Effects of Juvenile Hormone Analogs on New Reproductives and Colony Growth of Pharaoh Ant (Hymenoptera: Formicidae)

S. P. LIM[1] AND C. Y. LEE[1, 2]

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ABSTRACT Two juvenile hormone analogs (JHAs), pyriproxyfen and S-methoprene, were impregnated into dried tuna fish and fed to colonies of *Monomorium pharaonis* (L.) at very low concentrations (1.0, 2.0, 3.0, 4.0, and 5.0 μg/ml). Its effects on the production of sexuals and colonial growth were observed. Colonies treated with pyriproxyfen yielded sexuals with physical abnormalities. Both female and male sexuals developed bulbous wings, decreased melanization, and died shortly after emergence. Sexuals emerged from colonies treated with S-methoprene did not possess anomalous characteristics. Both pyriproxyfen and S-methoprene did not have significant effects on colonial growth because of the low concentrations of the baits. A commercial bait containing 0.3% S-methoprene (Bioprene-BM) also was evaluated for its efficacy on Pharaoh's ant colonies. Results showed that Pharaoh's ant colonies succumbed to the lethal effects of S-methoprene. Colony members were reduced significantly. Production of queens also decreased significantly in treated colonies and treated queens were unable to lay eggs. JHAs are slow acting and eliminate ant colonies at a relatively slow rate. At low concentrations, pyriproxyfen recorded baffling results, i.e., bulbous wings and demelanized exoskeleton, and it is vital that further studies are initiated to solidify these findings.

KEY WORDS juvenile hormone analogs, queen, pyriproxyfen, S-methoprene

JUVENILE HORMONES (JHS) ARE secreted by a pair of glands in the head known as the corpora allata (Wigglesworth 1940). JH has the ability to maintain insects with larval characteristics that makes it possible for the continued growth of the larval form (Wigglesworth 1964) and also may act as a gonadotropin in the adult (Dahm et al. 1976).

The metamorphosis-preventing activity in the corpora allata was first found by Wigglesworth in his classic parabiosis experiments with the blood-sucking bug *Rhodnius prolixus* Stål in 1935. Besides metamorphosis, JH also effects growth and morphogenesis of internal organs (Sehnal 1965, 1968; Hli[caron]nák 1968; Mouze and Schaller 1971; Mouze 1971; Riddiford 1972), ovarian follicular cells (Wigglesworth 1935, 1936; Joly 1945; Pfeiffer 1945; Scharrer 1946), reproduction (Doane 1961, Highnam 1962), accessory sex glands (Wigglesworth 1936, Thomsen 1942, Scharrer 1946, Sláma 1965), and polymorphism in ants (Brian 1959) and termites (Kaiser 1955, Lüscher 1961).

Juvenile hormone analogs (JHAs), however, are substances of different chemical composition that exhibit similar effects to those of the naturally secreted juvenile hormone (Novák 1975). Due to the suggestion of Williams (1956) to make use of the juvenile hormone in insect control, many programs were initiated to synthesize these compounds. Apart from their extremely high effectiveness, many JHAs also act specifically. A majority of insecticides are not only lethal to all insects and many other invertebrates but also are toxic to vertebrates. Conversely, JHAs act upon insects only and bare their effects to a specific group of insects. Furthermore, JHAs are not poisonous, even in the species where they are fully active, but they render their effects through physiological effect on morphogenesis that results in the destruction of the insect.

Over the years, many studies were conducted using various JHAs such as methoprene, hydroprene, fenoxycarb, teflubenzuron, and pyriproxyfen. Although many of these studies reported success in control of ants, very little information was reported on JHA's physiological effects on ants. Hence, this study was undertaken to report how pyriproxyfen and methoprene affect production of new reproductives and colony growth.

Materials and Methods

Ant Colonies. Healthy Pharaoh ant colonies were separated from stock colonies and given petri dishes to make artificial nests. The dishes were placed in an aluminum tray with dimensions of 40.0 by 24.5 by 8.0 cm. The inner sides of the aluminum trays were fluon-coated to prevent escape. Food and water were provided ad libitum.

[1] Urban Entomology Laboratory, Vector Control Research Unit, School of Biological Sciences, Universiti Sains Malaysia, 11800 Penang, Malaysia.
[2] Corresponding author, e-mail: chowyang@usm.my.

For each JHA, all colonies experienced the same conditions. Each colony consisted of 300–400 workers, 0.3 g of mixed stage brood, and no queen. These colonies were separated from the stock colonies into fluon-coated aluminum trays. The queen's absence was manipulated in these colonies to induce production of new reproductives. Ants were acclimatized for 3 d before a starvation period of 3 d. Dried, canned tuna fish impregnated with JHA was the only food source given throughout the experiment.

JHA Preparations. Pyriproxyfen (99%, technical grade, Sumitomo Chemical Enviro-Agro Asia Pacific Sdn. Bhd., Negeri Sembilan, Malaysia) and S-methoprene (95%, technical grade, Bábolna Bioenvironmental Centre Ltd., Budapest, Hungary) was diluted to five concentrations: 1.0, 2.0, 3.0, 4.0, and 5.0 μg/ml. Ethanol was used as the solvent because it acts only as the carrier of the active ingredient. These preparations were then immersed into ≈0.5 g of dried, ground tuna fish that were later stained using a nontoxic food dyed (True Blue, Star, Bush Boake Allen, London, United Kingdom).

After staining, each of the JHA-impregnated tuna fish preparations was triturated into ≈9.5 g of unstained, dried, ground tuna fish. They served as the only food source to the ants during the study. Food source for the control colonies was dried, stained tuna fish that has been immersed in ethanol without JHAs.

Experimental Design. Five replicates were set up for each of the concentrations. Data were collected every other day until day 31 after which data were taken weekly. The final data were taken a month after day 59.

Digital still pictures of all the replicates were taken at fixed intervals mentioned above and later used in counting the number of individuals in each colony. Observations also were made on the production of new reproductives with any anomalous characteristics. Data collected were subjected to Kruskal–Wallis (KW) analysis of variance (ANOVA), and the means were separated with KW multiple comparison test at 95% confidence interval.

A Hungarian commercial bait containing 0.3% S-methoprene as the active ingredient also was evaluated for its efficacy on colony elimination. Three treatments (Control, M-Matrix, and T-Matrix) were set up where each colony consisted of 300–500 workers, 0.3 g of brood, and four queens. These colonies were acclimatized for ≈3 d followed by a starvation period of 24 h before the initiation of the experiment.

Bait formulation was introduced on the day of commencement of the test. Data were taken every other day until day 7. Data were then taken weekly until the end of the experiment. The number of workers was counted using digital still pictures of all the replicates taken at the intervals when the amount of brood was estimated.

Data Collection. Compiled data were subjected to one-way ANOVA. Means were separated using Tukey's honestly significant difference (HSD) ($P < 0.05$). The tallied data for all individuals of each colony were totaled. The total number was used in calculating the intrinsic rate of increase (r_n) with the formula based on Grothaus et al. (1981) and Lee et al. (1996): $r_n = [\log_e(n_{t+1}) - \log_e(n_t)]/\text{time}$, where r_n is daily rate of population increase, n_t is population at time t, n_{t+1} is population at time t+1, and time is difference between t+1 and t. All the r_n calculated was subjected to KW ANOVA, and the means were separated with KW multiple comparison test at 95% confidence interval.

Table 1. Number (mean ± SD) of queens after being subjected to different concentrations of pyriproxyfen over time

Treatment concn (μg/ml)	Day 29	Day 45	Day 59	Day 83
Control	6.40 ± 4.35a	9.00 ± 5.69a	10.20 ± 4.20a	7.80 ± 4.80a
1.0	0.00 ± 0.00a	0.60 ± 0.40a	0.20 ± 0.20b	0.20 ± 0.20a
2.0	0.00 ± 0.00a	0.40 ± 0.40a	0.20 ± 0.20b	0.00 ± 0.00a
3.0	0.00 ± 0.00a	0.00 ± 0.00a	0.40 ± 0.40b	0.00 ± 0.00a
4.0	0.00 ± 0.00a	0.20 ± 0.20a	0.40 ± 0.40b	0.20 ± 0.20a
5.0	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00b	0.00 ± 0.00a

Means with the same letter are not significantly different ($n = 5$, $P > 0.05$; Tukey's HSD).

Results

Results demonstrated that new queens were able to emerge from both control as well as colonies treated with pyriproxyfen (Table 1). However, queens that emerged from treated colonies did not live long and most died within 1 wk after emergence. Emergence of males was inconsistent.

In the S-methoprene experiment, there were no apparent anomalous queens as in the experiments using pyriproxyfen. All emerged reproductives possessed normal-looking wings and level of melanization. In contrast, the production of male reproductives was not parallel with the production of females. The number of sexuals (both female and male) produced in all treatments was not significantly different from one another.

Bioprene-BM is a commercially marketed bait manufactured by Bábolna Bioenvironmental Centre Ltd. The two matrices tested showed encouraging results in controlling Pharaoh ant. Production of queens also was significantly lower in colonies fed with Bioprene-BM. This difference was first recorded at day 49 and remained until the end of the study at day 105 (Table 2). Intrinsic rate of increase also showed significant differences in colony growth among colonies in as early as day 21 (Table 3). At day 42, colonies fed with T-Matrix started showing significantly negative colonial growth. This could be explained by T-Matrix being more attractive to the ants than M-Matrix. This was also obvious in the brood numbers in all three treatments.

Discussion

Pyriproxyfen. Many previous studies conducted using JHAs have shown excellent results in controlling ants. In addition to death, there were reports on the

Table 2. Number (mean ± SD) of queens after being subjected to different matrices of Bioprene-BM overtime

Treatment	Control	M-Matrix	T-Matrix
Day 0–14	4.00 ± 0.00a	4.00 ± 0.00a	4.00 ± 0.00a
Day 21	4.00 ± 0.00a	4.00 ± 0.00a	3.50 ± 0.29a
Day 42	4.00 ± 0.00a	23.50 ± 7.93a	4.00 ± 0.00a
Day 49	38.50 ± 10.78a	5.50 ± 1.50b	10.25 ± 4.09b
Day 63	54.00 ± 8.19a	8.50 ± 4.50b	8.25 ± 4.59b
Day 77	68.25 ± 17.07a	8.25 ± 4.25b	8.75 ± 5.09b
Day 91	84.75 ± 14.64a	8.75 ± 4.75b	11.25 ± 7.59b
Day 105	88.00 ± 9.06a	9.75 ± 5.75b	10.50 ± 7.18b

Means with the same letter are not significantly different ($n = 3$, $P > 0.05$; Tukey's HSD).

reduction of queens' fecundity (Reimer et al. 1991, Vail and Williams 1995, Hsieh and Su 2000). However, very few of these studies reported abnormalities in terms of physiology.

Close observations revealed that these queens exhibit anomalous characteristics compared with queens from the control colonies. Both male and female reproductives that successfully emerged had bulbous wings (Figs. 1 and 2). These wings were often twisted and unable to fully expand. Lim (1994) found the same phenomenon in german cockroaches, *Blatella germanica* (L.), treated with juvenile hormones. This wing deformation induced by pyriproxyfen and fenoxycarb also was reported in studies by King and Bennett (1988, 1989), Reid et al. (1988, 1990), Kawada et al. (1989), and Koehler and Patterson (1991). In the cutworm *Spodoptera litura* (F.), Nomura and Miyata (2000) found that female adults treated with pyriproxyfen developed wing abnormalities.

In addition, queens had another prominent morphogenetic deformation, decreased melanization. These queens are of a lighter shade compared with the queens that emerged from control colonies (Fig. 3). This finding is similar to that of Bitondi et al. (1998) where pupal melanization of *Apis mellifera* L. is affected by treatment of pyriproxyfen. Staal (1961), Hidaka and Ohotaki, (1963), and Truman et al. (1973) also found similar antimelanization properties of juvenile hormones. However, several studies found increased melanization in *B. germanica* when treated with juvenoids (O'Farrell and Stock 1964, Das and Gupta 1974, Staal 1972). These discrepancies may be explained by differential response to juvenoids.

Reduced melanization also could be one of the reasons why most of these queens died at a relatively young age. Cuticular melanization is a developmental process regulated by hormones (Bitondi et al. 1998). Abdu et al. (2000) found that pyriproxyfen accelerates molting without any effect on molt increment. Bitondi et al. (1998) reported that pyriproxyfen promote acceleration in pupal development and precocious emergence in *A. mellifera.*

Molting is a developmental process that allows holometabolous and hemimetabolous insects to advance to subsequent developmental stages. By hastening this process, insects may not be ready, i.e., their exoskeletons may be not well formed enough to molt. The insects will have thinner exoskeleton that is more vulnerable to desiccation and subsequently death from dehydration.

Colony growth under the effects of pyriproxyfen did not show a significant trend. Previous studies using JHAs as the active ingredient in baits showed very successful results in controlling the pest species tested. However, it must be noted that in this study, used only a fraction of the concentration used in those commercial baits. A majority of these previous studies used concentrations ranging from 0.1 to 0.5%, and this could be the main reason for the irregularity.

Preliminary studies (unrecorded data) using higher concentrations (10 to 50 mg/ml) were too strong and eliminated ant colonies without showing obvious physiological deformity. Colonies were killed before any reproductives manage to emerge. In this study, only baits containing 1.0 to 5.0 μg/ml were used. These concentrations showed slower and subtler effects, which is why colony growth under such minute concentrations did not show a trend in reduction. Furthermore, the duration of this study was relatively short, and JHAs normally take longer to manifest effects.

S-Methoprene. The numbers of males were not equivalent to the numbers of female sexuals produced. As discussed above, male reproductives are thought to be capable of inseminating more than one female. Emerged sexuals also did not suffer from physical retardation similar to those treated with pyriproxyfen. The purity of S-methoprene used also could have caused this discrepancy compared with pyriproxyfen.

Table 3. Intrinsic rate of increase of the Pharaoh's ant colonies after being subjected to different matrices of Bioprene-BM overtime

Treatment (mean ± SD)	Control	M-Matrix	T-Matrix
Day 1	0.0249 ± 0.016a	−0.0444 ± 3.041 by 10^{-3}a	0.0219 ± 0.0316a
Day 7	0.0237 ± 6.26 × 10^{-3}a	−3.48 × 10^{-3} ± 2.22 × 10^{-3}a	−6.27 × 10^{-3} ± 6.21 × 10^{-3}a
Day 21	0.0389 ± 3.71 × 10^{-3}a	0.0224 ± 2.02 × 10^{-3}b	0.0162 ± 5.59 × 10^{-3}b
Day 42	0.0258 ± 1.20 × 10^{-3}a	6.30 × 10^{-3} ± 3.31 × 10^{-3}b	−1.91 × 10^{-3} ± 3.71 × 10^{-3}b
Day 63	0.0153 ± 8.81 × 10^{-4}a	−2.80 × 10^{-4} ± 3.13 × 10^{-3}b	−4.98 × 10^{-3} ± 2.40 × 10^{-3}b
Day 77	0.0124 ± 6.46 × 10^{-4}a	−3.97 × 10^{-3} ± 3.06 × 10^{-3}b	−7.64 × 10^{-3} ± 1.71 × 10^{-3}b
Day 91	0.0120 ± 8.76 × 10^{-4}a	−5.27 × 10^{-3} ± 2.48 × 10^{-3}b	−9.70 × 10^{-3} ± 2.21 × 10^{-3}b
Day 105	0.0111 ± 3.97 × 10^{-4}a	−8.28 × 10^{-3} ± 2.19 × 10^{-3}b	−0.0122 ± 1.63 × 10^{-3}b

Means with the same letter are not significantly different ($n = 3$, $P > 0.05$; Tukey's HSD).

Fig. 1. Female reproductive with bulbous wings.

Fig. 2. Male reproductive with bulbous wings.

Fig. 3. Comparison of melanization between normal queen (top) and demelanized queen (bottom).

Pyriproxyfen and S-methoprene used were of 99.0 and 95.0% pure, respectively.

Concentrations of S-methoprene baits were another factor to be considered. Because of the extremely low concentrations used in this study, colony growth was not significantly affected in such a short time. Most previous studies concerning baits used 0.5 to 1% methoprene in the effort to eradicate ant colonies (Edwards and Clarke 1978, Rupes et al. 1978, Urban and Varjas 1999) and have been successful.

Methoprene also has been shown to induce soldier development in *Pheidole bicarinata* Mayr. Topical application of methoprene not only induced development of soldier but also affected the timing of metamorphosis and the size of both major and minor workers (Wheeler and Nijhout 1983). In addition, methoprene and various numbers of IGR have been used as potential termiticide (Su and Scheffrahn 1990). Termites responded differently with effects varying from production of presoldiers and intercastes in *Zootermopsis nevadensis* Hagen (Wanyonyi and Lüscher 1973, Wanyonyi 1974) to the destruction of hindgut protozoans in *Reticulitermes flavipes* (Kollar) Howard and Haverty 1978).

Previous comparison studies of two different JHAs gave inconsistent results. Cupp and O'Neal (1973) found that methoprene was better in controlling fire ants than hydroprene, whereas Troisi and Riddiford (1974) found the opposite. This irregularity was suggested to be caused by variation in experimental conditions. Concentrations are also important in determining the outcome of the study. High concentrations usually result in death of study insects, and low concentrations gave various, peculiar results.

Bioprene-BM. The concentrations of these baits (M-Matrix and T-Matrix) were much higher compared with the previous two studies with pyriproxyfen and methoprene. Although queens still manage to emerge after feeding on baits, they are not capable of laying eggs, which continued as long as the baits were the only food source.

Queens that fed on methoprene were reported to possess shrunken ovaries (Edwards and Clarke 1978). There also were reports on the recovery of the queen's ability to lay eggs. Sterilized queens recuperated and started to lay eggs again (Rupes et al. 1978). These queens lived longer than those fed with miniscule amounts of JHAs. This disparity remains inexplicable, but it might be because of disruptions during larval development. Deterrence of embryonic development under the influence of IGRs has been reported (Riddiford 1972) and could be the reason of this bizarre observation.

Brood numbers registered the lowest number in colonies fed with T-Matrix, and this number was significantly different from that of the other treatments. Reimer et al. (1991) found similar results in *P. megacephala* colonies treated with fenoxycarb and pyriproxyfen.

At the conclusion of this study (day 105), complete eradication was still unachievable, although data showed significantly lower colony growth. JHA are relatively slow-acting baits. Vail et al. (1996) stated that a reduction of >85% in worker numbers were only observed until 8 wk after the second application with 1% pyriproxyfen baits. Two other preceding studies by Edwards and Clarke (1978) and Wilson and Booth (1981) reported that eradication of Pharaoh ants by using methoprene took 18 and 20 wk, respectively. Therefore, elimination of infestation by using methoprene requires a longer time to be achieved.

In summary, JHAs act slowly in eliminating ant colonies. They first reach the brood (when baits are in solid particle) and then spread slowly by trophallactic workers to the entire colony. Unlike metabolic inhibitors that act much quicker, JHAs are able to reach colony members that often eludes fast-acting insecticides. At low concentrations, they produce baffling physiological changes that need further investigations.

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