera. Such insertions were not observed in any other holometopteran (orthopteroid insects: i.e., Neoptera excluding Paraneoptera and Holometabola) nor holometabolous orders, but were observed in some species of Paraneoptera (e.g., Pedicinus sp. had an 800 bp insertion). A very large insertion at E23 has also been reported for holometabolous Strepsiptera (twisted wings) by Gillespie et al. (in press), but sequences from this order are not analyzed in our study. Finally, Zoraptera was on a very long branch in the ML tree (Fig. 1), indicating an accelerated substitution rate of the 18S of Zoraptera.

3.2. Phylogenetic analyses

The trees obtained from our data set (Fig. 1) were generally in agreement with the tree obtained by Kjer
Fig. 1. Tree obtained by ML analysis of the 18S rDNA data (−ln L = 32543.23325). The tree is rooted on *Limulus polyphemus* (horseshoe crab). Branch lengths are proportional to ML estimated branch lengths. The numbers associated with the nodes are bootstrap values or posterior probabilities obtained by ML/Bayes analyses. Bootstrap values higher than 50% and/or Bayesian posterior probabilities higher than 90% are indicated. Monophyly of Insecta, Neoptera and Holometabola are constrained for ML bootstrapping (indicated by CON). No constraints are given for tree searches.
254 (2004), which showed high congruence with the traditional classification of insect orders. However, four results from our analyses differed from Kjer’s (2004) tree (outlined below).

(1) Monophyly of Pterygota (winged insects) was recovered by our ML analyses; in contrast, the tree obtained by Kjer (2004) placed wingless apterygota Tricholepidon gertschi (Thysanura: silver fish) as a sister taxon of Odonata (dragon flies). The ML bootstrap value for monophyly of Pterygota was low (<50%), and the present Bayesian consensus placed T. gertschi as a sister of Odonata with 54% posterior probability.

(2) Monophyly of Paraneoptera was not recovered by either ML or Bayesian analyses. Monophyly of Paraneoptera was recovered by Kjer (2004), but with low posterior probabilities (64–87%). The present results indicated a sister group relationship between Holometabola and Hemiptera + Thysanoptera. The posterior probability for non-monophyly of Paraneoptera was 92%, but the ML bootstrap value was lower than 50%.

(3) A close relationships between Holometabola and Paraneoptera and between Orthoptera (grasshoppers) and Paraneoptera + Holometabola were recovered by the present analyses as well as by Kjer (2004). Although the posterior probabilities...
4. Discussion

4.1. 18S of Zoraptera

Kjer (2004) suggested that the 18S sequence of Zorotypus snyderi analyzed by Wheeler et al. (2001) might be an acarine contaminant, at least in part. However, new obtained 18S sequences for four species of Zoraptera show a close match with the 18S of Z. snyderi. MP and NJ analyses based on the smaller fragment available for previously published sequences indicate that the 18S sequences from five zorapteran species compose a monophyletic group (100% bootstrap supports), and they are divided into two well supported clades: Oriental (Z. sp.MY1, Z. sp.MY2 and Z. sp.VN: 100% support) and North American species (Z. snyderi and Z. hubbardi: 100% support). In addition to the close match of the nucleotide sequences, all zorapteran sequences including Z. snyderi have indels at the same position of helix 18 (Fig. 3).

It is very unlikely that extractions from five species extracted in three different laboratories contain the same contaminant (Z. snyderi at lab of Wheeler and colleagues, USA, Z. hubbardi at Illinois Natural History Survey, USA and Z. sp.MY1, Z. sp.MY2 and Z. sp.VN at Hokkaido University, Japan). In addition, one of three base positions (Fig. 4), which was thought to be evidence of acarine contaminant by Kjer (2004), is variable within Zoraptera, and the nucleotide in that position in some zorapterans agrees with that of the other insects. The phylogenetic trees based on these 18S sequences placed Zoraptera within Neoptera, which is reasonable in light of morphological evidence (e.g., Kristensen, 1975, 1981). The intra-ordinal relationships of Zoraptera based on these sequences are also very reasonable, agreeing with morphological observations (the three Oriental species have an ovoid coil on the phallosome, which is lacking in the New World species; Engel and Grimaldi, 2000; New, 1978, 2000; Yoshizawa, pers. obs.). Therefore, we conclude that the zorapteran 18S sequence analyzed by Wheeler et al. (2001) is not a contaminant, and that the fragment near helix 36 in the 18S of Zoraptera is highly variable, which causes convergence with the acarine sequences, a possibility also considered by Kjer (2004).

In addition to the region near helix 36 (Fig. 4), the 18S of Zoraptera shows other unique characteristics, including an accelerated substitution rate (Fig. 1), modification of secondary structures (Figs. 2 and 3), and long insertions. These phenomena are uniquely and uniformly observed in all the 18S sequences of Zoraptera, and thus a correlated origin of these phenomena is likely. A correlation of unique molecular evolutionary trends is detected in the mitochondrial genomes of lice, which includes accelerated substitution rates, modifications of rRNA secondary structures, long insertions/deletions, increased GC contents, and genome rearrangements (Johnson et al., 2003; Page et al., 2002; Shao et al., 2003; Yoshizawa and Johnson, 2003). However, the forces that cause these trends in molecular evolution is less understood.

4.2. Phylogenetic analyses

Kjer (2004) showed that 18S sequences aligned according to a secondary structure model provide reasonable results for the phylogeny of insects. The results obtained by the present analyses are basically in agreement with Kjer (2004), so here we focus only on some novel findings or incongruence between our trees and Kjer (2004).

In the present analyses, a sister group relationship between Zoraptera and Dictyoptera is recovered by both ML and Bayesian methods. Zoraptera + Dictyoptera received 99% posterior probability. Morphologically, Zoraptera and Dictyoptera share a reduced pterothoracic phragmata and dorsolongitudinal muscles (Boudreaux, 1979) and a derived wing venation (Kukalová-Peck and Peck, 1993). Therefore, there is also some morphological support for this placement of Zoraptera.

Additional sequences of 18S for Thysanoptera are newly available for our broader study (Johnson et al., 2004). Morphologically, a close relationship between Thysanoptera and Hemiptera has been suggested (Kristensen, 1975, 1981; Yoshizawa and Saigusa, 2001, 2003). In contrast, the combined data set produced by direct optimization (Wheeler et al., 2001) recovered a sister relationship between Thysanoptera and Psocodea. Wheeler et al. (2001) mentioned that
there were no morphological apomorphies supporting
Thysanoptera + Psocodea, but that the result had
strong molecular support (10 transitions and 4 trans-
versions in 18S). The 18S alignment analyzed here
recovers a sister relationship between Thysanoptera
and Hemiptera, whereas a sister relationship between
Thysanoptera and Psocodea receives only 1% boot-
strap support and 0.8% posterior probability. In addi-
tion, a sister relationship between Thysanoptera and
Psocodea is not recovered by MP analysis. Therefore,
it is evident that 18S has little phylogenetic signal
supporting Thysanoptera + Psocodea, and the present
results are congruent with morphological data.

While several of our results agree with morphological
characters, incongruence between the present results and
morphological characters occurs with respect to Para-
neoptera. Monophyly of Paraneoptera is strongly sup-
ported by morphological autapomorphies such as
modified mouth parts, derived wing base structures, a
single abdominal ganglion, and the absence of cerci
(Kristensen, 1975, 1981; Yoshizawa and Saigusa, 2001,
2003). However, the present results suggest a paraphyl-
etic grade of Paraneoptera (i.e., Hemiptera + Thysa-
noptera sister to Holometabola) with posterior
probability 92%. ML bootstrap support for the non-
monophyly of Paraneoptera is very low (<50%). There
is no morphological evidence published supporting
Holometabola + (Hemiptera + Thysanoptera). There-
fore, further evidence is needed to resolve whether
Paraneoptera is monophyletic.

A close relationship between Orthoptera and
Paraneoptera + Holometabola was recovered by our
analyses as well as by Kjer (2004). However, this rela-
tionship is also unexpected from the morphological point
of view. Although the support for this relationship ob-
tained by Kjer (2004) was very weak (38–76% posterior
probability), the present Bayesian analysis provides
strong support for the clade (100% posterior probabil-
ity). However, ML bootstrap support for the clade is very
low (<50%). As far as we are aware, no one has ever sug-
gested a close relationship between Orthoptera and Para-
neoptera + Holometabola based on morphology.

Remarkable differences between bootstrap support
and posterior probability are frequent at deep and short
nodes as mentioned above. Recent analyses of empirical
and simulated data sets revealed that posterior probabil-
ity is excessively high and can provide erroneous conclu-
sions more often (Cummins et al., 2003; Erixon et al.,
2003; Simmons et al., 2004). Inflation of posterior prob-
ability is known to be especially frequent for short nodes
(Alfaro et al., 2003; Lewis et al., in press). Nodes sup-
porting Condylognatha + Holometabola and Orthop-
tera + Paraneoptera + Holometabola are very short,
and bootstrap supports for these clades are very low
(<50%) compared to high posterior probabilities
(>92%). Therefore, further morphological and molecu-
lar data sets are required to test these clades. ML boot-
strap support for Zoraptera + Dictyoptera is also
relatively low (54%) in comparison to a high posterior
probability (99%). However, the basal node supporting
this sister relationship is not short, and is almost as long
as, or even longer than the basal nodes of very well sup-
ported groups, such as Archaeognatha (91% bs, 100%
pp), Neoptera (constrained for ML bootstrap, 100%
pp), Holometabola (constrained for ML bootstrap,
100% pp) and Mecoptera + Siphonaptera (96% bs and
99% pp). Therefore, a different explanation may be re-
quired for the low ML bootstrap support for Zorapte-
ra + Dictyoptera clade in comparison to a high posterior
probability. One possible explanation is that NNI
branch swapping was used for ML bootstrapping. As
mentioned previously, a neighbor-joining starting tree
for ML estimation was problematic especially for the
placement of Zoraptera, and NNI branch swapping
was not sufficient to escape from long-branch attraction
problems. Because more thorough searches should more
readily converge on the most likely tree, bootstrap sup-
port for some clades should be improved by the use of
TRB branch swapping for ML bootstrapping. However,
TBR is computationally infeasible for the present data
set and processor power available.

The present result is based only on a single gene and
thus represents gene tree. In addition, unusual charac-
teristics of the zorapteran 18S sequences might be prob-
lematic for resolving the placement of this order. Thus,
although the present result provides a very reasonable
phylogenetic tree for insect orders and relatively strong
support for a Zoraptera + Dictyoptera clade, it will be
important to test the present results with additional
morphological and molecular data.

4.3. Concluding comment

The 18S sequences aligned according to secondary
structure model provide very reasonable insect phyloge-
ny. It is especially notable that both Kjer (2004) and pres-
ent analyses provided well resolved and very reasonable
phylogenetic hypotheses among deep hexapod lineage
(e.g., monophyly of Hexapoda), even though previous
analyses of molecular data failed to provide a reasonable
result (Bitsch et al., 2004). Samples of Zoraptera are new-
ly analyzed, and a close relationship between Zoraptera
and Dictyoptera is recovered by molecular data for the
first time. In addition, examination of “molecular mor-
phology” indicate unique evolutionary trends in the
zoraptoran 18S. Such interesting findings have also been
provided for some insect ribosomal RNA by examina-
tions of secondary structure (Ouvrard et al., 2000; Page
et al., 2002; Yoshizawa and Johnson, 2003). Secondary
structure-based manual alignment is valuable for both
phylogenetic analyses and examinations of molecular
morphology (Gillespie et al., in press; Kjer, 2004).
5. Uncited reference

Brodsky et al. (1992).

Acknowledgments

We thank the following individuals: A B. Idris, H. Kojima, D. Morris, S. Nomura, R. Rakitov, and N. Takahashi for providing specimens; G. Ito for information on orthopteroid phylogeny; J. Gillespie for allowing to access his unpublished paper; K. Kjer and an anonymous referee for valuable comments. KY thanks Y. Saito and M. Ohara for allowing the use of molecular facilities and laboratories. KY’s collecting trip to Malaysia was supported by JSPS grant (142550161 to O. Yata). This study was partly supported by JSPS grant (1577052) to K.Y. and NSF grant (DEB-0107891) to K.P.J.

Appendix A.

Additional taxa included in the present study. Species not listed here are from Kjer (2004). Ectopsocus perkinsi [Ectopsocus sp. of Johnson et al. (2004): re-identification based on DNA voucher by KY] and Pedicinus sp. are replacement samples of Ectopsocidae Gen. sp. and Pediculus humanus of Kjer (2004), respectively. Zorotypus snyderi and Drosophila melanogaster were included only for the analysis of 18S secondary structure and/or preliminary phylogenetic inference.

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