Involvement of Cis-Acting Elements in Molecular Regulation of JH-Mediated Vitellogenin Gene 2 of Female Periplaneta americana

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Vitellogenins (Vgs) are yolk protein precursors that are regulated by juvenile hormone (JH) and/or 20-hydroxyecdysone (20E) in insects. JH acts as the principal gonadotropin that stimulates vitellogenesis in hemimetabolous insects. In this study, we cloned and characterized the Periplaneta americana Vitellogenin 2 (Vg2) promoter. Multiple sites for putative transcription factor binding were predicted for the 1,804 bp Vg2 promoter region, such as the Broad-Complex, ecdysone response element (EcRE), GATA, Hairy, JH response element (JHRE), and Methoprene (Met)-binding motif, among others. Luciferase reporter assay has identified that construct −177 bp is enough to support JH III induction but not 20E suppression. This 38 bp region (from −177 to −139 bp) contains two conserved response element half-sites separated by 2 nucleotides spacer (DR2) and is designated as Vg2RE (−168GAGTCACCGAGTCGCCGCTG−149). Mutation assay and luciferase assay data using mutated constructs verified the crucial role of G residues in Vg2RE for binding the isolated fat body nuclear protein. In Sf9 cells, a luciferase reporter placed under the control of a minimal promoter containing Vg2RE was induced by JH III in a dose- and time-dependent manner. Nuclear proteins isolated from previtellogenic female fat body cells bound to Vg2RE, and this binding was outcompeted by a 50-fold excess of cold Drosophila melanogaster DR4 and Galleria mellonella JH binding protein response elements (Chorion factor-I/Ultraspireacle). Affinity pull-down experiment with nuclear extracts of previtellogenic female fat body, using 31-bp probe Vg2RE as bait, yielded a 71 kDa candidate nuclear protein that may mediate the regulatory action of the JH III.

Keywords: vitellogenesis, juvenile hormone, 20-hydroxyecdysone, cis-regulatory elements, hemimetabola, periplaneta, transcriptional regulation
INTRODUCTION

The American cockroach, Periplaneta americana, thrives in temperate climate bands across the globe. Cockroaches live in houses, groceries, stores, and hospitals causing disease in humans, such as allergic reactions that include lung and skin reactions. They are also potential mechanical vectors for several pathogens, such as Clostridium perfringens, Pseudomonas aeruginosa, and Salmonella enterica serotype Bredeney causing anthrax, cholera, and diphtheria, respectively (Baumholtz et al., 1997; Atiokeng Tatang et al., 2017). Their widespread occurrence is due to a high reproductive capacity and rich nutrients supplement to the future developed embryos by female cockroaches. Hence, the synthesis of vitellogenin (Vg), the major yolk protein precursors, in the fat body culminates the female reproductive success, and the underlying mechanisms have attracted the substantial interest of researchers. However, so far, few studies have investigated the hormone-mediated transcriptional regulation of Vg in hemimetabolous insects (Elgendy et al., 2019; Wu et al., 2021).

Juvenile hormone (JH), the insect-specific sesquiterpenoid hormone, and the molting hormone, 20-hydroxyecdysone (20E), are the two major hormones that govern the reproduction of female insects (Liu et al., 2018; Li et al., 2019). JH is the dominant controlling hormone in most hemimetabolous insects, such as Orthoptera (Locusta migratoria) (Glinka and Wyatt, 1996; Song et al., 2014; Luo et al., 2017), Blattodea (Blatella germanica, Diploptera punctate, and P. americana) (Comas et al., 1999, 2001; Marchal et al., 2014; Kamruzzaman et al., 2020), and Hemiptera (Nilaparvata lugens, Pyrrhocoris apterus, and Cimex lectularius) (Smykal et al., 2014; Gujar and Palli, 2016; Lu et al., 2016a,b). In holometabolous insects, such as Tribolium castaneum, although 20E is involved in reproduction, JH is still the primary hormone governing reproduction (Parthasarathy et al., 2010). Vitellogenesis in many lepidopteran species occurs prior to adult emergence, where 20E dominates (Ramaswamy et al., 1997). The 20E is the leading regulator in dipterans, such as mosquitoes and flies, but JH still plays a key role in 20E-mediated events (Raikhel et al., 2005).

Extensive studies have indicated the involvement of the JH receptor Methoprene-tolerant (Met) in the antitumorparich JH signaling. Met has a conserved role in JH-controlled processes in both hemimetabolous and holometabolous insects, such as oogenesis, oviposition, and regulation of Vg mRNA levels, fecundity reduction, mating regulation, sex pheromone production, and regulation of lipid metabolism (Minakuchi et al., 2008, 2009; Parthasarathy et al., 2008, 2010; Konopova et al., 2011; Lozano and Bellès, 2011; Kayukawa et al., 2012; Zou et al., 2013; Marchal et al., 2014). In contrast, there are very few reports on the role of Met, and other JH binding proteins, such as Hairy, CF-II (Chorion factor 2), FoxO (fork head transcription factor), and Br-CZ (Broad-Complex) during reproductive events in the insects (Mao et al., 2020; Tsang et al., 2020). For example, Li et al. (2018) have determined that insulin/IGF signaling (IIS) and target of rapamycin (TOR) indirectly promote P. americana vitellogenesis through JH-Met/Kr-h1 Krüppel homolog 1 that form a positive feedback regulatory loop via the doublesex (Dsx).

In many adult insects, such as T. castaneum, L. migratoria, Helicoverpa armigera, P. apterus, N. lugens, Bactrocera dorsalis, and Sogatella furcifera, JH requires the Met/Taiman (Tai) complex to achieve its previtellogenic and vitellogenic regulations on the fat body competency and Vg synthesis (Parthasarathy et al., 2010; Zou et al., 2013; Guo et al., 2014; Smykal et al., 2014; Song et al., 2014; Lin et al., 2015; Gujar and Palli, 2016; Wang et al., 2017; Ma et al., 2018; Yue et al., 2018; Hu et al., 2019). L. migratoria, with a panoistic ovary where terminal oocytes are ovulated together, has been a longstanding model system for studying JH-dependent female reproduction (Wyatt and Davey, 1996; Roy et al., 2018). Detection of Met/Tai as the nuclear JH receptor helps to understand the regulation of JH-induced transcription, controlling insect metamorphosis, and reproduction (Gijbels et al., 2019).

The molecular mechanisms of JH regulation in insect vitellogenesis and oogenesis are still obscure. The fact that Vg is directed by an endogenous cis-acting promoter has been investigated in Aedes aegypti and Anopheles stephensi through a transgenic approach (Nirmala et al., 2006; Kokoza and Raikhel, 2011). However, how the Vg cis-regulatory elements regulate gene expression in hemimetabolous insects such as P. americana is still unclear. Elucidating the Vg cis-regulatory elements in P. americana may, thus, contribute to further understanding the physiological roles of Vg and the advancement of genetic manipulation technologies, e.g., RNA interference (RNAi)-based population management via RNAi-aided knock-down of Vg isoforms and their regulatory gene(s), suppressing egg formation and embryonic development of this pest.

In the previous studies, in P. americana, we identified a direct repeat separated by a 2-nucleotide spacer designated, VgJHRE, that is similar to the Drosophila ecdysone response element (EcRE) direct repeat 4 (DR4) (Elgendy et al., 2019). Moreover, nuclear proteins were successfully bound to VgJHRE which suggested that the P. americana Vg1 (Pavg1) is hormonally regulated by transcription factors interacting with the upstream regulatory elements found in the Vg1 promoter region, such as other insect Vg genes (Chen et al., 2004; Zhu et al., 2007; Lin et al., 2017; Elgendy et al., 2019).

The present study aimed to clarify the molecular regulatory mechanism of Periplaneta americana vitellogenin gene 2 (Vg2) by JH III. A cloned 1,804 bp promoter region of Vg2 from P. americana is characterized by several putative cis-regulatory elements. The luciferase reporter system identified a 204 bp promoter region that will support JH III induction and 20E suppression. This promoter region harbors a cis-acting element named Vg2RE. The non-vitellogenic female nuclear protein extract (NPE) contains a 71 kDa protein that specifically binds to the newly identified Vg2 cis-acting elements, Vg2RE. This candidate nuclear protein is still under study. These findings suggest that Vg2RE efficiently drives the expression of Vg2 to support sufficient yolk formation for the developed embryo through the classical JH molecular action including nuclear protein candidates, such as Met receptor and FoxO.
protein. However, other identified cis-binding elements imply the complexity of such regulation and the induction and/or repression of Vg2 expression during repetitive vitellogenic cycles.

**MATERIALS AND METHODS**

**Insects**
Colonies of *P. americana* were maintained as described in Elgendy et al. (2019). Fat bodies from nymphs (last instar) and adult males and females were collected for the preparation of nuclear extracts and gDNA isolation.

**Promoter Sequencing and Primer Extension Analysis**
The Vg2 promoter has been cloned as described by Elgendy et al. (2019) with the primers Vg2-Prom1 and Vg2-Prom2 (Supplementary Table 1). The longest promoter fragment was subcloned into the pGL3-Basic vector (Promega, Madison, WI, USA). The transcription start site (TSS) was experimentally determined using a primer extension kit (Promega) and γ-32P ATP end-labeled reverse primer (Vg2p-R) following the instruction manual.

Fat bodies were collected from 1-day-old females. Genomic DNA was isolated using the Mammalian Genomic DNA Kit (Sigma, St. Louis, MO, USA). The purity of the nucleic acid samples was assessed based on the A260/A280 ratio (Sambrook and Russell, 2001). The Vg2 promoter sequence was identified using the BD GenomicWalker™ Kit (BD Bioscience, Clontech, San Jose, CA USA). For this purpose, six genomic DNA libraries were constructed by digesting genomic DNA with DraI, EcoRV, HincIII, PvuI, SspI, and Stul. The resulting DNA fragments were purified and ligated to GenomeWalker adaptors. Further, 1 µl of each DNA library was subjected to primary PCR with AP1 (provided with the kit) and Vg2-Prom1 primer (Supplementary Table 1). The primary PCR mixtures were diluted and used as templates for secondary PCR with AP2 (provided with the kit) and Vg2-Prom2 primer. Secondary PCR products were inserted into pT7Blue, a TA cloning vector (Novagen, Nottingham, UK). Sequencing was performed using the ABI Prism BigDye Terminator Cycle Sequencing Kit (PE Applied Biosystems, Foster, CA USA) and a 3100 Genetic Analyzer sequencer (PE Applied Biosystems, Foster, CA USA). For this purpose, six genomic DNA libraries were constructed by digesting genomic DNA with DraI, EcoRV, HincIII, PvuI, SspI, and Stul. The resulting DNA fragments were purified and ligated to GenomeWalker adaptors. Further, 1 µl of each DNA library was subjected to primary PCR with AP1 (provided with the kit) and Vg2-Prom1 primer (Supplementary Table 1). The primary PCR mixtures were diluted and used as templates for secondary PCR with AP2 (provided with the kit) and Vg2-Prom2 primer. Secondary PCR products were inserted into pT7Blue, a TA cloning vector (Novagen, Nottingham, UK). Sequencing was performed using the ABI Prism BigDye Terminator Cycle Sequencing Kit (PE Applied Biosystems, Foster, CA USA) and a 3100 Genetic Analyzer sequencer (PE Applied Biosystems, Foster, CA USA). The longest promoter fragment was subcloned into the pGL3-Basic vector (Promega, Madison, WI, USA). The TSS was experimentally determined using a primer extension kit (Promega) and γ-32P ATP end-labeled reverse primer (Vg2p-R) following the instruction manual.

**Plasmid Construction**
The 1,804-bp 5′ flanking region of the *PaVg2* promoter was cloned between the SacI and HindIII (Takara, Kyoto, Japan) sites of the pGL3-Basic vector. Luciferase reporter constructs with different length deletions of the *PaVg2* promoter were cloned using sense primers with SacI at their 5′ ends and an antisense GL-2 primer (Supplementary Table 1). The sequences of the constructs were confirmed using the GL-2 and RV3 primers. The pGL3-Basic vector was used as an internal control for transfection efficiency.

**Site-Directed Mutagenesis**
Site-directed mutagenesis was carried out on the in silico identified putative Vg2RE from −169 to −139 bp. The base change was done using the site-directed, ligase-independent mutagenesis (SLIM) methodology as described by Chiu et al. (2008) and primers sequence in Supplementary Table 2. An aliquot of 20 µl from each reaction was used for transformation. The clones were screened by sequencing for the desired mutations.

**Cell Culture, Transfection, and Luciferase Assay**
*Spodoptera frugiperda* SF9 cells were cultured in SF900 II SFM supplemented with 10% fetal bovine serum (Life Technologies Polska, Poland) and 50 µg/ml gentamycin (Sigma) at 28°C. Transient transfections of SF9 cells were performed as described previously by Elgendy et al. (2019). Briefly, SF9 cells were seeded in a 12-wells plate (6 × 105 cells/well) that was incubated overnight at 28°C before transfection. Further, 1 µg of each reporter construct was co-transfected with 0.5 µg of pRL-Actin5C using 4 µl of Tfx™-20 reagent (Promega) in 400 µl of serum-free media (SFM; GIBCO, Invitrogen, MA, USA) for 12 h. Then, the transfection mixture was removed, and 1 ml of growth medium (SF900 medium with 10% fetal bovine serum) was added to each well. The growth medium was added and after 48 h the cells were harvested and lysed using 100 µl of lysis buffer (Promega). The cells were frozen at −70°C, thawed to enhance cell lysis, centrifuged at 4°C for 2 min, and 20 µl of the supernatant was used for the assay. The assay was performed using the Bright-Glo™ Luciferase Assay System (Promega) and an ATTO Luminescencer PSN (ATTO, Tokyo, Japan). The results were normalized against *Renilla* luciferase activity and plotted as relative luciferase activity (RLA); each experiment was repeated three times.

To study the time-course of the hormonal effect, SF9 cells were transfected with 1 µg of each reporter construct and 3 µl of Tfx™-20 reagent (Promega) in 400 µl of SFM (GIBCO, Invitrogen) for 12 h, at which time the transfection mixture was removed and 1 ml of growth medium (SF900 medium with 10% fetal bovine serum) with or without hormone was added to each well. After 48 h, the growth medium was added, and cells were harvested and lysed with 200 µl of luciferase lysis reagent (Promega). Cells were frozen at −70°C and thawed to enhance cell lysis. The lysate was centrifuged at 4°C for 2 min and the supernatant was used for the assay. The assay was performed using the Bright-Glo™ Luciferase Assay System (Promega) and an ATTO Luminescencer PSN (ATTO, Tokyo, Japan). The results were normalized against total protein concentration; each experiment was repeated three times. Luciferase activity was normalized to the protein concentration per 20 µl of cell lysate supernatant used in each luciferase reaction.
Preparation of Nuclear Extracts and DNA Binding Assay

Nuclear extracts were prepared from Sf9 and insect fat body cells according to methods described recently by Elgendy et al. (2019). To characterize the identified 31-bp, PaVg2RE, single-stranded oligonucleotides (Supplementary Table 1) were annealed to a double-stranded probe and end-labeled with γ-32P-ATP (MP Biomedical, Tokyo, Japan) by the DNA 5'-End-Labeling System (Promega). The oligonucleotides were then purified by passing the samples through MicroSpin G-25 Columns (GE Healthcare, IL, USA). In each binding reaction, 5–7 μg of nuclear protein and 0.1 pmol of the labeled probe were incubated in electrophoretic mobility shift assay (EMSA) buffer [25 mM HEPES pH 7.6, 5 mM MgCl2, 34 mM KCl, 50 ng/µl poly (dI-dC), and 10% glycerol] for 30 min at room temperature.

For phosphorylation, nuclear protein extract (NPE) was supplemented with adenosine triphosphate (ATP) to a final concentration of 1 mM and incubated at 22°C for 20 min before the binding reaction. For phosphatase treatment, NPE was incubated with 1.0 U calf intestinal alkaline phosphatase (CIAP; Takara) at 22°C for 20 min before adding the labeled probe. For the super-shift experiments, an antibody was added to the binding reaction, and the labeled probe was finally added. The bound DNA-protein complex was resolved using 5% non-denaturing polyacrylamide gels (prerun for 45 min) in 1 × Tris-borate-EDTA (TBE) buffer at a constant voltage of 150 V.

For the super-shift experiments, an antibody was added to the binding reaction, and the labeled probe was finally added. The bound DNA-protein complex was resolved using 5% non-denaturing polyacrylamide gels (prerun for 45 min) in 1 × TBE buffer at a constant voltage of 150 V. Super-shift experiments were performed using Drosophila monoclonal anti-EcR and anti-Ultraspireacle common region antibodies (AG 10.2; DDA 2.7). Antibodies were generously provided by Drs. C. Thummel (University of Utah, UT, USA) and C. Bass (EMBL, Heidelberg, Germany). In addition, this study used polyclonal antibodies against B. mori EcR (AB) and USP (AB), which were generous gifts from Dr. H. Fujiwara (University of Tokyo, Japan). The gels were exposed to MP3 Hyperfilm (Amersham). The inhibitory region from −1,402 to −1,237 bps was amplified using PCR, purified from the agarose gel, and then labeled and used for EMSA as previously described.

Many response element oligonucleotides Vg1RE hspDR4, hspTR, jhbp21, JHRE, and CF1/USP (Supplementary Table 1) were purchased from Invitrogen (Tokyo, Japan). For DNA binding studies, a pair of sense and antisense oligonucleotides were annealed, and the quality and concentrations of the oligonucleotides were verified by polyacrylamide gel electrophoresis (PAGE) before use in the competition assays. A maximum of 50-fold more oligonucleotide than the labeled Vg2RE probe was used in each reaction. The binding reaction was performed as described for EMSA, and the competitor oligonucleotide was added simultaneously with the labeled Vg2RE probe.

Pull-Down Assay

The 31 bp (Vg2RE) wild-type forward and reverse probes were synthesized, biotinylated at the 5’ end of the sense strand, and annealed in equimolar amounts. Then, Dynabeads M-280 streptavidin (Dynal, Inc., Lake Success, NY, USA) were washed three times in phosphate-buffered saline (pH 7.4) containing 0.1% BSA and two times with Tris-EDTA containing 1 M NaCl. Between washes, the beads were pulled down by a magnet (Promega). Each double-stranded biotinylated DNA probe (10 pmol) was assayed with 250 μg of beads, and the mixture was incubated for 40 min at room temperature with continuous mixing. The beads were then washed two times in Tris-EDTA with 1 M NaCl and two times in 1 × binding buffer (EMSA binding buffer). Fat body nuclear extracts (35 μg) were preincubated for 5 min in 1 × binding buffer with 2.0 μg of poly (dI-dC) in a total volume of 100 μl. Dynabeads M-280 streptavidin (250 μg) bound to the probe (10 pmol) were then added to the mixture and incubated for an additional 20 min at room temperature. Proteins bound to the probe were pulled down with a magnet, and then, the beads were washed once with ×0.5 binding buffer containing 0.5 μg/ml and subsequently pulled down. The beads were re-suspended in ×1 sample buffer and boiled for 10 min. Then, the beads were subjected to 10% sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE). Electrophoresis was performed at 200 V for 50 min, and protein bands were visualized by silver staining (Silver Stain Plus, Bio-Rad, CA, USA).

Statistical Analysis

The experiments were conducted with three independent replications (transfections at three different times), and on each occasion were performed three times. An unpaired Student’s t-test was used for comparison of the two data sets. In all cases, P < 0.05 were considered significant. Statistical analysis was performed with IBM-SPSS Statistics v.22 (IBM, Armonk, NY, USA).

RESULTS

Sequencing of Vg2 Promoter and Search for Potential Regulatory Elements

The genomic walking procedure was used to clone and sequence the Vg2 promoter of P. americana (PaVg2). A 1,850 bp genomic fragment was cloned into the TA cloning vector pT7blue (Novagen), sequenced from both directions (Figure 1), and deposited in GenBank (AB449028). This genomic sequence includes a promoter region from −1 to −1,804 and cDNA fragment from +1 to +46 including 11 nucleotides extension from the previously cloned Vg2 cDNA by Tufail et al. (2001). The genomic region from +46 to −1,804 showed a typical TATA box at −30 bp upstream of the identified TSS (Figure 1). The TSS was determined using the TRANSFAC program and confirmed by primer extension assay (Figure 2) and numbered as +1.

The Vg2 promoter (+46 to −1,804 bp) was examined for potential regulatory elements with Match and Patch 2.0
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FIGURE 1 | Nucleotide sequence of the Vitellogenin 2 (Vg2) promoter. The nucleotides are numbered from the transcription start point as +1. The name of the binding factor is written under its consensus sequence. TATA box, GAGA, and GATA elements are shown in bold red, bold green, and bold black capital letters, respectively. Juvenile hormone response element (JHRE): blue color. Ecdysone response element (EcRE): red color. Broad complex (Br-CZ) dashed underline. Chorion factor (CF-II): gray box. Hairy is underlined. E-Box and C-Box: yellow box. E74A: violet color. E75: red underline. FoxO: blue box. Tissue-specific expression (TSE): dot underlined. The direct repeat Vg2 RE-DR2 is bold, inside frames. Arrows indicate the directions of the inverted repeats IR.

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The Effect of Hormones on the Transcription Activity of the PaVg2 Promoter in Sf9 Cell Line

The JH III induction of reporter activity through the full length and −204 bp PaVg2 promoter is both JH III dose- and exposure time-dependent (Figure 4). The induction of reporter activity started at as low as 25 nM JH III, augmented with increasing concentration of JH III, and peaked at 100 nM concentration of JH III (Figure 4A). The reporter activity decreased at JH III concentrations greater than 100 nM. This may be due to the potential cytotoxicity of in vitro hormone preparations to the cells. JH III itself is likely, not cytotoxic but is insoluble in an aqueous medium at a concentration higher than $10^{-5}$ M. Above that concentration, it can form a film on top of the medium that can disrupt the proper aeration of cell culture. The induction of reporter activity increased with time and reached a maximum at 48 h after adding the hormone. There was a decrease in reporter activity by 60 and 72 h after adding hormone (Figure 4C). Also, the minimum promoter length (−204 bp) showed the same induction pattern of the full-length promoter under exposure to a serial dilution of JH III (Figure 4B). The suppression of transcription activity was observed when 20E was added alone or mixed with JH III in both full-lengths (Figures 3B, 4A) and −204 bp of Vg2 promoter (Figure 3B). The −1,404 bp and basic pLG3 constructs showed no effect upon hormone treatment, suggesting the presence of suppressor elements in the region between −1,404 and −1,237 bp. Control medium alone, without any hormones, had a limited effect on transcription activity.

Characterization of PaVg2RE

For identification of PaVg2RE, a competition assay was performed using 31-bp double-stranded oligonucleotides based on the REs of hspDR4, hspIR, jhbp21, JHRE, CF1/USP, and Vg1RE (Elgendy et al., 2019) (Supplementary Table 1). The binding of Vg2RE by the fat body NPE was effectively abolished by unlabeled...
### TABLE 1 | Possible regulatory elements located in the promoter region of the Vg2 gene.

| Regulatory element | Sequences | Position | Homology |
|--------------------|-----------|----------|----------|
| JHRE               | ATGATTAGTCAGAAAGATATT | −1,294 | Budworm JHE |
|                    | GCAAGGCTCTAGTGAGCTGG  | −1,019 | L. migratoria Vg |
|                    | ATTAGCATTTAAGCA      | −662  | G. mellonella JHBP |
|                    | CTCAGTCGGCGTCGGCTT   | −278  |          |
| EcRE               | CGCTTCACACCTCAGGA   | −1,089 | Drosophila 20E-responsive gene |
|                    | CGCTTCAGGAATGGA     | −555   |          |
| E-box              | CACATG             | −1,574 |          |
| C-box              | CACCGG             | −181   |          |
| Met                | CACCGTAG           | −181   |          |
| CRE                | ATTAT              | −1,471 and −488 |          |
|                    | ATQAAT             | −484 and −401 |          |
|                    | CATTGT             | −618   |          |
|                    |                   |         |          |
| E74A binding site  | CAAGGAGGAAGTGA     | −1,424 |          |
|                    | TCAGGAAA          | −1,325 |          |
| E75 binding site   | GTACACCCTAAGA      | −1,209 |          |
| GATA binding site  | TGATAA             | −1,413 |          |
|                    | AGATA              | −1,280 |          |
|                    | CGATA              | −567   |          |
|                    | CGATAA             | −371   |          |
| GAGA binding site  | CGAGAT             | −1,600 |          |
|                    | GGAGA              | −1,388 |          |
|                    | CGAGAA             | −1,126 |          |
|                    | TGAGAC             | −393   |          |
| TSE element        | CTACAATT           | −1,373 |          |
| RXR binding site   | ACTGAACTG          | −1,318 | Mammalian retinoid-X receptor |
|                    | GAAATGACCC         | −1,054 |          |
| FoxO               | TTTAAATAA          | −1,833 |          |
|                    | ATAAACAA           | −957   |          |
|                    | TTTAAATA           | −705   |          |
|                    | ATAAACAT           | −651   |          |
| Br-CZ              | TACCTTTGTGGTG      | −1,587 |          |
|                    | TCTTGTGACACAA      | −892   |          |
|                    | TTTAATTTAACAA      | −725   |          |
|                    | CTGTTCACATTC       | −630   |          |
|                    | ATGAAATTAGAAT      | −484   |          |
|                    | TTTCTTTAAAT        | −256   |          |
| Hairy              | TTGGAGGGAGGTGTA    | −1,804 |          |
|                    | AATAGCCGCTGGTA     | −1,240 |          |
|                    | TTGTGACGTGGCTG     | −870   |          |
|                    | AGTCGGCGTCGGCTT    | −275   |          |
| CFII               | CTATATAT           | −1,732 |          |
|                    | TATATATAG          | −1,670 |          |
|                    | AATATATAT          | −1,641 |          |
|                    | CTATATAT           | −352   |          |
|                    | TCTATATAT          | −195   |          |
| Vg2RE-DR2          | GGAGTCCACGGAGTCCGGCTG | −169 |          |
FIGURE 3 | Identification of the juvenile hormone (JH) responsive region in the Vg2 promoter. A 1,804-bp DNA fragment upstream of the TSS was isolated, and 5′ deletion fragments (−1,548, −1,404, −1,237, −870, −347, −216, −177, −139, and −74 bp) were produced by PCR and cloned into a luciferase reporter vector (pGL3). These constructs were assayed in Sf9 cells. In this, 1 µg of each reporter plasmid construct was transfected with 3 µl of TfxTM−20 reagent. After 12 h, the cells were treated with medium alone or medium with 1 µM JH III, 1 µM 20E, or 1 µM JH III and 1 µM 20E. Luciferase activity was assayed 48 h after treatment. (A) The assay was performed using the Bright-GloTM Luciferase Assay System (Promega) and results were normalized against Renilla luciferase activity and plotted as relative luciferase activity (RLA); each experiment was repeated three times. Values are presented as the mean ± SD. (B) For each reporter plasmid construct, luciferase activity was assayed 48 h after the addition of hormones JH III, 20E, and both JH III and 20E mixture. Data are presented as mean ± SD. Bars marked with * or # are significantly different (P < 0.05) as compared to the media (control media without hormones) or the combined JH III and 20E treatment, respectively.

Vg1RE cold probe and EcREs, DR4, and IR, of D. melanogaster (Figure 5, lanes 3, 5, and 6). Vg2RE-protein complex was competed by jhbp21 of L. migratoria, JHRE, and CF1/USP of G. mellonella (Figure 5, lanes 7, 8, and 9, respectively). The JHREs jhbp21 (L. migratoria) and JHRE (C. fumiferana) showed the lowest competition (Figure 5, lanes 7 and 8).

To identify the nucleotides in the PaVg2RE (−169 to −139 bp) critical for binding to the fat body nuclear protein (s), the wild-type Vg2RE probe used for EMSA was competed with 50-fold excess cold mutant probes (M1–M9) (Supplementary Table 2). The results presented in Figure 6B showed that mutants M3, M4, and M5 competed well with the wild-type (W) probe, indicating that the binding affinity of the probes for the nuclear protein was greater than that of the wild one. M1 and M2 were less competitive than the W, while M6–M9, in which DR2 half-sites...
or IR were eliminated, showed no competition. This finding indicated that these mutants had no binding affinity for the nuclear protein. SLIM was used to clone different mutated −204 bp constructs (M1–M9) (Supplementary Table 2). Subsequently, the mutated constructs M1–M9 were used to express the firefly luciferase gene in the Sf9 cell line in the presence of JH III. The luciferase assay results showed that mutants M3 (G\_−166 and G\_−158 changed to T), M4 (T\_−165 and T\_−157 changed to C), and M5 (G\_−168, G\_−169, G\_−161, and G\_−160 were deleted) reduced the JH III-mediated induction of the reporter gene by 65% compared with the W (Figure 6A). On the other hand, M6–M9 increased reporter gene induction by JH III. These results indicated that the G and T residues of both halves of the Vg2RE, DR2 (GAGTCA), and the IR are crucial for binding of the nuclear protein. Furthermore, the luciferase signal decreased as the binding to DR2 increased (Figures 6A,B), which suggests that the expression of Vg2 is through a binding repression factor/protein.

**Candidate Vg2RE Binding Protein (Pull-Down Assay)**

An EMSA clearly showed that the NPEs from nymphs, male, and 1-day-old female adults contained proteins that bind specifically to the 31-bp probe (Figure 7A, lanes 2, 3, and 4). The intensity of the Vg2RE-NPE complex decreased in the fat body of 5-day old vitellogenic female insects (Figure 7A, lane 5). At this time, there is less nuclear binding protein in the fat body due to the low concentration of JH III in vitellogenic female insects. So, several anti-EcR and anti-USP (the holometabolous D. melanogaster and B. mori) antibodies were used to characterize the PaVg2RE binding protein but no supershifted bands were detected (Figure 7B).

The nuclear protein(s) binds to the radio-labeled Vg2RE probe, after incubation with ATP but not after incubation with CIAP (Figure 7C). The addition of JH III to the dephosphorylated NPE cannot restore their binding to the Vg2RE probe. This indicated that the presence of JH III cannot directly interfere with the phosphorylation state of NPE (Figure 7C).

In the study, we attempted to identify the Vg2RE-binding protein from female fat body nuclear extracts by employing the 31-bp probe (−169 to −139 bp) affixed to the magnetic beads. A 71 kDa protein was isolated as visualized by electrophoretic separation and silver staining (Figure 8). This protein is present in vitellogenic female fat body nuclear extracts but at low concentrations. The purification protocol yielded a 71 kDa
protein band in two independent experiments, and in the second experiment, the protein concentration was increased for visualization by the silver staining. This purification was justified as a potential strategy for the isolation and characterization of candidate receptors in upscaled use of materials in the future.

**DISCUSSION**

Cockroaches are an ideal model for analyzing the JH molecular signal pathways as it controls gonadotrophic events in adult female and anti-metamorphic events during immature stages (Comas et al., 1999, 2001; Cruz et al., 2003; Maestro et al., 2010; Marchal et al., 2014; Li et al., 2018; Zhu et al., 2020). In adult cockroach species (B. germanica, D. punctata, and P. americana), JH is known to promote oocyte growth, Vg production in the fat body, and uptake of Vg by the oocytes (Engelmann and Mala, 2000, 2005; Comas et al., 2001). For several decades, the Vg gene has been extensively studied due to its variable copy numbers and multiple functions in several oviparous species. P. americana has two Vg genes with the relative expression level of Vg2 being more abundant during the female vitellogenic cycle (Tufail et al., 2001). This finding prompted us to inspect the mechanism controlling Vg genes expression at the molecular level. To achieve this aim, a genomic fragment of 1,804 bp, 5-flanking region of Vg2 was cloned, sequenced, and putative binding elements for transcription factors were predicted in silico using TRANSFAC database, which contains experimentally validated regulatory elements (AliBaba 2.1, Match and Patch, http://www.gene-regulation.com/pub/programs.html). Others were identified through matching with the known elements (Figure 1; Table 1). Then, luciferase assays and electrophoretic mobility shift, competition, and mutation assays were employed to detangle molecular associations of JH, JH receptors, and coactivators/co-inhibitors and cis-elements.

**Transcription Binding Elements in Vg2 Promoter Region**

Multiple putative cis-elements for binding transcription factors were detected in the Vg2 promoter, such as TATA box, JHRE, EcRE, CF-II, FoxO, Hairy, Br-CZs, Met, E74A, E75, E-Box, C-Box, CRE, and tissue-specific element (TSE) (Figure 1; Table 1).

*Periplaneta americana* *Vitellogenin 2* promoter contains four putative GATA, many GAGA and TSE binding elements which influence the fat body tissue-specific expression of the Vg2 gene. Similarly, several studies have indicated that the transcriptional activation of Vg is regulated by GATA and GAGA factors in *A. aegypti* and *D. melanogaster* (Fossett et al., 2001; Martin et al., 2001; Walzter et al., 2002; Park et al., 2006). At the regulatory level, the occurrence of E-box motifs and CREs in a promoter region may drive the rhythmic expression of a particular gene(s) (Rund et al., 2013), e.g., aralkylamine N-acetyltransferase acting in different aspects of vitellogenesis and the regulation of circadian rhythms of locomotor activity in *P. americana* (Kamruzzaman et al., 2020, 2021). CRE-dependent transcription and cAMP signaling constitute integral components of core molecular clocks, serving to regulate daily rhythmic transcription.
of circadian clock genes/clock-controlled genes and signal transduction of biogenic amines and neuropeptides (Belvin et al., 1999; Vleugels et al., 2013; Fernandez-Chiappe et al., 2020). In A. aegypti, a conserved E-box motif, contained within JHRE, is required for JH induction of Kr-h1 (Cui et al., 2014).

Many putative binding elements for ecjsyne and ecjsyne cascade genes such as Br-CZs, E74A, and E75 were also identified in the PaVg2 promoter. Both Br-CZ and E74A are involved in many important processes in insects, such as metamorphosis, oogenesis, and vitellogenesis (Chen et al., 2004; Dubrovsky, 2005; Spokony and Restif, 2007). Br-CZ is involved in the reproductive regulation in the mosquito A. aegypti, B. mori, Bombus lantschouesis, and the cockroach B. germanica (Piliachs et al., 2010; Cruz et al., 2012; Hansen et al., 2014; Yang et al., 2014; Lin et al., 2017), and its functions are closely related to the ecjsyne signaling pathway.

Also, the PaVg2 promoter contains four putative binding elements for JH and its candidate receptor Met (one element) and Hairy (four elements). There were multiple putative binding elements for transcription factors, FoxO and CF-II, which might act as repressors or enhancers, according to their phosphorylation state (Sok et al., 2008; Sheng et al., 2011; Wu et al., 2020). FoxO silencing in B. germanica, resulted in increased Vg mRNA levels in the fat body and a rise in JH biosynthetic activity (Suren-Castillo et al., 2012) and. FoxO also enhanced polyplody of fat body cells of L. migratoria in preparation for the large-scale Vg synthesis required for synchronous maturation of multiple eggs (Wu et al., 2020).

Detection of DR2 Element in the Proximal Vg2 Promoter Region

Based on the luciferase reporter experiments, the promoter region of PaVg2 can be divided into the proximal region (−1 to −204 bp) with many putative binding elements which activate or induce the PaVg2 expression and the second middle region (−204 to −1,548 bp) showing an intermediate induction of the luciferase assay due to presence of putative binding elements for both JH and 20E and their early and late response proteins hierarchy. Finally, the distal region (−1,548 to −1,804 bp) showed the highest induction level (Figure 3).

The luciferase assay of the −1,404 bp construct showed a significant reduction almost equal to the control construct even in the presence of JH III. EMSA using this 145-bp inhibitory probe (from −1,404 to −1,240 bp) showed no binding with NPE of the vitellogenic fat body of the female insects (data not shown). This finding suggests that 20E represses the cockroach Vg2 gene via 20E-induced TF protein response elements present in the fragment.

Detailed inspection for the −204 bp constructs that gave the highest luciferase activity revealed a 6 bp direct repeat with 2-nucleotide spacer DR2, GAGTCA (−168GAGTCA CGGAGTCA−155), which overlapped with 10 bp inverted repeat, IR (−158GTCGCCGCTG−149). This identified DR2 is homologous to many of holometabolous hormone response elements: direct repeat half-site of DR4 (AGGTCA) from the D. melanogaster heat shock protein 27 gene (hsps27), JH binding protein (jhb) response element (AGGGTCACTACCATA) of G. mellonella JH binding protein gene, juvenile hormone esterase response element (JHERE) (AGATTATTAGATTA) of C. fumiferana JH esterase gene and juvenile hormone-binding protein 21 (jhb21) (GAGGTTCGAGAGGTTCGAG−155) of L. migratoria JH binding protein 21 gene. These DR2s are 95% homologous to Vg1 DR2 identified from P. americana (Elgendy et al., 2019).

The mutants of the Vg2RE 31-bp probe were used to conduct luciferase and competition EMSA assays. The results showed that mutants with substitutions of the first G to A and T to C in both half-sites of the DR2 AGGTCA from the wild-type probe, which subsequently resulted in the reduction of reporter activity. Other mutants and deletion of any half-site of DR2 and IR did not show any competition with the wild-type probe. These results indicate that the G and T bases are the most important residues. Kethidi et al. (2004) showed that oligonucleotides containing two AGGTCA elements that are separated by a 4-nb spacer competed well with wild probe (AGATTATTAGATTA).

In the EMSA, the Vg2RE-binding complex was effectively completed away by EcRE DR4 and IR of D. melanogaster and JHRE CFI/USP of the G. mellonella jhb gene cold probes. Moreover, the binding complex was eliminated by VgIRE of P. americana. These results may explain why this binding complex plays a role in the JH and 20E hormonal crosstalk. Because the
identified Vg2RE contains a conserved DR2 and IR response element, the proteins that bind to these elements likely belong to the nuclear receptor superfamily (Kethidi et al., 2004), such as EcR and Ultraspirel (USP). However, the NPE–Vg2RE complex did not show any supershift results using D. melanogaster and B. mori EcR and USP antibodies. This result may be due to low homology between holometabolous nuclear receptor EcR and USP and those of cockroaches.

**Inductive/Repressive Roles of Vg2RE-DR2 Element**

Electrophoretic mobility shift assay results showed that NPE of nymph, male, and previtellogenic female fat bodies bound specifically to the Vg2RE probe but that of vitellogenic female NPEs did not (Weaver et al., 1984; Weaver and Edwards, 1990). We, therefore, postulate that binding of a candidate nuclear protein to Vg2RE leads to the repression of Vg2 expression in nymph and male P. americana. However, this needs detailed study in the future. Similarly, Sheng et al. (2011) found that binding of FoxO to T. castaneum Vg2 gene promoter inhibited its transcription but after adult beetle emergence, JH stimulated FoxO phosphorylation, which in turn released FoxO binding and induced Vg2 transcription. Other binding repression has been detected for the CF1/USP element II found in the jhbp gene (resembling the 5’ half-site of EcRE) showing an inhibitory effect on the transcriptional activity of the jhbp promoter. Thus, it may be concluded that CF1/USP elements play a repressive function in the jhbp gene (Sok et al., 2008). Also, in the differentiation of the imaginal tissues, the unliganded ecdysone receptor acts as a repressor to interrupt the sequence of differentiation at different points, coordinating the response to the rising 20E titers. The release of repression by 20E may, therefore, function as a gate at the onset of metamorphosis (Schubiger et al., 2005). In D. punctata knock down of the JH receptor, Met at the first gonadotropin cycle effectively reduced the expression of Vg in the fat body and oocytes maturation (Marchal et al., 2014).

**A Putative NPE Binding to Vg2RE-DR2**

Electrophoretic separation and silver staining visualization of the bound nuclear protein pulled down by the 31-bp Vg2RE probe showed a 71 kDa protein. This protein exhibits specific binding and could be a partner of the hormone-receptor complex. Vg2RE contains a conserved DR2 and IR response element; the proteins that bind to this JHRE likely belong to the nuclear receptor superfamily (Kethidi et al., 2004).

Zhu et al. (2020) postulated that double sex protein, Dsx, might be a molecular link in the JH regulation of vitellogenesis in P. americana. However, Dsx-RNAi did not completely abolish JH-induced Vg expression in the P. americana fat body suggesting that other transcripational factors, i.e., GATA (Park et al., 2006) could be involved in the JH induction of Vg expression.

One of the candidate binding proteins of Vg2RE (DR2) is CF1/USP protein, because in the competition EMSA, the Vg2RE-NPE complex was effectively abolished by unlabeled EcREs DR4 and IR of D. melanogaster and JHREs CF1/USP of G. mellonella, jhbp21 (Figure 7B). An interaction between USP and DNA relies on recognition of the consensus sequence (GGGTCA) and the ionic interactions of several phosphate groups outside from this element (Sok et al., 2008; Niewiadomska-Cimicka et al., 2011). The results in Figure 7C suggest that only the phosphorylated nuclear protein binds to Vg2RE(DR2) and the addition of JH III does not interfere the phosphorylation state of the NPE (Figure 7C). This suggests another direct or indirect role of JH III at the cellular level other than the nucleus. In T. castaneum Vg2 expression is induced after FoxO phosphorylation which is stimulated by JH (Sheng et al., 2011). Other nuclear binding protein candidates are Met or Taiman, which suppressed Vg gene expression of the linden bug, P. apterus when one or both are knocked down (Smykal et al., 2014). The different JH binding protein(s) suggested that JH has a common receptor but different partners in the transduction of JH signals. JH also can act via plasma membrane receptors (Davey, 2000; Liu et al., 2015). In D. melanogaster, JH induces protein expression in the accessory glands by Met, PKC, and calcium (Yamamoto et al., 1988; Wilson et al., 2003). It will be important to understand how both the intracellular and membrane receptors of JH interact to regulate metamorphosis and reproduction in insects.

**CONCLUSIONS**

We cloned the Vg2 promoter from the American cockroach as a model of a JH-dependent gene. Then, we identified hormone response element homologs of the DR4 of the D. melanogaster EcR response element using both the luciferase reporter assay and EMSA. Additionally, we detected a 71 kDa protein that binds to this identified response element. The EcR response elements and Vg2RE share the half-sites AGGTCA, which indicates that these elements also share a transcriptional regulatory protein that plays a role in both JH and ecdysone hormone signaling in insects, depending on the target tissue and the developmental stage. The results represent the first attempt to describe functional elements in the Vg gene from a hemimetabolous insect and provide a necessary step for elucidation of the complexity of JH-induced gene expression. As it is possible that different cell lines or hormone treatments could yield different results, it would be of great interest to clone many of the candidate transcription factor protein genes for use in RNA interference experiments to elucidate the hormone signal transduction mechanisms of JH.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

**AUTHOR CONTRIBUTIONS**

MaT and AE designed the research. AE, AM, and BD performed different aspects of the formal analysis and wrote the original draft. MaT, BD, and AM reviewed and edited the final drafts. All the authors approved the submission of this manuscript.
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SUPPLEMENTARY MATERIAL
The Supplementary Material for this Article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2021.723072/full#supplementary-material

Supplementary Table 1 | List of primers and probes used in the present study.

Supplementary Table 2 | The wild-type (Vg2W) and mutant sequences (M1–M9) used in this study.

REFERENCES
Abrahamsen, N., Martinez, A., Kjaer, T., Sondergaard, L., and Bownes, M. (1993). Ci-regulatory sequences leading to female-specific expression of yolk protein genes 1 and 2 in the fat body of Drosophila melanogaster. Mol. Gen. Genet. 237, 41–48.

Attiokeng Tatang, R. J., Tsila, H. G., and Wabo Poné, J. (2017). Medically important parasites carried by cockroaches in Melong subdivision, littoral, Cameroon. J. Parasitol. Res. 2017:7967325. doi: 10.1155/2017/7967325

Baumholtz, M. A., Parish, L. C., Witkowski, J. A., and Nutting, W. B. (1997). The medical importance of cockroaches. Int. J. Dermatol. 36, 90–96. doi: 10.1046/j.1365-4632.1997.00077.x

Belvin, M. P., Zhou, H., and Yin, J. C. (1999). The Drosophila dCREB2 gene affects the circadian clock. Neuron. 22, 777–787. doi: 10.1016/S0896-6273(99)00736-9

Chen, L., Zhu, J., Sun, G., and Raikhel, A. S. (2004). The early gene Broad is Drosophila dCREB2 Belvin, M. P., Zhou, H., and Yin, J. C. (1999). The

Cruz, J., Mane-Padros, D., Zou, Z., and Raikhel, A. S. (2012). Distinct roles of isoforms of the heme-liganded nuclear receptor E75, an insect ortholog of the vertebrate Rev-Erb, in mosquito reproduction. Mol. Cell. Endocrinol. 349, 262–271. doi: 10.1016/j.mce.2011.11.006

Cruz, J., Martin, D., Pascual, N., Maestro, J. L., Piulachs, M. D., and Belles, X. (2003). Quality does matter: juvenile hormone and the onset of vitellogenesis in the German cockroach. Insect Biochem. Mol. Biol. 33, 1219–1225. doi: 10.1016/j.ibmb.2003.06.004

Cui, Y., Sui, Y., Xu, J., Zhu, F., and Palli, S. R. (2014). Juvenile hormone regulates Aedes aegypti Krüppel homolog 1 through a conserved E box motif. Insect Biochem. Mol. Biol. 52, 23–32. doi: 10.1016/j.ibmb.2014.05.009

Davey, K. G. (2000). The modes of action of juvenile hormones: some questions we ought to ask. Insect Biochem. Mol. Biol. 30, 663–669. doi: 10.1016/S0965-1748(00)00037-0

Dubrovsky, E. B. (2005). Hormonal cross talk in insect development. Trends Endocrinol. Metab. 16, 6–11. doi: 10.1016/j.tem.2004.11.003

Elgendy, A. M., Tufail, M., Mohamed, A. A., and Takeda, M. (2019). A putative direct repeat element plays a dual role in the induction and repression of in insect vitellogenin-1 gene expression. Comp. Biochem. Physiol. Part B 234, 1–8. doi: 10.1016/j.cbpb.2019.04.003

Engelmann, F., and Mala, J. (2000). The interactions between juvenile hormone (JH), lipophorin, vitellogenin, and JH esterases in two cockroach species. Insect Biochem. Mol. Biol. 30, 793–803. doi: 10.1016/S0965-1748(00)00051-5

Engelmann, F., and Mala, J. (2005). The cockroach Lecithocera maderae needs more than juvenile hormone, vitellogenin and reserves to make a yolky egg. J. Insect Physiol. 51, 465–472. doi: 10.1016/j.jinsphys.2005.01.003

Elgendy, A. M., Tufail, M., Mohamed, A. A., and Takeda, M. (2019). A putative direct repeat element plays a dual role in the induction and repression of in insect vitellogenin-1 gene expression. Comp. Biochem. Physiol. Part B 234, 1–8. doi: 10.1016/j.cbpb.2019.04.003

Fernandez-Chiappe, F., Herrmann-Luibl, C., Peteranderl, A., Reinhard, N., Sonthian, P. R., Hieke, M., et al. (2020). Dopamine signaling in wake-promoting clock neurons is not required for the normal regulation of sleep in Drosophila. J. Neurosci. 40, 9617–9633. doi: 10.1523/JNEUROSCI.1488-20.2020

Fossett, N., Tevosian, S. G., Gajewski, K., Zhang, Q., Orkin, S. H., and Schulz, R. A. (2001). The Friend of GATA proteins U-shaped, FOG-1, and FOG-2 function as negative regulators of blood, heart, and eye development in Drosophila. Proc. Natl. Acad. Sci. U. S. A. 98, 7342–7347. doi: 10.1073/pnas.1311215798

Gibéls, M., Lenaerts, C., Vanden Broeck, J., and Marchal, E. (2019). Juvenile hormone receptor Met is essential for ovarian maturation in the Desert Locust, Schistocerca gregaria. Sci. Rep. 9:10797. doi: 10.1038/s41598-019-47253-x

Glinka, A., and Wyatt, G. (1996). Juvenile hormone activation of gene transcription in locust fat body. Insect Biochem. Mol. Biol. 26, 13–18. doi: 10.1016/0965-1748(95)00045-3

Guar, H., and Palli, S. (2016). Krüppel homolog 1 and E93 mediate juvenile hormone regulation of metamorphosis in the common bed bug, Cimex lectularius. Sci. Rep. 6:26092. doi: 10.1038/srep26092

Guo, W., Wu, Z., Song, J., Jiang, F., Wang, Z., Deng, S., Walker, V.K., and Zhou, S. (2014). Juvenile hormone-receptor complex acts on mcn4 and mcn7 to promote polyplody and vitellogenesis in the migratory locust. PLoS Genet. 10, e1004702.

Hansen, A. I., Attardo, G. M., Rodriguez, S. D., and Drakeand, L. L. (2014). Four-way regulation of mosquito yolk protein precursor genes by juvenile hormone-, edcsyne-, nutrient-, and insulin-like peptide signaling pathways. Front. Physiol. 5:103. doi: 10.3389/fphys.2014.00103

Hu, K., Tian, P., Tang, Y., Yang, L., Qiu, L., He, H., et al. (2019). Molecular characterization of vitellogenin and its receptor in Sogatella furcifera, and their function in oocyte maturation. front. Physiol. 10.1532. doi: 10.3389/fphys.2019.01532

Kamrzzaman, A. S. M., Hiragaki, S., Watari, Y., Natsukawa, T., Yasuhara, A., Ichihara, N., et al. (2021). Clock-controlled arylalkylamine N-acetyltransferase (aaNAT) regulates circadian rhythms of locomotor activity in the American cockroach, Periplaneta americana via melatonin/MT2-like receptor. J. Pineal Res. 71:e12751. doi: 10.1111/jpi.12751

Kamrzzaman, A. S. M., Mikani, A., Mohamed, A. A., Elgendy, A. M., and Takeda, M. (2020). Crosstalk among indoleamines, neuropeptides and JH/20E in regulation of reproduction in the American cockroach, Periplaneta americana. Insects 11:155. doi: 10.3390/insects11030155
Martín, D., Wang, S. F., and Raikhel, A. S. (2001). The vitellogenin gene of the German cockroach, Periplaneta americana: cloning, expression, and regulation by juvenile hormone and allatostatins in the German cockroach embryo. Insect Biochem. Mol. Biol. 31, 637–644. doi: 10.1016/j.ibmb.2001.04.004

Mao, Y., Li, Y., Gao, H., and Lin, X. (2020). Krüppel homologue 1 interacts directly with the juvenile hormone and 20-hydroxyecdysone within the ring gland to determine developmental transitions in Drosophila. Insect Biochem. Mol. Biol. 52, 94–101. doi: 10.1016/j.ibmb.2014.07.001

Park, J. H., Attardo, G. M., Hansen, I. A., and Raikhel, A. S. (2006). GATA factor translation is the final downstream step in the amino acid target of juvenile hormone-mediated vitellogenin gene expression in the anautogenous mosquito Aedes aegypti. J. Biol. Chem. 281, 11167–11176. doi: 10.1074/jbc.M601517200

Parthasarathy, R., Sun, Z., Bai, H., and Palli, S. R. (2010). Juvenile hormone regulation of vitellogenin synthesis in the red flour beetle, Tribolium castaneum. Insect Biochem. Mol. Biol. 40, 405–414. doi: 10.1016/j.ibmb.2010.03.006

Parthasarathy, R., Tan, A., Bai, H., and Palli, S. R. (2008). Transcription factor AsVg1 broad suppresses precocious development of adult structures during larval-pupal metamorphosis in the red flour beetle, Tribolium castaneum. Mech. Dev. 125, 299–313. doi: 10.1016/j.mod.2007.11.001

Pulachia, M. D., Pagone, V., and Bellês, X. (2010). Key roles of the Broad-Complex gene in insect embryogenesis. Insect Biochem. Mol. Biol. 40, 468–475. doi: 10.1016/j.ibmb.2010.04.006

Raikhel, A. S., Brown, M. R., and Belles, X. (2005). “Hormonal control of reproductive processes,” in Comprehensive Molecular Insect Science, eds L. I. Gilbert, K. Iatrou, and S. S. Gill (Boston, MA: Elsevier), 433–491.

Ramaswamy, S. B., Shu, S., Park, Y. L., and Zeng, F. (1997). Dynamics of juvenile hormone-mediated gonadotropism in the Lepidoptera. Arch. Insect Biochem. Physiol. 35, 539–558. doi: 10.1002/(SICI)1520-6377(1997)35:4<539::AID-ARCH12>3.0.CO;2-B

Roy, S., Saha, T. T., Zou, Z., and Raikhel, A. S. (2018). Regulatory pathways controlling female insect reproduction. Annu. Rev. Entomol. 63, 489–511. doi: 10.1146/annurev-ento-020117-043258

Rund, S. S., Gentile, J. E., and Duffield, G. E. (2013). Extensive circadian and light regulation of the transcriptome in the malaria vector Anopheles gambiae. BMC Genomics 14:218. doi: 10.1186/1471-2164-14-218

Sambrook, J., and Russell, D. (2001). Molecular Cloning: A Laboratory Manual, 3rd Edn. New York, NY: Cold Spring Harbor Laboratory Press.

Schubiger, M., Carre, C., Antoniewski, C., and Truman, J. M. (2005). Ligand-dependent de-repression via EcR/USP acts as a gate to coordinate the differentiation of sensory neurons in the Drosophila wing. Development 132, 5239–5248. doi: 10.1242/dev.02093

Sheng, Z. T., Xu, J. J., Bai, H., Zou, F., and Palli, S. R. (2011). Juvenile hormone regulates vitellogenin gene expression through insulin-like peptide signaling pathway in the red flour beetle, Tribolium castaneum. J. Biol. Chem. 286, 41924–41936. doi: 10.1074/jbc.M111.269845

Smykal, V., Bajgar, A., Provaznik, J., Fexova, S., Buricova, M., Takaki, K., et al. (2014). Juvenile hormone signaling during reproduction and development of the linden bug, Pyrrhocoris apterus. Insect Biochem. Mol. Biol. 45, 69–76. doi: 10.1016/j.ibmb.2013.12.003

Sok, A. J., Andruszewska, G., Niewiadomska-Cimicka, A., Grad, I., Rymarczyk, P., and Szadkowska, A. (2009). Transcription factor induced by 20-hydroxyecdysone collaboratively regulate juvenile hormone- and allatostatin-mediated transcriptional activation by the methoprene-tolerant, Met knockdown in the adult female cockroach, Galleria mellonella. J. Biol. Chem. 286, 5239–5248. doi: 10.1074/jbc.M108.018596

Stoops, R. F., and Restifo, L. L. (2007). Anciently duplicated Broad Complex exons have distinct temporal functions during tissue
Wang, Z., Yang, L., Song, J., Kang, L., and Zhou, S. (2017). An isoform of Waltzer, L., Bataillé, L., Peyrefitte, S., and Haenlin, M. (2002). Two isoforms of Serpent containing either one or two GATA zinc fingers have different roles in Drosophila haematopoiesis. EMBO J. 21, 5477–5486. doi: 10.1093/emboj/cdf545

Wang, Z., Yang, L., Song, J., Kang, L., and Zhou, S. (2017). An isoform of Taiman that contains a PRD-repeat motif is indispensable for transducing the vitellogenic juvenile hormone signal in Locusta migratoria. Insect Biochem. Mol. Biol. 82, 31–40. doi: 10.1016/j.ibmb.2017.01.009

Weaver, R. J., and Edwards, J. P. (1990). The role of the corpora allata and associated nerves in the regulation of ovarian cycles in the oviparous cockroach Periplaneta americana. J. Insect Physiol. 36, 51–59. doi: 10.1016/0022-1910(90)90150-E

Weaver, R. J., Strambi, A., and Strambi, C. (1984). The significance of free ecdysteroids in the haemolymph of adult cockroaches. J. Insect Physiol. 30, 705–711. doi: 10.1016/0022-1910(84)90034-9

Wilson, T. G., Demoor, S., and Lei, J. (2003). Juvenile hormone involvement in Drosophila melanogaster male reproduction as suggested by the Methoprene-tolerant(27) mutant phenotype. Insect Biochem. Mol. Biol. 33, 1167–1175. doi: 10.1016/S0303-7207(03)00006-3

Wu, Z., He, Q., Zeng, B., Zhou, H., and Zhou, S. (2020). Juvenile hormone acts through FoxO to promote Cdc2 and Orc5 transcription for polyploidy-dependent vitellogenesis. Development 147,dev188813. doi: 10.1242/dev.188813

Wyatt, G. R., and Davey, K. G. (1996). Cellular and molecular actions of juvenile hormone. II. Roles of juvenile hormone in adult insects. Adv. Insect Physiol, 26, 1–155. doi: 10.1016/S0006-2806(08)60030-2

Yamamoto, K., Chadarevian, A., and Pellegrini, M. (1988). Juvenile hormone action mediated in male accessory glands of Drosophila by calcium and kinase C. Science 239, 916–919. doi: 10.1126/science.3124270

Yang, M., Wei, Y., Jiang, F., Yang, W., Guo, X., He, J., et al. (2014). MicroRNA-133 inhibits behavioral aggregation by controlling dopamine synthesis in locusts. PLoS Genet. 10:e1004206. doi: 10.1371/journal.pgen.1004206

Yue, Y., Yang, R. L., Wang, W. P., Zhou, Q. H., Chen, E. H., Yuan, G. R., et al. (2018). Involvement of Met and Kr-h1 in JH-mediated reproduction of female Bactrocera dorsalis (Hendel). Front. Physiol. 9:482. doi: 10.3389/fphys.2018.00482

Zhou, S., Zhang, J., Hirai, M., Chinzei, Y., Kayser, H., Wyatt, G. R., et al. (2002). A locust DNA-binding protein involved in gene regulation by juvenile hormone. Mol. Cell. Endocrinol. 190, 177–185. doi: 10.1016/S0303-7207(01)00602-5

Zhu, J., Chen, L., and Raikhel, A. S. (2007). Distinct roles of Broad isoforms in regulation of the 20-hydroxyecdysone effector gene, Vitellogenin, in the mosquito Aedes aegypti. Mol. Cell. Endocrinol. 267, 97–105. doi: 10.1016/j.mce.2007.01.006

Zhu, S., Liu, F., Zeng, H., Li, N., Ren, C., Su, Y., et al. (2020). Insulin/IGF signaling and TORC1 promote vitellogenesis via inducing juvenile hormone biosynthesis in the American cockroach. Development 147:dev188805. doi: 10.1242/dev.188805

Zou, Z., Saha, T. T., Roy, S., Shin, S. W., Backman, T. W., Girke, T., et al. (2013). Juvenile hormone and its receptor, Methoprene-tolerant, control the dynamics of mosquito gene expression. Proc. Natl. Acad. Sci. U. S. A. 110, E2173–E2181. doi: 10.1073/pnas.1305293110

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