Residual Efficacy of Methoprene for Control of *Tribolium castaneum* (Coleoptera: Tenebrionidae) Larvae at Different Temperatures on Varnished Wood, Concrete, and Wheat

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ABSTRACT The residual efficacy of the juvenile hormone analog methoprene (Diacon II) was evaluated in bioassays using larvae of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) exposed on unsealed concrete or varnished wood treated with a liquid formulation and held at different temperatures. When these two types of surfaces were stored at 20, 30 or 35°C for 0–24 wk, the percentage of adult emergence on concrete increased with time. In contrast, there was no adult emergence from larvae exposed to varnished wood at 24 wk after treatment at any of these temperatures. The presence of flour reduced residual efficacy of methoprene on concrete, but not on varnished wood, with no differences between cleaning frequencies. Methoprene was also stable for 48 h on concrete held at 65°C and wheat, *Triticum aestivum* L., held at 46°C. Results show that methoprene is stable at a range of temperatures commonly encountered in indoor food storage facilities and at high temperatures attained during insecticidal heat treatments of structures. The residual persistence of methoprene applied to different surface substrates may be affected more by the substrate than by temperature.

KEY WORDS methoprene, concrete, varnished wood, residual efficacy, surface treatment

The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), is a common insect pest found in flour mills, processing plants, food warehouses, and retail stores (Mullen 1992; Arbogast et al. 2000; Campbell et al. 2002; Campbell et al. 2010a,b). Control methods for this species include the use of residual contact insecticides applied to structural surfaces (Arthur 1998, Arthur and Dowdy 2003, Arthur 2009), aerosols applied as space treatments (Arthur 2008, Arthur and Campbell 2008, Sutton et al. 2011), and whole-plant fumigations (Campbell et al. 2010a). Heat treatments also can be used to control this insect pest in flour mills (Boina et al. 2008) and in various commodities (Beckett et al. 2007).

Methoprene is a juvenile hormone analog that is an insect growth regulator (IGR) that prevents the development of immature insects to the adult stages (Oberlander and Silhacek 2000). Specific tests have shown that exposure of *T. castaneum* larvae to methoprene prevents development to the adult stage (Shanthy et al. 1995, Arthur 2008, Wijayaratne and Fields 2010). It has little or no mammalian toxicity (oral lethal dose$_{50}$ for rats >34,600 mg/kg) (Ware and Whitacre 2004) and is generally effective at low application rates (Hoppe 1981, Daglish 2008, Jenson et al. 2009, Daglish and Nayak 2010, Wijayaratne and Fields 2010, Wijayaratne et al. 2012). Methoprene is registered for use in the United States as a commodity treatment, surface application, or as aerosol application under the trade name Diacon II (Central Life Sciences, Schaumburg, IL). Resistance of stored-product insects to various organophosphate insecticides has been reported for >40 yr (Champ and Campbell-Brown 1970, Champ and Dyte 1976, Collins and Wilson 1987, Collins 1990, Arthur 1996, Subramanyam and Hagstrum 1996), and methoprene alone or in combination with other insecticides has proven to be a good alternative for those insect populations resistant to organophosphates and to pyrethroids (Daglish 2008). There are several reports of the efficacy of the IGRs hydroprene and pyriproxyfen used as surface treatments to control *T. castaneum* (Arthur and Hoernemann 2004, Arthur et al. 2009), but there are no reports concerning methoprene applied to different surface substrates to control *T. castaneum*. Although studies have shown that the presence of food material either during or after adult *T. castaneum* are exposed to contact or aerosol insecticides can increase survival (Arthur 2009), no data are available that assess sanitation

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and cleaning in conjunction with methoprene efficacy on *T. castaneum* larvae. Also, there are no data on the stability of methoprene at temperatures commonly used for heat treatments. The objectives of this study were to determine 1) residual efficacy of methoprene on different surfaces held at different temperatures for different durations, 2) if the presence of flour and cleaning affects residual efficacy of methoprene, and 3) persistence of methoprene at high temperatures on short-term exposure.

Materials and Methods

Experiments at Normal Temperatures. Plastic petri dishes (8.4 cm in diameter) (Fisher, Ottawa, ON, Canada) were used as the experimental units. The bottom portions of these petri dishes were filled with driveway patching concrete (Rockite, Hartline Products Co. Inc., Cleveland, OH) or fir plywood varnished with Varathane (Rust-Oleum Corporation, Vernon Hills, IL). One kilogram of concrete powder was mixed with 500 ml of distilled water for ≈5 min by using a magnetic stirrer. This was poured into the bottom portions of petri dishes to a depth of ≈0.5 cm and allowed to dry for several days at room temperature. Varnished wood disks were cut to fit the bottoms of the petri dish, placed inside, and caulked around the edges (Draftstop, Canadian Adhesives Ltd., Brampton, ON, Canada) to keep insects on the top surface. A few weeks after preparation, the petri dishes were used in the experiment.

The formulation of methoprene used in this study was Diacon II (Central Life Sciences, Schaumburg, IL). This was an emulsifiable concentrate formulation with 33.3% active ingredient (*S*-methoprene, 288 mg/ml). A solution provided by the manufacturer that contained the inert ingredient (adjuvants), but no methoprene, was used as the untreated control. In the surface-treatment experiments, methoprene was applied at the label rate (3 mg active ingredient/m^2). The solutions that provide the amount of methoprene equivalent to the label rate were prepared by diluting the appropriate volume of methoprene in distilled water. From this diluted solution, 0.5 ml was sprayed on to each surface in two aliquots (0.25 ml each). For different replicates, independent solutions were prepared. The adjuvant solution used for spraying was prepared by diluting a volume of adjuvants equivalent to that used with methoprene. Solutions were prepared immediately before spraying. These solutions were applied in a fume hood using an artist's air brush (model H 1L, Paasche Airbrush Company, Chicago, IL), at 103 kPa. For a given experiment, during each replicate spraying, the order of spraying of surfaces was randomized. To avoid contamination, spraying with adjuvants was done first, and those surfaces sprayed with adjuvants were kept in a separate laboratory. After the spraying, the surfaces were air-dried overnight.

The test insects used were *T. castaneum* late-instar larvae (10–12 d old from hatching) reared on flour medium that contained 95% unbleached whole wheat flour and 5% brewer's yeast (MP Biomedicals, LLC, Solon, OH). These larval cultures were prepared by introducing 200 adults to 250 g of the flour medium for 3 d for oviposition in incubators maintained at 30.5°C and 45% RH in complete darkness. Temperature and relative humidity were monitored using HOBO data loggers (Onset Computer Corporation, Bourne, MA). For each bioassay dish, 500 mg of flour (Mettler AE 166, Greifensee, Zurich, Switzerland) was placed in a small pile on the test surface to allow sufficient food resources for the larvae to emerge as adults. In each bioassay, new batch of twenty *T. castaneum* larvae of approximately equal size were placed on petri dishes with flour, and the dishes returned to the incubator. Adult emergence was assessed at two and 3 wk after the introduction of larvae. Emerged adults were removed at 2 wk to minimize cannibalism.

To evaluate the effects of temperature, the concrete and varnished wood surfaces were treated with either the adjuvant mixture or the methoprene solution, as described above. After insecticide application, the surfaces were air-dried overnight, and these surfaces were then maintained at 20, 30, or 35°C for 0, 8, 12, 16, 20, or 24 wk before being used in the larval bioassays, prepared as described above. In the bioassays conducted after a particular duration, there were four replicates of each treated surface at each temperature.

The presence of flour as a contaminant on the surface and the resulting efficacy of methoprene after the flour was removed was assessed at 30°C. A set of concrete and varnished wood surfaces treated with adjuvants or methoprene were provided with 7 g of unbleached wheat flour to cover the surfaces (≈0.5–0.75 cm in depth) and were held at 30°C for 0, 8, 12, 16, 20, or 24 wk. At the end of each duration, the wheat flour was removed (the flour poured out and the remaining flour brushed off with a cosmetic brush (K4750, Symak Sales Co. Inc., Montreal, QC, Canada), and larval bioassays were prepared and conducted as described previously. The effect of the cleaning was evaluated at 30°C only for concrete surfaces by using one of four treatments: 7 g of flour and no cleaning, flour and cleaning every 4 wk, flour and cleaning once a week, or no flour and no cleaning. Each cleaning was followed by the provision of another 7 g of flour on the surfaces. Cleaning entailed removal of flour and brushing off remaining flour with the cosmetic brush. The larval bioassays were conducted at 30°C, at the end of 0, 4, 8, or 16 wk. When the cleaning and bioassays coincided every 4 wk, cleaning was performed immediately before the bioassay. For the bioassay at 0 wk, cleaning was represented by the addition of 7 g of flour to the surfaces and cleaning it after 24 h. There were four replicates per cleaning protocol.

Experiments at High Temperatures. The effect of high temperatures on the residual efficacy of methoprene was evaluated in this experiment. Concrete and varnished wood surfaces were prepared and sprayed as previously described with solutions of either the adjuvants or methoprene and held at 65°C for 0, 6, 12, 24, or 48 h in a laboratory oven (Thermocenter TC40/TC100, Salvis Lab, Rotkreuz, Switzerland). Each petri

dish was covered by its lid and placed directly on an oven shelf, without stacking or touching adjacent petri dishes. After removal from the oven, dishes were allowed to cool to room temperature, and larval bioassays conducted. There were four replicates for each treatment.

A final set of experiments evaluated methoprene efficacy on hard red spring wheat, *Triticum aestivum* L., with ≈14% moisture content. Insecticide solutions were formulated to give target application rates 0.0030, 0.0083, 0.0165, or 0.0330 ppm (wt:wt) on wheat. Various volumes of methoprene were dissolved in 1 liter of distilled water so that 3 ml sprayed on 300 g of wheat would give different concentrations. Water and adjuvants (0.033 ppm) were used as controls. Individual lots of 300 g of a mixture of 80% whole wheat with 20% cracked wheat (wheat medium) was laid as a single grain layer on a wax sheet and sprayed with 3 ml of a particular concentration, using an artist's air brush (Wijayaratne and Fields 2010). The treated wheat was hand tumbled in a plastic bag for 30 s to facilitate mixing of the treated wheat. For a given concentration, there were four replicate sprayings. Six subsamples of 20 g each were taken from each lot 300 g, the remainder was discarded. Each of these was placed into a 35-ml glass vial and was used in the six durations of heat exposure. Vials were held at 46 ± 0.5°C for 0, 3, 6, 12, 24, or 48 h in an oven (Thermocenter TC40/ TC100, Salvis Lab, Rotkreuz, Switzerland) and then transferred to an incubator maintained at 30°C and total darkness. There were four replicates for each treatment concentration and duration. After 24 h, 20 similarly-sized *T. castaneum* late-instar larvae were introduced in to each vial and held at 30°C in total darkness. After 3 wk, adults were counted.

Experimental Design. The experiment that examined the effects of surface, temperature, and duration had a complete randomized four-factor factorial design. The four factors were the surface type (concrete or varnished wood), treatment (adjuvants or methoprene), temperature to which the surfaces were exposed (20, 30, or 35°C), and duration at each temperature before the bioassay (0, 8, 12, 16, 20, or 24 wk). The experimental design for effect of flour was a completely randomized four-factor factorial design. The four factors were the surface type (concrete or varnished wood), treatment (adjuvants or methoprene), presence–absence of flour, and duration at 30°C before the bioassay (0, 8, 12, 16, 20, or 24 wk). The experiment on effect of cleaning on concrete surfaces was a completely randomized three-factor factorial design. The three factors were the treatment (adjuvants or methoprene), presence–absence of flour, and duration at 30°C before the bioassay (0, 4, 8, or 16 wk).

The experiment on the effect of high temperatures on residual efficacy was a completely randomized three-factor factorial design. The three factors were the treatment (adjuvants or methoprene), surface type (concrete or varnished wood), and duration at 65°C (0, 6, 12, 24, or 48 h). The experiment for residual efficacy of methoprene on wheat maintained at high temperature was a completely randomized two-factor factorial design. The two factors were the concentration (water, adjuvants, 0.0030, 0.0083, 0.0165, or 0.0330 ppm), and duration at 46°C (0, 3, 6, 12, 24, or 48 h).

Data Analysis. Residual efficacy of methoprene was determined as the percentage of adults emerged. The percentage of adults emerged was transformed using the square root of the arcsine to accommodate the unequal variances associated with percentage data. These data were analyzed by factorial analysis of variance (ANOVA) procedures of the SAS (SAS Institute 2002–2008). Significance was tested at $P < 0.05$.

The specific analysis performed varied with the experiment. In general, the data were analyzed to determine effect of treatment (methoprene versus adjuvants), surface type (concrete versus varnished wood), temperature of exposure, and duration of exposure. After the initial analysis, significant effects were further characterized by statistical modeling. In the experiment that tested effects of surface, temperature and duration, the emergence was regressed on the duration, *t*-tests were used to test the null hypothesis that the slope and intercept were significantly different than zero. In the experiment that tested effect of cleaning, correlation between cleaning frequency and adult emergence was sought. In the experiment that tested residual efficacy of methoprene on wheat maintained at high temperature, contrasts were employed to determine whether there was a difference between water and adjuvants on adult emergence.

Results

Experiments at Normal Temperatures. Surfaces treated with adjuvants had significantly higher adult emergence than those treated with methoprene ($F_{1,216} = 1978$; $P < 0.0001$). With adjuvants, adult emergence on concrete and varnished wood was 99.9 ± 0.1 and 99.6 ± 0.2%, respectively. Because the adjuvants did not affect adult emergence, data were then analyzed only for the methoprene treatments. From methoprene treated surfaces, concrete had greater adult emergence than varnished wood surfaces ($F_{1,108} = 111$; $P < 0.0001$). There was no adult emergence on varnished wood, even after 24 wk. Adult emergence on concrete increased with duration ($F_{5,54} = 5.83$; $P = 0.0002$), but there were no significant differences in adult emergence between the three temperatures ($F_{2,54} = 1.92$; $P = 0.16$), and no interaction of temperature with duration ($F_{10,54} = 0.35$; $P = 0.96$). Therefore, for a given duration, emergence data for three temperatures were pooled. These average adult emergences were ≈22 and 50% after 8 and 16 wk, respectively (Fig. 1). On these pooled data, the average emergence was significantly affected by the duration ($F_{5,66} = 6.27$; $P < 0.0001$). There was a positive correlation between duration and emergence (emergence [%] = 4.4 ± 7.6 + 2.5 ± 0.5 × duration (wk); coefficients ± SE; adjusted $R^2 = 0.252$; intercept $t = 0.58$, $P = 0.563$, slope: $t = 4.998$, $P < 0.0001$) (Fig. 1). Lack-of-fit was tested and found nonsignificant ($F_{4,66} = 1.53$; $P = 0.204$), indicating that there is no

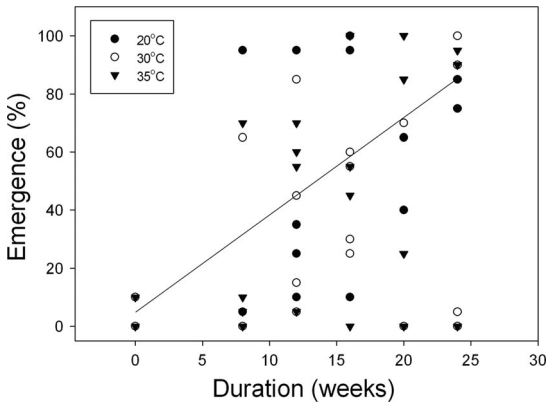

Fig. 1. Average adult emergence from *T. castaneum* late-instar larvae exposed to concrete surfaces treated with the label rate of methoprene for 3 wk. Before introducing larvae, the surfaces were held at 20, 30, or 35°C for 0–24 wk ($n = 12$; 20 larvae per replicate).

significant nonlinearity in the pattern of emergence over the duration.

In the experiment that examined the effect of flour, the surfaces treated with adjuvants had at least 93.8 ± 3.8% adult emergence and was greater than emergence on the methoprene treatments ($F_{1,144} = 1{,}892$; $P < 0.0001$). For surfaces treated with methoprene, no adults emerged on varnished wood (0% emergence); hence, the value was significantly different from that of concrete ($F_{1,72} = 295$; $P < 0.0001$) (Table 1). The adult emergence on the surfaces with flour was compared with that on corresponding surfaces that had similar conditions and used in the previous experiment (same surface type sprayed with the same solution) but had no flour. As on surfaces that did not have flour, there was no adult emergence on varnished wood surfaces treated with methoprene that subsequently received flour. In general, the residual efficacy changed with the presence or absence of flour ($F_{1,72} = 70.1$; $P < 0.0001$) and duration ($F_{5,72} = 10.6$; $P < 0.0001$). The interaction of surface by duration was also significant ($F_{5,72} = 10.6$; $P < 0.0001$). Because the emergence on varnished wood did not change from zero during the 24 wk, a subsequent ANOVA was performed only on concrete. In the overall analysis, there was a significant difference in the adult emergence on concrete surfaces with respect to duration ($F_{5,36} = 10.7$; $P < 0.0001$), presence of flour ($F_{1,36} = 70.1$; $P < 0.0001$), and the interaction of duration by presence of flour ($F_{5,36} = 3.1$; $P = 0.02$). Adult emergence on surfaces with flour was significantly higher than emergence on surfaces without flour at 8-, 12-, 16-, and 20-wk durations. This significant interaction shows that declines in residual efficacy due to the presence of flour differed with the time lapse (e.g., amount of change at 24 wk was different than that at 0 wk).

In the experiment that evaluated effects of cleaning on concrete, surfaces treated with adjuvants had 100% adult emergence at all times, and they had significantly higher adult emergence than those treated with methoprene ($F_{1,90} = 155$; $P < 0.0001$) (Table 2). Comparing the treatments that were not cleaned and either had flour or no flour after spraying (Table 2), there was a significant difference of duration on adult emergence ($F_{3,24} = 5.96$; $P = 0.004$) (Table 1). There was no effect of flour on emergence ($F_{1,24} = 2.72$; $P = 0.11$). Also, there were no significant differences in the adult emergence due to cleaning frequency ($F_{2,45} = 2.45$; $P = 0.0975$). Comparing only the treatments that had cleaning, there was a significant positive correlation between cleaning frequency and emergence when the data from durations 4, 8, and 16 wk were combined ($r^2 = 0.123$, $P = 0.039$; $n = 36$). However, for a given duration, there was no significant correlation between cleaning frequency and emergence ($P > 0.10$; $n = 12$).

Experiments at High Temperatures. In these experiments, the concrete and varnished wood surfaces treated with adjuvants had 100% adult emergence. The adult emergence on surfaces treated with adjuvants was significantly higher than on methoprene-treated surfaces ($F_{1,60} = 1{,}557$; $P < 0.0001$). Adult emergence was significantly higher on concrete surfaces than on varnished wood surfaces ($F_{1,60} = 44.0$; $P < 0.0001$). Because there was no variation from zero in the adult emergence on varnished wood surfaces treated with methoprene, only the data on concrete surfaces were used in the subsequent analysis. The adult emergence on concrete surfaces treated with methoprene did not differ with the duration at 65°C ($F_{4,15} = 1.35$; $P = 0.27$) (Table 3).

In the experiment that examined the residual efficacy on wheat, based on the contrast statements used in analysis, there was no significant difference between water and adjuvants in terms of adult emergence ($F_{1,108} = 1.52$; $P = 0.22$). However, there was a significant difference in adult emergence between the controls (water and adjuvants) and methoprene con-

Table 1. Percentage of adult emergence (mean ± SEM) from late-instar larvae of *T. castaneum* held on methoprene-treated concrete surfaces (with or without flour) for 3 wk at 30°C ($n = 4$; 20 larvae per replicate)

Presence of flour	Adult emergence (%)					
	0 wk	8 wk	12 wk	16 wk	20 wk	24 wk
Without	2.5 ± 2.5a	16.3 ± 16.3a	37.5 ± 18.0a	42.5 ± 8.8a	17.5 ± 17.5a	48.8 ± 26.8a
With	5.0 ± 5.0a	96.3 ± 3.8b	100 ± 0b	100 ± 0b	92.5 ± 7.5b	100 ± 0a

The surfaces were held at 30°C for 0-24 wk before introducing larvae. Means followed by the same letter in a column are not significantly different according to Tukey's test ($P < 0.05$).

Table 2. Percentage of adult emergence (mean ± SEM) from late-instar larvae of *T. castaneum* held on methoprene-treated concrete surfaces for 3 wk at 30°C (n = 4; 20 larvae per replicate)

Presence of flour	Cleaning frequency every 4 wk	Adult emergence (%)			
		0 wk	4 wk	8 wk	16 wk
Without	0	2.5 ± 2.5	26.7 ± 26.7[a]	71.7 ± 25.9[a]	76.7 ± 14.5[a]
With	0	5.0 ± 5.0	58.8 ± 22.9	76.3 ± 12.8	87.5 ± 7.5
With	1		61.3 ± 24.2	82.5 ± 12.7	96.3 ± 2.4
With	4		88.8 ± 8.3	100 ± 0	100 ± 0

Before introducing larvae, the surfaces were held at 30°C for 0–16 wk with different cleaning frequencies.
[a] This treatment had three replicates instead of four.

centrations ($F_{1,108}$ = 66.3; $P < 0.0001$). Therefore in the subsequent analysis, only the data with different methoprene concentrations were used to find the changes in the residual efficacy. The adult emergence significantly differed with the methoprene concentration ($F_{3,72}$ = 70.6; $P < 0.0001$). However, there was no effect of duration at 46°C ($F_{5,72}$ = 1.07; P = 0.38) or methoprene concentration by duration interaction ($F_{15,72}$ = 0.73; P = 0.75) on adult emergence, revealing that methoprene is stable for 48 h at 46°C (Fig. 2).

Discussion

Insecticidal control on different surface substrates depends on several factors, including but not limited to the surface and its cleanliness, the insecticide and formulation, duration of exposure, and insect species (Watters 1970, Toews et al. 2003, Guedes et al. 2008, Arthur et al. 2009). Degradation of a particular insecticide with time is common and is an important factor when assessing residual efficacy (Sutton et al. 2011); however, the rate of decline in efficacy also varies depending on the insecticide, formulation, substrate, and temperature (Watters et al. 1983, Arthur 2009).

In this study, residual efficacy of methoprene decreased with time on concrete, whereas on varnished wood it did not. There is little information on the degradation of methoprene on surfaces over time. Methoprene on cardboard paper loses its efficacy by 23%, after storage at 30°C for 50 d (Tan and Tan 1980). Hydroprene, a closely related juvenile hormone analog, applied on concrete declines in activity through 56-d posttreatment period (Arthur et al. 2009).

In our test, residual efficacy declined more quickly on concrete than on varnished wood. The varnished layer covering the wooden surface may have acted as a physical barrier for the penetration of methoprene into the wood; thus, the presence of higher amounts of methoprene on its surface would have reduced the adult emergence. A previous study shows that methoprene is less effective at preventing the emergence of *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) when applied to concrete than on wood or laminated paper (Jenson et al. 2009). Many insecticides are less persistent on concrete than other surfaces (Williams et al. 1983, White and Leesch 1996, Hagstrum and Subramanyam 2006), although there are exceptions, such as the higher residual efficacy for deltamethrin dust (Arthur 1997) and for the halogenated pyrrole chlorfenapyr on concrete compared with unvarnished plywood (Arthur 2008). In field trials with aerosols containing methoprene, the residues were persistent on concrete (Arthur 2010). This discrepancy may be a result of differential particle sizes being applied in surface liquid treatments compared with aerosols. In the current test, varnishing the wood may have contributed to the greater residual persistence compared with concrete.

There are several possible reasons for the general lack of residual efficacy on concrete surfaces. The high porosity of concrete may enhance penetration of the insecticide emulsion into the concrete, thereby reducing the amount of residue on the surface and less

Table 3. Percentage of adult emergence (mean ± SEM) from late-instar larvae of *T. castaneum* held on methoprene-treated concrete surfaces for 3 wk at 30°C (n = 4; 20 larvae per replicate)

Duration at 65°C (h)	Adult emergence (%)
0	23.8 ± 8.3
6	35.0 ± 5.4
12	22.5 ± 12.7
24	35.0 ± 12.7
48	10.0 ± 10.0

Before introducing larvae, the surfaces were held at 65°C for 0–48 h.

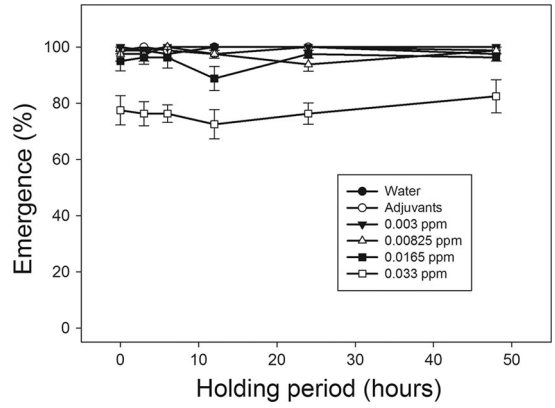

Fig. 2. Percentage adult emergence (mean ± SEM) from *T. castaneum* late-instar larvae exposed to wheat treated with different concentrations of methoprene for 3 wk. Before introducing larvae, wheat was held at 46°C for 0–48 h (n = 4; 20 larvae per replicate).

is transferred to the insect. Also, concrete has high pH (≈10.5), and this increases hydrolysis of insecticides (White and Leesch 1996). Sealing concrete increases persistence of the contact insecticide cyfluthrin (Arthur 1994) that also may be necessary to enhance effectiveness of methoprene.

Adult *T. castaneum* have increased survival when provided with food during or after exposure to insecticide (Arthur 2009, Toews et al. 2010). Mechanisms by which flour reduces efficacy of insecticides on surfaces have been suggested, including providing a barrier for the contact of insects with insecticide residues on the surface, supplying nutrition to the insects, or removing insecticide on the insect body via some physical and or chemical interaction (Arthur 2000). Regular cleaning reduces the food available to insects and is an important component of management programs in elevators, warehouses, and cereal processing facilities to control stored-product insects (Hagstrum and Subramanyam 2006). However, the removal of flour on surfaces may have a negative effect on insecticidal efficacy of IGRs such as methoprene that are directed toward control of immature life stages of *T. castaneum.* Additional studies are needed in grain storage facilities with real cleaning methods to better estimate the duration of methoprene efficacy. Although residual efficacy on varnished wood was not reduced by flour, the presence of high amounts of flour would favor the population build up if larvae do not come into contact with the residues on the surface. In such conditions, cleaning of surfaces is required, and future research is needed to determine whether methoprene is removed by the combination of the presence of flour and cleaning on varnished wood.

These experiments show that methoprene is stable from 20 to 35°C for several months and representative conditions for indoor conditions of flour mills and food processing plants. In addition, these studies show methoprene stability for at least 48 h on concrete held at 65°C and wheat held at 46°C, suggesting that methoprene would be compatible with insecticidal heat treatments in structures or commodities. This is good, as some insecticides degrade faster as temperature increases (Hagstrum and Subramanyam 2006). For example, the residual efficacy of chlorpyrifos methyl applied on wheat declines more when held at 35°C than at 15°C (Arthur et al. 1992). Further research is required to determine how the duration of methoprene efficacy is reduced. The current study shows that varnished wood is a better surface for methoprene application, compared with concrete. In contrast, the rapid decline in efficacy on unfinished concrete surfaces suggests that methoprene alone would not be a successful long-term control agent on concrete floors and walls, and needs alternatives as reapplication of methoprene is expensive. Depending on how much pest population build-up a grain storage manager can tolerate, this reapplication may need to take place every eight or 12 wk on concrete surfaces. In contrast, such reapplication is not necessary on varnished wood for 24 wk after application. However, further research is necessary to determine when methoprene begins to fail on varnished wood. Mixing methoprene with some other insecticide that is effective on unfinished concrete and sealing the concrete with paint, or varnish may be considered (Arthur 1994).

The results of efficacy of methoprene surface treatments in relation to the presence of flour and its cleaning warrant further research, especially when considering the fact that the immature stages may be predominant in a resident infestation of *T. castaneum* within a milling or storage facility (Campbell et al. 2010a,b). Therefore, increasing insecticidal efficacy toward the immature populations that may be present in these hidden refugia within a milling facility would be a consideration for pest management programs. Other cleaning practices such as vacuuming or blowing of air on the concrete floor may affect differentially on the duration of residual efficacy of methoprene. Because the toxicity of a given insecticide differs with different insect species, it is also important to test other stored-product insect species for the residual efficacy of methoprene under the conditions used in these experiments.

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