De novo formation of an aggregation pheromone precursor by an isoprenyl diphasphate synthase-related terpene synthase in the harlequin bug

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Insects use a diverse array of specialized terpene metabolites as pheromones in intraspecific interactions. In contrast to plants and microbes, which employ enzymes called terpene synthases (TPSs) to synthesize terpene metabolites, limited information from few species is available about the enzymatic mechanisms underlying terpene pheromone biosynthesis in insects. Several stink bugs (Hemiptera: Pentatomidae), among them severe agricultural pests, release 15-carbon sesquiterpenes with a bisabolene skeleton as sex or aggregation pheromones. The harlequin bug, Murgantia histrionica, a specialist pest of crucifers, uses two stereoisomers of 10,11-epoxy-1-bisabolen-3-ol as a male-released aggregation pheromone called murgantiol. We show that MhTPS (MhIDS-1), an enzyme unrelated to plant and microbial TPSs but with similarity to trans-isoprenyl diphasphate synthases (IDSs) of the core terpene biosynthetic pathway, catalyzes the formation of (15R,65S)-1,10-bisaboladien-1-ol (sesquipiperitol) as a terpene intermediate in murgantiol biosynthesis. Sesquipiperitol, a so-far-unknown compound in animals, also occurs in plants, indicating convergent evolution in the biosynthesis of this sesquiterpene. RNAi-mediated knockdown of MhTPS mRNA confirmed the role of MhTPS in murgantiol biosynthesis. MhTPS expression is highly specific to tissues lining the cuticle of the abdominal sternites of mature males. Phylogenetic analysis suggests that MhTPS is derived from a trans-IDS progenitor and diverged from bona fide trans-IDS proteins including MhIDS-2, which functions as an (E,E)-farnesyl diphasphate (FP) synthase. Structure-guided mutagenesis revealed several residues critical to MhTPS and MhFPSS activity. The emergence of an IDS-like protein with TPS activity in M. histrionica demonstrates that de novo terpene biosynthesis evolved in the Hemiptera in an adaptation for intraspecific communication.

Hemiptera | Pentatomidae | harlequin bug | aggregation pheromone | terpene synthase

Terpenes play important roles in mediating chemical interactions of microbes, plants, and animals (1–4). In particular, volatile terpene compounds function as long- and short-distance semiochemicals in organismal interactions (5–10). Insects are well known to release volatile terpenes as interspecific signals in chemical defense or as alarm, aggregation, and sex pheromones in intraspecific communication (11–16). Despite these important functions, little is yet known about the formation of terpene specialized metabolites in insects.

In bacteria, fungi, and plants, volatile terpenes with 10-carbon (monoterpenes) and 15-carbon (sesquiterpenes) side chains are produced from isoprenyl diposphates, geranyl diposphates (GPP) and farnesyldipholphate (FPP), respectively, by enzymes called terpene synthases (TPSs) (17–23). As central intermediates in the core terpene metabolism, GPP and trans-or cis-FPP are assembled by trans-or cis-isoprenyl diposphates synthases (IDSs) in condensations of the 5-carbon unit dimethylallyl diphotphate (DMAPP) with one or two molecules of its isomer isopentenyldiphosphate (IDP). Despite their low sequence similarity, plant- and microbial-type TPS and IDSs are from core metabolism to specialized TPS function. Although plants employ a core terpene metabolism that supports juvenile hormone biosynthesis and has been associated with pheromone production (27, 28), to date no plant- or microbial-type TPS genes have been reported from insect genomes. The absence of these genes has led to the general presumption of the biosynthesis of terpenes in hemipteran insects. Knowledge of pheromone biosynthesis in stink bugs may lead to the development of new controls of these pests.

Significance

Many insects release volatile terpenes for chemical communication. However, the biosynthetic origin and evolution of these bioactive chemicals are mostly unknown. We show that the harlequin bug, Murgantia histrionica, a stink bug pest (Hemiptera) of crucifer crops, produces a terpene aggregation pheromone by an enzyme that is unrelated to microbial and plant terpene synthases. M. histrionica terpene synthase activity is highly sex- and tissue-specific and makes a sesquiterpene alcohol, so far unknown in animals, as pheromone precursor. The enzyme evolved from ancestral isoprenyl diphasphate synthases and provides new evidence for de novo biosynthesis of terpenes in hemipteran insects. Knowledge of pheromone biosynthesis in stink bugs may lead to the development of new controls of these pests.


The authors declare no conflict of interest.

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Data deposition: Sequences reported in this paper have been deposited in the GenBank database (accession nos. MG662378.1 for MhTPS and MG662379.1 for MhFPSS).

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Functional characterization of cytochrome P450 reductase. α is shown involving and products were analyzed by GC-MS. (by 23 PNAS β | E8635 in the presence of Mg vol. 115 no. 37 (by sesquipiperitol 39). Among α is transcribed at high levels in males, with a

IDS Phyllotreta striolata 31 25 quiterpene aggr 4 42) R?

Mh IDS-1 transcriptome, two transcripts encode TPSs, suggesting an evolutionary origin of these enzymes from IDS progenitors. Whether insects other than beetles, especially those of earlier evolutionary origin, biosynthesize volatile terpenes de novo is unknown.

Here, we show that within the Hemiptera, stink bugs (Pentatomidae) use IDS-like proteins in pheromone biosynthesis.

Several pentatomids release sesqui-terpene aggregation/sex pheromones with a bisabolen carbon skeleton (32–39). Among these, the harlequin bug Murganta histrionica, a crucifer specialist, produces a mixture of (35,6S,7R,10S) and (35,6S,7R,10R) stereoisomers of 10,11-epoxy-1-bisabolen-3-ol as a male-released aggregation pheromone dubbed murgantiol (40–42) 1 (Fig. 1).

We demonstrate that an enzyme with homology to IDS proteins (MhTPS) converts (E,E)-FPP 2 to sesquipiperitol 3 as the presumed stereospecific alcohol precursor of murgantiol (Fig. 1), while a second trans-IDS protein (MhFPPS) catalyzes the formation of the MhTPS substrate (E,E)-FPP from IPP and DMAPP. MhTPS is transcribed at high levels in males, with a predominant localization in the subcuticular tissue of the abdominal sternites. A significant role of MhTPS in pheromone biosynthesis was confirmed by RNAi-mediated knockdown of MhTPS mRNA in M. histrionica males leading to reduced emission of murgantiol. Phylogenetic comparison of the M. histrionica enzymes with other insect IDS proteins suggests that in the Hemiptera proteins with TPS activity evolved from a

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<td>1.5 1.0 0.5 0.0</td>
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Fig. 1. Functional characterization of MhIDS-1 (MhTPS) from M. histrionica. Recombinant MhIDS-1 protein was expressed in E. coli and Sf9 cells and partially purified by affinity chromatography. Proteins were incubated with (E,E)-FPP 2 in the presence of Mg^{++} and products were analyzed by GC-MS. (A) GC-MS chromatograms of enzyme products. Sf9 control cells express a housefly cytochrome P450 reductase. *, nonenzyme product; 1, (1S,6S,7R)-sesquipiperitol; cu, γ-curcumene; far, (2E,6E)-farnesol; sesq, β-sesquiphellandrene; zi, α-zingiberene. (B) Mass spectra of enzymatic products with (1S,6S,7R)-sesquipiperitol standard 3. (C) Formation of sesquipiperitol 3 by M. histrionica TPS activity (boxed). A putative single or two-step pathway to murgantiol 1 is shown involving isomerization and epoxidation reactions. EV, empty vector; MdCPR, Musca domestica cytochrome P450 reductase.
microbial- and plant-type TPSs, insect TPS enzymes evolved more recently from IDS proteins and this event has occurred in multiple insect lineages including hemipteran insects.

**Results**

**Identification and Functional Characterization of IDS-Like Genes in *M. histronica***. We hypothesized that in the murgantiol biosynthetic pathway of *M. histronica* an enzyme with terpene synthase activity synthesizes a bisabolene-type hydrocarbon or alcohol terpene precursor, which presumably undergoes further modification(s) including epoxidation to form the pheromone end products (Fig. 1). To identify genes involved in the formation of the murgantiol pheromone precursor, we queried a transcriptome dataset from different sexes and developmental stages of *M. histronica* (43) with plant and microbial TPS sequences and trans-IDS-type sequences of *I. pini* and *P. striolata* (GECQ01420512.1; MG662378.1) mRNA levels in *M. histrionica* (SI Appendix, Fig. S1). Truncation of *MhTPS* protein (SI Appendix, Fig. S1). Truncation of *MhTPS* resulted in the loss of enzymatic activity.

Kinetic analysis of *MhTPS* with (E,E)-FPP as the substrate revealed an apparent *K_m* value of 4.0 ± 0.7 μM and a *V_max* of 675.3 ± 53.7 pmol/mg. The *k_cat* value was 0.03 ± 0.003 s⁻¹ and *k_cat/K_m* was 7.5 ± 0.5 × 10⁻⁶ s⁻¹·mM⁻¹. *K_m*, *k_cat*, and *k_cat/K_m* values of *MhTPS* were similar to those of plant sesqui-TPS enzymes such as (E)-β-caryophyllene synthase from *Artemisia annua* (47).

Recombinant *MhTPS* did not produce zingiberenol 4 as a possible precursor of murgantiol. We tested whether changes in cofactor type and concentration or modifications of pH conditions would alter the enzymatic product profile and activity. No change in product specificity was observed when Mg²⁺ was substituted with Co²⁺, although this metal ion has been found to modify product specificity of a GPP/FPP synthase in the leaf beetle *Phaedon interpunctella* (P-ID1-1) (48). Activity increased by approximately twofold between 0.1 and 10 mM Mg²⁺, while the opposite was the case for Co²⁺ (SI Appendix, Fig. S3D). Activity was highest at pH 7 (SI Appendix, Fig. S3E) and no change in product outcome was found under lower or higher pH conditions.

In contrast to *MhTPS*, partially purified recombinant *MhIDS-2* protein did not show any TPS activity when assayed with different isomers of FPP or GPP as substrates. Instead, *MhIDS-2* produced (E,E)-FPP from IPP and DMAPP, indicating that this protein functions as a trans-IDS (SI Appendix, Fig. S4). The enzyme was unable to synthesize any other isomer of FPP, which suggests that (E,E)-FPP is the main isomeric form produced by *M. histronica* (SI Appendix, Fig. S4). Removal of a putative transit peptide (M₁-S₁₅₅) (SI Appendix, Fig. S1) led to a substantially higher production of (E,E)-FPP by the truncated *MhIDS-2* protein (SI Appendix, Fig. S4). Because of its FPPS activity, we designate *MhIDS-2* hereinafter as *MhFPPS*.

**Absolute Configuration of Sesquipiperitol**. To further support the role of sesquipiperitol as a precursor of murgantiol, we determined the stereospecific configuration of sesquipiperitol at C-6 and C-7, which we predicted to be the same as that of murgantiol (SI Appendix, SI Results, SI Materials and Methods, and Figs. S2 and S5). Oxidation of enzymatically produced sesquipiperitol to sesquipiperitone 5 concluded a relative 65,7R or 6R,7S configuration (SI Appendix, Fig. S2). Further conversion of sesquipiperitol to bisabolane 7 determined the configuration at C-7 to be (R) (SI Appendix, Fig. S5A). This result unambiguously confirmed a 65,7R configuration of sesquipiperitol 3, which is identical to the C-6, C-7 configuration of murgantiol 1. Chiral GC analysis and 2D NMR recordings determined an (S) configuration at C-1 (SI Appendix, SI Results, SI Materials and Methods, and Fig. S5 B and C).

**Sex- and Tissue-Specific Expression of *MhTPS***. We compared transcript abundance of *MhTPS* and *MhFPPS* between different sexes, developmental stages, and tissues by RT-PCR and qRT-PCR analyses. In agreement with mRNA levels determined by transcriptome analysis (43), *MhTPS* transcript levels were significantly higher (~37-fold) in mature males than in mature and immature females (Fig. 2A and SI Appendix, Fig. S6A). *MhTPS* transcript abundance in mature males was also significantly higher than that of nymphs and immature males, which do not emit murgantiol (Fig. 2A). As expected from transcriptome data (43), *MhFPPS* transcript levels were comparatively higher than those of *MhTPS*.

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in mature females (SI Appendix, Fig. S64). Tissue-specific transcripts of MhTPS localized to the tissue lining the cuticle of the abdominal sternites of mature males, while 200- to 2,000-fold lower transcript levels of MhTPS were observed in the thorax, fat body, and midgut (Fig. 2B and SI Appendix, Fig. S6B).

**Sesquipiperitol Synthase Activity in M. histrionica Protein Extracts.** To further confirm that the enzymatic activity for the formation of sesquipiperitol is present in protein lysates of M. histrionica, we extracted protein from the cuticle-specic tissue of mature male bugs and incubated the lysate with (E,E)-FPP. GC-MS analysis of hexane extracts obtained from the aqueous phase of the assay demonstrated the specific formation of sesquipiperitol in the presence of (E,E)-FPP (Fig. 3A). By contrast, protein extracts from cuticle-associated tissue of mature females did not produce sesquipiperitol, confirming the male-specific biosynthesis of this compound (Fig. 3A). Sesquipiperitol was not synthesized in extracts of the male head and thorax, fat body, or gut tissue when incubated with (E,E)-FPP, which further supports the tissue specificity of this enzymatic reaction (Fig. 3B). We did not find further conversion of sesquipiperitol to the putative downstream intermediate zingiberenol or to murgantiol or other products, suggesting that possible downstream enzymatic activities were not supported or potentially inhibited under our selected extraction and assay conditions. Alternatively, compound conversion might have been hampered by the loss of tissue integrity and compartmentalization.

**Verification of in Vivo MhTPS Function in Murgantiol Biosynthesis.** To verify the in vivo role of MhTPS in murgantiol biosynthesis, we injected males 3–5 d posteclosion with MhTPS-derived sequence-specific dsRNA. Transcript abundance was significantly reduced (~35- to 40-fold) 13–15 d postinjection compared with males injected with lacZ or Ringer’s solution, or non-injected males (P < 0.0001) (Fig. 4A). Pheromone analysis of males at the same time postinjection showed significantly lower emission (approximately sevenfold) of murgantiol in MhTPS dsRNA males than control males (Fig. 4B), confirming a substantial role of MhTPS in murgantiol biosynthesis.

**Phylogenetic Analysis of M. histrionica TPS and FPPS and Determination of Residues with Function in TPS and IDS Catalytic Activity.** A phylogenetic analysis based on maximum likelihood was performed to assess the evolutionary relationship of M. histrionica TPS and FPPS with other insect IDS and TPS enzymes (Fig. 5). The dataset included trans-IDS proteins from Coleoptera, Lepidoptera, and Hemiptera with known GPPS/FPPS or FPPS activities, the GPPS/TPS from I. pini, and the recently characterized IDS and TPS enzymes from P. striolata. To compare the relationship of the M. histrionica enzymes with similar enzymes in the Pentatomidae, we retrieved IDS-like sequences from the brown marmorated stink bug Halyomorpha halys based on publicly available transcriptome datasets of this insect (49). For H. halys two IDS-like sequences were identified, of which the IDS-1 sequence clusters with M. histrionica TPS (MG662378.1) (38.3% sequence identity), suggesting that H. halys IDS-1 might be a functional TPS enzyme. M. histrionica TPS and H. halys IDS-1 form a clade separated from I. pini GPPS/TPS, a cis-IDS (FPFP) and the TPS clade of P. striolata (Fig. 5). M. histrionica FPPS (MG662379.1) and the more closely related H. halys IDS-2 protein are positioned in a larger clade of insect proteins with GTA/IDS activities (SI Appendix, Fig. S7).

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**Fig. 2.** Relative transcript abundance of MhTPS in M. histrionica determined by qRT-PCR. (A) MhTPS transcript abundance at different developmental stages and in different sexes. Young is 3-d adult; mature is 15-d adult. (n = 3, ±SD). (B) MhTPS transcript abundance in different tissues of adult males. Ab, Cuticle, tissue lining the abdominal cuticle; Ab, ST, Abdominal soft tissue minus midgut. (n = 3, ±SD). Gene expression was normalized against 18S RNA. Transcript abundance is shown relative to that in nymphs (A) or the male head tissue (B) (set to 1). Significance was determined using one-way ANOVA and means grouped by Tukey’s honestly significant difference test.

**Fig. 3.** Terpene synthase activity in crude protein extracts of M. histrionica by sex (A) and tissue (B). (A) Tissue of the abdominal cuticle of mature male or female M. histrionica was homogenized in assay buffer and assayed with 100 μM (E,E)-FPP. (B) Different tissues from mature male M. histrionica were homogenized in assay buffer and assayed with 50 μM (E,E)-FPP. Volatile products were extracted with an equal volume of hexane and analyzed with GC-MS. 3, sesquipiperitol; far, (E,E)-farnesol.
Sequence comparisons between insect IDS and IDS-derived TPS enzymes show that both types of proteins contain a conserved first and second aspartate-rich motif (FARM and SARM, respectively) (SI Appendix, Fig. S1). These motifs are required for the coordinated binding of Mg\(^{2+}\) ions with the allylic substrate to initiate catalysis through carbocation formation and rearrangement (24–26). While residue substitutions occur in the SARM of TPSs from I. pini and P. striolata, no such substitutions are present in the TPSs of stink bugs (SI Appendix, Fig. S1). Notably, in comparison with bona fide trans-IDS proteins, the TPS proteins substitute aromatic with nonaromatic amino acid residues at positions 4 and 5 upstream of the FARM. (SI Appendix, Fig. S1, box M1). To determine whether these substitutions affect the orientation of (E,E)-FPP at the active site of the enzyme, we positioned (E,E)-FPP in the active site of crystallized Gallus gallus FPPS and an M. histrionica TPS homology model. This comparative positioning via ligand docking indicated that the amino acid changes upstream of the FARM (GgFPPS F112, F113 – MhTPS M118, S119) likely cause a different orientation of the prenyl side chain of the FPP substrate (Fig. 6A). Accordingly, M118F and S119F substitutions through site-directed mutagenesis resulted in the loss of TPS activity of the recombinant MhTPS protein (Fig. 6B). By contrast, the reciprocal substitutions F95M and F96S in a truncated MhFPPS protein did not abolish IDS activity but converted the enzyme into a 20-carbon geranylgeranyl diphosphate (GGPP) synthase (SI Appendix, Fig. S8B). In comparison with (E,E)-FPP, docking of DMAPP in both MhTPS and GgFPPS models did not result in different positions of this allylic diphosphate (SI Appendix, Fig. S94). However, DmFPPS did not have substantial inhibitory effects on the MhTPS-catalyzed reaction of (E,E)-FPP to sesquiperipetal, indicating a limited affinity of the enzyme for this allylic diphosphate. (SI Appendix, Fig. S9B).

To further define determinants of TPS or IDS catalytic specificity, we identified amino acids that are exclusively conserved in TPS or IDS sequences (SI Appendix, Fig. S1). Most of these residues were found on helices and loops outside of the predicted active side cavity of the MhTPS model, making their impact on catalysis less predictable. Among residues of further interest were S\(_{177}\)DAW\(_{80}\) in MhTPS because these amino acids replace a highly conserved KKR motif in MhFPPS and other IDS proteins (SI Appendix, Fig. S1, box M2) with W80 positioned at the bottom of the active-site cavity (SI Appendix, Fig. S9C). Reciprocal substitution of these residues in MhTPS and MhFPPS abolished both TPS and IDS activities, indicating their critical functions in both enzymes (SI Appendix, Fig. S8A and B). Loss of activity was also observed when residues K\(_{135}\)K\(_{137}\) in MhTPS (K135 is a conserved amino acid in insect TPSs) were substituted with the corresponding R\(_{170}\)P\(_{172}\) sequence of full-length MhFPPS, which contains a Cys residue highly conserved in insect IDS proteins (SI Appendix, Fig. S1, box M3). The same situation was found for the reverse mutation in MhFPPS (SI Appendix, Figs. S1, S8 A and B, and S9D), again indicating critical functions of these residues in both proteins.

**Discussion**

*M. histrionica* TPS Functions as a Sesquiterpene Alcohol Synthase. We found that the TPS activity associated with the recombinant MhTPS enzyme and with crude lysates of male *M. histrionica* stereospecifically convert (E,E)-FPP to the (13,63,7R) isomer of sesquipiperitol 3. The synthesis of sesquipiperitol most likely proceeds by formation of a bisabolyl cation followed by a hydride shift and subsequent quenching of the carbocation by water (SI Appendix, Fig. S10). The 6,5,7R configuration of sesquipiperitol corroborates its function as an intermediate in the formation of

![Figure 4](https://example.com/fig4.png)

**Fig. 4.** Effects of RNA interference on *M. histrionica* MhTPS expression and murganitol emission. (A) MhTPS transcript abundance in adult males 12 d postinjection normalized to 18S rRNA. LacZ was used as a negative control (n = 3, ±SEM). (B) Amount of murganitol detected in headspace collections 10–12 d postinjection (n = 9, ±SEM). Bars in each figure with the same letter are not different according to a generalized log-linear model (α = 0.05). (A) \(\chi^2 = 63.13, P < 0.0001\). (B) \(\chi^2 = 4883.3, P < 0.0001\).

![Figure 5](https://example.com/fig5.png)

**Fig. 5.** Majority-rule phylogram inferred from maximum-likelihood analysis of FPPS and TPS enzymes of *M. histrionica* (bold) with related IDS proteins of *H. halys*, TPS and IDS proteins of *P. striolata*, GPPS/TPS of *I. pini*, and other insect trans-(GPPS)/FPPS proteins. The maximum likelihood method was based on the Le and Gascuel (59) (LG G+) model. Bootstrap values (n = 1,000 replicates) are shown next to each node. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. Proteins with known or putative TPS activity are highlighted by the gray box. The tree was rooted using a GPPS from *D. melanogaster*. Full species names are listed in *SI Appendix, Fig. S7*. 

**Note:** Figure 5 has a scale bar indicating the number of substitutions per site.
the murgantiol stereoisomers. An RNAi-based approach further confirmed the role of the MhTPS-catalyzed reaction in murgantiol biosynthesis. The 10,11-epoxy-1-bisabolene-3-ol stereoisomers also constitute pheromone components of the brown marmorated stink bug H. halys (32), suggesting that the IDS-1 gene of H. halys has a function similar to that of MhTPS. Moreover, related TPS activities presumably operate in other pentatomids to make bisabolene-type sex pheromones or their corresponding precursors, such as isomers of zingiberone in the rice stalk stink bug, Tribolium limbativentris, and the rice stink bug Oebalus p副局长 (34, 37); the sesquiterpene alpha-curcumene; zingiberene, and beta-sesquiphellandrene in the red-shouldered stink bug Thyanta pallidovirens (38); and (Z)-α-bisabolene epoxides in the Southern green stink bug Nezara viridula (33, 50). Until our finding of sesquiperisol as an enzymatic product in M. histrionica, this terpenoid and its biosynthesis had not been reported in animals. The occurrence of sesquiperisol as a natural product in different plant species (44–46) suggests convergent biosynthetic evolution of this compound by both plant- and insect-derived TPS proteins. Since several terpenes are used as identical semiochemicals by both plants and insects, it can be assumed that similar processes of convergent evolution have occurred in the synthesis of these compounds.

**Terpene Formation in M. histrionica Is Highly Sex- and Tissue-Specific.** According to the sex-specific release of murgantiol, we found that MhTPS lost activity when nonaromatic amino acids at positions 4 and 5 upstream of the FARM motif were substituted with aromatic amino acids of equivalent position in insect IDSs. This effect was likely caused by a modified position of the FPP substrate. Molecular docking of (E,E)-FPP in the active-site cavity of an MhTPS homology model showed an extension of the FPP prenyl side chain into the cavity (Fig. 6a), which appears to be critical for facilitating a subsequent cyclization and formation of the terpene product. For IDS enzymes, substitutions of aromatic and nonaromatic amino acids upstream of the FARM determine the chain length of the enzymatic product: nonaromatic residues facilitate the synthesis of products with extended prenyl chains in long-chain trans-IDS enzymes (≥C20) (54). Indeed, substitution of the two Phe residues with Met and Ser upstream of the FARM in MhFPPS resulted in a change from FPPS to GGPPS activity (SI Appendix, Fig. S8B). This change in IDS product specificity correlates with the presence of nonaromatic residues in other insect GGPP synthases (55).

**IDS-Type Terpene Synthases Evolved in the Hemiptera.** The phylogenetic analysis indicates that pentatomid and coleopteran TPSs are derived from a trans-IDS progenitor that diverged early from true trans-IDS enzymes. The separate clustering of pentatomid TPSs from P. striolata and I. pini TPSs (Fig. 5 and SI Appendix, Fig. S7) suggests that proteins with TPS activity might have emerged independently in these and other insect taxa. However, phylogenetic comparisons with additional TPSs from other insect lineages will be necessary to further support this hypothesis.

In our approach to identify residues that discriminate between TPS or IDS catalytic activity, we found that MhTPS lost activity when nonaromatic amino acids at positions 4 and 5 upstream of the FARM motif were substituted with aromatic amino acids of equivalent position in insect IDSs. This effect was likely caused by a modified position of the FPP substrate. Molecular docking of (E,E)-FPP in the active-site cavity of an MhTPS homology model showed an extension of the FPP prenyl side chain into the cavity (Fig. 6A), which appears to be critical for facilitating a subsequent cyclization and formation of the terpene product. For IDS enzymes, substitutions of aromatic and nonaromatic amino acids upstream of the FARM determine the chain length of the enzymatic product: nonaromatic residues facilitate the synthesis of products with extended prenyl chains in long-chain trans-IDS enzymes (≥C20) (54). Indeed, substitution of the two Phe residues with Met and Ser upstream of the FARM in MhFPPS resulted in a change from FPPS to GGPPS activity (SI Appendix, Fig. S8B). This change in IDS product specificity correlates with the presence of nonaromatic residues in other insect GGPP synthases (55).

**Loss of MhTPS Activity was Also Observed when Residues S29–D48 were Substituted with KKxR, a Highly Conserved Motif in Insect IDS Proteins.** The charged side chain of the introduced Arg residue facing toward the hydrocarbon moiety of IPP (56). Therefore, the loss of MhTPS activity by reversely substituting the KKxR motif with the SDAW sequence is most likely due to improper binding of the IPP substrate. Reciprocal substitutions of the highly conserved Lys and Cys residues downstream of the FARM of TPS or IDS proteins, respectively, also caused a loss of activity in both mutants. Although, according to our model, these residues are positioned on a loop without immediate proximity to the docked substrate (SI Appendix, Fig. S9D), they may be involved in substrate binding and/or in the closure of the active site upon substrate binding, as has been shown, for example, for loop residues on the β-domain of TPS enzymes (57).

In summary, we were able to identify residues with critical function in TPS and IDS activity. Further structural analysis, ideally via protein crystallization and combinatorial mutations paired with the identification of epistatic residue networks (58), will be necessary to fully identify the residues controlling the transition from insect IDS to TPS enzyme activity. This evolutionary transition likely required a combination of residue substitutions to change substrate affinities and specificities for

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**Fig. 6.** Functional analysis of amino acid residues upstream of the first aspartate-rich motif of MhTPS. (A) Position of (E,E)-FPP in the active site of G. gallus FPPS (green) and the M. histrionica TPS homology model (blue). Residues used for site-directed mutagenesis are illustrated. (B) TPS activity of the MhTPS wild type and protein variant with residue substitutions at positions 4 and 5 upstream of the FARM motif. (15,65,77)-R-sesquiperisol; far, (E,E)-farnesol.
DMAPP and IPP and gain a cyclization function following the binding of (E,E)-FPP as a single allylic substrate.

Materials and Methods
Two putative trans-IDS-like genes (MhIDS-1, MhIDS-2) identified in the transcriptome of M. histrionica were amplified as full-length cDNAs from RNA extracted from adult males and females in the prokaryotic expression vector pEXPS-N/TOPO, generating an N-terminal histidine tag. A truncated version of MhIDS-2 lacking a putative N-terminal transit peptide was cloned in the same vector, and a truncated version of MhIDS-1 was synthesized and cloned in the pET19b expression vector. For expression in insect cells, the full-length MhIDS-1 cDNA was cloned without an N-terminal His-tag into the BaculoDirect vector. Recombinant partially purified MhIDS-1 and MhIDS-2 proteins expressed in E. coli and lysates of Sf9 cells expressing MhIDS-1 were tested for TPS and IDS activities and the reaction products were analyzed by GC-MS and liquid chromatography tandem MS, respectively. Identification and determination of the stereospecific configuration of the main enzymatic product of MhIDS-1 (MhTps), sesquipediol, were performed by systematics and chemical transformations in combination with chiral GC and NMR analysis. Kinetic properties of MhTps were examined in assays using [1-3H](E,E)-FPP as substrate. Developmental, sex- and tissue-specific expression of the MhTPS transcript or MhTPS activity were determined by qRT-PCR and TPS activity assays of crude lysates of different developmental stages. MhTPS involvement in pheromone production was verified by injecting young males of M. histrionica with dsRNA of MhTPS or lacZ (control) followed by qRT-PCR and pheromone analysis in the headspace. Phylogenetic analysis was performed using maximum likelihood. MhTPS and MhFPFPs protein variants were generated by site-directed mutagenesis, expressed in E. coli, and analyzed for TPS and FPPS activity. Further details on organisms, experimental and analytical procedures, data analysis, phylogenetic analysis, protein homology modeling and substrate docking are provided in an SI Appendix, SI Materials and Methods.

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