Evaluation of Two Least Toxic Integrated Pest Management Programs for Managing Bed Bugs (Heteroptera: Cimicidae) With Discussion of a Bed Bug Intercepting Device

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ABSTRACT The cost and effectiveness of two bed bug (*Cimex lectularius* L.) integrated pest management (IPM) programs were evaluated for 10 wk. Sixteen bed bug–infested apartments were chosen from a high-rise low-income apartment building. The apartments were randomly divided into two treatment groups: diatomaceous earth dust–based IPM (D-IPM) and chlorfenapyr spray–based IPM (S-IPM). The initial median (minimum, maximum) bed bug counts (by visual inspection) of the two treatment groups were 73.5 (10, 352) and 77 (18, 3025), respectively. A seminar and an educational brochure were delivered to residents and staff. It was followed by installing encasements on mattresses and box springs and applying hot steam to bed bug–infested areas in all 16 apartments. Diatomaceous earth dust (Mother Earth-D) was applied in the D-IPM group 2 d after steaming. In addition, bed bug–intercepting devices were installed under legs of infested beds or sofas or chairs to intercept bed bugs. The S-IPM group only received 0.5% chlorfenapyr spray (Phantom) after the nonchemical treatments. All apartments were monitored bi-weekly and retreated when necessary. After 10 wk, bed bugs were eradicated from 50% of the apartments in each group. Bed bug count reduction (mean ± SEM) was 97.6 ± 1.6 and 89.7 ± 7.3% in the D-IPM and S-IPM groups, respectively. Mean treatment costs in the 10-wk period were \$463 and \$482 per apartment in the D-IPM and S-IPM groups, respectively. Bed bug interceptors trapped an average of 219 ± 135 bed bugs per apartment in 10 wk. The interceptors contributed to the IPM program efficacy and were much more effective than visual inspections in estimating bed bug numbers and determining the existence of bed bug infestations.

KEY WORDS *Cimex lectularius*, apartments, control, integrated pest management

Bed bug (*Cimex lectularius* L.) infestations have increased rapidly in recent years throughout the United States, as well as in Canada, Europe, Australia, and some African countries (Harlan 2006). In the United States, 29% of professional pest management companies are involved in bed bug management (Gangloff-Kaufmann et al. 2006). The number of bed bug infestations increased from 1 to 87 within 26 mo in a high-rise apartment building. Bed bug bites cause raised, inflamed reddish wheals, which may itch for several days (Thomas et al. 2004, Ter Poorten and Prose 2005). Although they are not known to transmit human diseases, bed bugs severely reduce quality of life by causing discomfort, anxiety, sleeplessness, and ostracism (Hwang et al. 2005). Residents living in bed bug–infested apartments often discard their furniture and sleep on sofas or floors.

Insecticide applications are always recommended for bed bug elimination (Doggett 2007), yet exclusive reliance on insecticides has not always proven successful in effectively eliminating bed bugs (Potter et al. 2006, 2008; Wang et al. 2007). Furthermore, widespread bed bug resistance to pyrethroids in the United States is becoming evident (Romero et al. 2007) and if not curbed will further exacerbate management difficulties. In addition, applying insecticides directly to mattresses or sofas creates a high risk of human/pesticide exposure.

Low-income housing is particularly challenged by bed bug infestations because (1) the pest control budget is usually limited and not adequate for eradicating bed bug infestations and (2) resident cooperation is often limited because of their financial capability or social behavior. For instance, some residents may refuse to give up their furniture or wash bed bug–infested materials, as recommended by pest control professionals. Incidents of misuse of pesticides by "do-it-yourselfers" were reported by pest control companies (Potter 2008). Many chemicals purchased by consumers for bed bug control, such as bleach, rubbing alcohol, boric acid dust, and pyrethroid aerosol spray, are not labeled or not effective for controlling

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bed bugs. Some consumers seek chemicals for bed bug control from internet vendors. Overall, there is a lack of knowledge among consumers not only about what pesticides can be used for bed bug control but also what nonchemical control options are available. Therefore, there is a critical need for developing effective and least toxic (i.e., use nonchemical options and insecticides with low toxicity to humans and other animals) bed bug management techniques.

Nonchemical methods are always advocated as an important part of bed bug management programs to reduce bed bug populations (Kells 2006, Doggett 2007). Recommended methods include hygiene, physical removal, heat, steam, cold, and mattress encasements. Nonchemical tools are touted as being both more immediate and safer than insecticides (Potter et al. 2007). However, adoption of nonchemical only methods is dubious because they are thought to provide minimal residual effect and are often expensive.

Integrated pest management (IPM) strategies, integrating both chemical and nonchemical tactics, are generally recognized as potentially more effective and sustainable than chemical-only controls. However, specific IPM techniques within an IPM strategy may vary. In addition, data on the cost effectiveness of bed bug IPM programs are lacking. Availability of such data has been found to be a determining factor in the public adoption of IPM programs in public schools (Fournier et al. 2003). This is expected to be equally true in bed bug IPM implementation. The objective of this study is to evaluate the cost and effectiveness of two least toxic bed bug IPM strategies in apartments: (1) diatomaceous earth dust-based IPM (D-IPM), which included hand removal, bed bug interceptors, mattress encasements, hot steam, and diatomaceous earth dust, and (2) 0.5% chlorfenapyr-based IPM (S-IPM), which included hand removal, mattress encasements, hot steam, and 0.5% chlorfenapyr spray, but no bed bug interceptors. The chemicals used in the IPM programs have very low toxicity (diatomaceous earth) or reduced risk (chlorfenapyr) as recognized by the U.S. Environmental Protection Agency.

Materials and Methods

Study Site and Selection of Apartments. The study site was a 15-story apartment building located in Indianapolis, IN. The building had 225 one-bedroom apartments occupied by low-income elderly or disabled people. The first bed bug infestation was reported to the management office in December 2005. Approximately 87 apartments experienced bed bug infestations as of February 2007.

A careful visual inspection was conducted in apartments with reported bed bug infestations. In each apartment, the bed was disassembled and thoroughly inspected with the aid of a flashlight and forceps. Other upholstered furniture, wheelchairs, perimeters of the floors, curtains, and boxes stored under the bed or in the closets were inspected for bed bugs. Sixteen apartments with at least 10 bed bugs per apartment were identified. Eight of them never received treatment before this study. Three apartments were treated by a pest control contractor with pyrethroid spray and dust 2–4 wk before our survey. Residents applied pyrethroid aerosol spray, bleach, or boric acid dust in eight apartments. In addition, four residents discarded their infested beds and used a sofa or air mattress as a bed. One resident replaced his beds three times during the 6-mo period. The 16 apartments were randomly assigned into one of the following two groups: D-IPM and S-IPM. Detailed number of bed bugs (excluding eggs) and their distribution pattern were recorded.

Treatment Protocol. Within a week after inspection, mattress encasements (Protect-A-Bed, Northbrook, IL) were installed over mattresses and box springs in 14 apartments. Two apartments did not receive encasements because no bed or only an air mattress was in the apartments. After encasement installation, hot steam was applied to bed frames, floors under the beds, perimeter of the floor, sofas, and other infested furniture in all 16 apartments. Two steam machines were used: Steamy 4100 (Hi-Tech Cleaning Systems, Columbus, OH) and Ladybug XL2300 (Advanced Vapor Technologies, Edmonds, WA). Bed linens were placed in plastic bags and the residents were asked to launder them. Residents were also advised to both launder their bedding materials weekly and reduce clutter as part of the bed bug management program.

In the D-IPM group, bed bug interceptors were installed under infested bed frame legs and/or sofa legs to intercept bed bugs traveling between the furniture and the floors. The bed bug interceptors consisted of two plastic bowls (Fig. 1). The large bowl (IKEA New Haven, New Haven, CT) was 6 cm high with a 18-cm diameter at the bottom and a 15-cm diameter at the top. Fabric was glued to its exterior wall to allow bed bugs to climb the bed bug interceptors. The inner wall of the bowl was smooth. Bed bugs that reached the top of the bowl were subject to falling into the bottom of the bowl, which contained $\approx$40 ml of 50% ethylene glycol as a killing agent. The small bowl was a plastic container 7 cm high with a 9-cm bottom diameter and a 10.5-cm top diameter. The small bowl was placed inside the large bowl and formed a trench between the large and the small bowl. The inner bottom of the small bowl was covered with a mixture of diatomaceous earth (50%) and talcum powder (50%) as killing agent. Furniture legs were placed inside the small bowl. Bed bugs from the room that were trying to reach the human host on bed or sofa would climb the large bowl and fall into the killing agent (ethylene glycol). Bed bugs from furniture crawling into the small bowl by furniture legs were not able to escape into the large bowl because of the small bowl's hard smooth inner surface and talcum power (as an extra preventative measure).

Diatomaceous earth (Mother Earth-D; Whitmire Micro-Gen Research Laboratories, St. Louis, MO) was applied to bed frames, sofa (the back, underside, and seams), along baseboards and molding, and electric

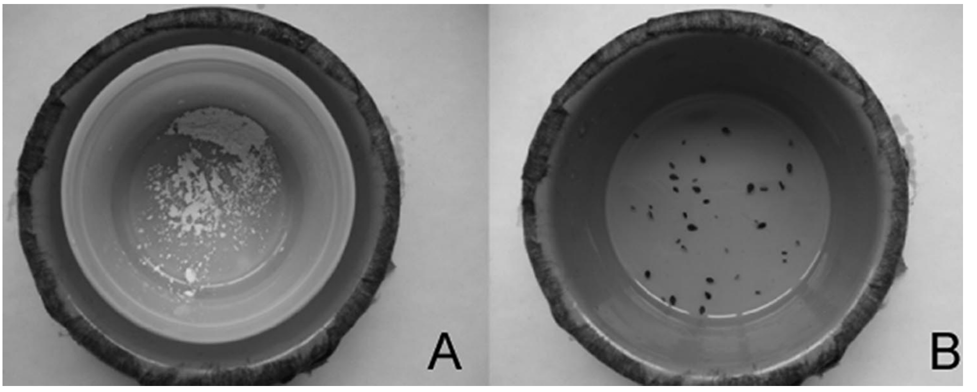

Fig. 1. Bed bug interceptor placed under furniture legs for intercepting bed bugs traveling between the furniture and the floor. (A) Top view of a bed bug interceptor that consisted of a small and a large plastic bowl; ≈40 ml 50% ethylene glycol was in the large bowl as a killing agent; a mixture of diatomaceous earth (50%) and talcum powder (50%) was placed in the small bowl for killing bed bugs and preventing escape. (B) The small bowl was removed to show the bed bugs trapped in the large bowl.

outlets 2 d after steaming. The dust was not applied immediately after steaming to avoid potential loss of efficacy because of moisture left by the steaming process.

In the S-IPM group, 0.5% chlorfenapyr (Phantom insecticide; BASF, Research Triangle Park, NC) was applied to bed frames and headboards, along baseboards and molding, sofas and chairs (the back, underside, and seams), floors under the beds, and other bed bug harborage areas (such as infested wheelchairs and curtains) immediately after steaming. No bed bug interceptors were installed under infested furniture legs in this treatment group because some beds did not have frames and our objective was to evaluate the effectiveness of the two IPM programs.

Additional hot steam, dust, or spray was applied as necessary during 2-, 4-, 6-, 8-, and 10-wk follow-up inspections except for the last inspection. Two or three entomologists (the authors and two research assistants) worked together in each apartment. Those apartments adjacent to the test apartments were monitored and treated monthly by the existing pest control contractor.

Program Evaluation. The test apartments were visually reinspected at 12- to 18-d intervals for 10 wk after the initial treatment. Bed bugs discovered during these inspections were either hand removed (with forceps) or killed with hot steam. The number of bed bugs in bed bug interceptors was recorded, and these were removed during each bi-weekly inspection. The technician time (time in an apartment multiplied by the number of technicians) spent for servicing each apartment was recorded.

The costs of materials and labor were estimated using the following rates: encasements, $100/set (for a full-size mattress and box spring); diatomaceous earth dust, $0.025/g; chlorfenapyr, $0.671/liter; bed bug interceptors, $2/bed bug interceptor; labor, $60/h. The cost for hot steaming was negligible and not included in calculating the IPM program cost.

Data Collection and Analysis. The service time, initial bed bug counts (logarithmic transformed), and number of hot steam or chemical applications were compared between the two IPM groups using analysis of variance (ANOVA; SAS Institute 2003). Effect of the two IPM strategies on visual counts (cube root transformed) was evaluated using repeated measurement analysis and the initial count as covariant. Similarly, the effectiveness of the two IPM strategies was compared with the chemical-only (cyfluthrin dust and deltamethrin spray) strategy that was conducted on the same property by the same research team (Wang et al. 2007). Five apartments that had >10 bed bugs from the 2007 study were included. The difference of bed bug counts between large and small bowls of the bed bug interceptors and differences between visual inspection counts and bed bug interceptor counts in each apartment were compared using the Student's *t*-test (SAS Institute 2003).

Results

Initial Bed Bug Counts and Distribution. The initial visual inspection identified 16 heavily infested apartments. These were randomly divided into two groups. The median (minimum, maximum) counts were 73.5 (10, 352) in the D-IPM group and 77 (18, 3025) in the S-IPM group. The mean counts (mean ± SEM) were 103 ± 38 and 507 ± 366, respectively, and were not significantly different from each other ($F = 0.79$; df = 1,14; $P = 0.39$).

The average relative abundance of bed bugs by location was as follows: mattress, 22%; box spring, 60%; bed frame, 4%; sofa and chair, 13%; other areas, 1%.

Effectiveness of the IPM Treatments. Figure 2 shows the bed bug count (by visual inspection) reduction after the IPM implementation. D-IPM resulted in significantly greater mean count reduction than S-IPM ($F = 3.9$; df = 10,69; $P < 0.001$). At week 2, both treatments resulted in >74% count reduction.

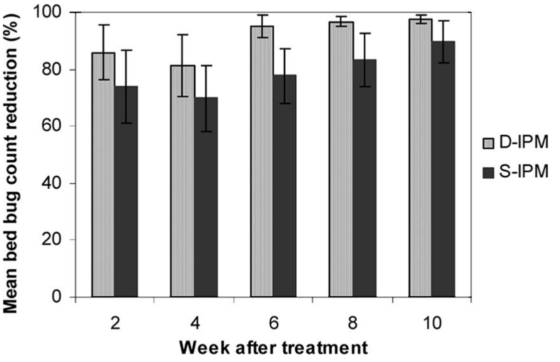

Fig. 2. Bed bug count reduction (mean ± SEM) after implementation of D-IPM and S-IPM in apartments.

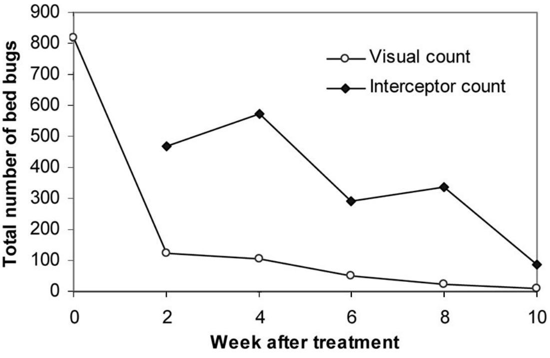

Fig. 3. Bed bug counts from visual inspections and bed bug interceptors in eight apartments.

By week 10, mean bed bug count reduction by D-IPM and S-IPM were 97.6 ± 1.6 and 89.7 ± 7.3%, respectively. Bed bugs were eradicated (based on visual inspections and resident interviews) from 50% of the apartments in both groups. The maximum numbers of bed bugs found in each apartment at week 10 was 4 and 32 in the D-IPM and S-IPM groups, respectively.

Effectiveness of Bed Bug Interceptors for Detecting Bed Bug Infestations and Reducing Bed Bug Numbers. Many more bed bugs were trapped in bed bug interceptors than were discovered through visual inspections (Table 1; Fig. 3). The mean bed bug counts per apartment from bed bug interceptors (10 wk trapping period) and visual inspections (five bi-weekly inspections) were 219 ± 135 and 39 ± 22, respectively. The bed bug interceptor counts were significantly higher than the visual counts (t = 7.0; df = 7; $P <$ 0.001).

The large and small plastic bowls comprising the bed bug interceptors caught an average of 207 ± 127 and 13 ± 8 bed bugs in each apartment. In each apartment, there were significantly more bed bugs in large bowls than in the small bowls ($t = 7.6$; df = 7; $P <$ 0.001), indicating there were more bed bugs from the rooms off the beds and sofas than those on the beds and sofas after the initial treatment (installing encasements, steaming, and applying insecticides). Based on the total bed bug numbers found through initial visual inspection and cumulative counts in bed bug interceptors, the mean (minimum, maximum) percentage of bed bugs on beds and sofas was 56% (23, 88%) at the beginning of the study.

Cost of the IPM Programs. There were no significant differences in the mean number of steam and chemical applications and mean service time between the two IPM strategies (Table 2). A total of 319 g of diatomaceous dust (D-IPM) and 16 liters of 0.5% chlorfenapyr spray (S-IPM) were applied. The average insecticide cost per apartment was only $1.01 for the dust and $1.35 for the spray. Thus, the vast majority of the included cost was technician time and mattress encasements. For apartments that received one set of encasements, the mean IPM program cost was $463 and $482 per apartment in the D-IPM and S-IPM groups, respectively.

Discussion

Results from this study suggest several important considerations in bed bug management: (1) bed bug interceptors are a valuable tool for estimating bed bug populations, reducing bed bug numbers, and providing immediate relief to residents from bed bug bites; (2) IPM regimens such as those used in this study reduce pesticide use and human/insecticide exposure risks; (3) effective residual insecticides are needed for bed bug elimination; (4) multiple inspections and treatments are necessary to eradicate bed bug infestations.

Table 1. Comparison of bed bug counts from visual inspections and bed bug interceptors

Apartment	No. bed bug interceptors	Furniture type	Total bed bug counts in 10 wk: Bed bug interceptors	Total bed bug counts in 10 wk: Visual inspection (total of five inspections)
1	10	Bed, sofa	411	102
2	8	Bed, sofa	41	2
3	4	Bed	21	1
4	4	Bed	38	6
5	4	Bed	8	3
6	4	Bed	90	22
7	8	Bed, chair	43	7
8	6	Sofa[a]	1103	166

[a] The bed was discarded by resident in this apartment.

Table 2. Treatment information of the two bed bug IPM programs over 10 wk

Treatment information	D-IPM	S-IPM
Number of hot steam applications	2.3 ± 0.5a	2.6 ± 0.5a
Number of chemical applications	2.6 ± 0.3a	2.5 ± 0.3a
Total technician time (min)	346 ± 57a	381 ± 47a

Values are mean ± SEM. Means in the same row followed by the same letters indicate no significant differences ($P > 0.05$).

Bed bug interceptors placed under furniture legs provided a mechanical barrier to bed bugs traveling between the floor and the furniture. Metal cans and glass containers were used in the early 1900s to reduce bed bug bites (Pinto et al. 2007). We found one resident placed oil-filled metal cans under bed legs to prevent bed bug bites during our field inspections before this study. Adding cloth to the bed bug interceptors in this study enabled bed bugs to climb the bed bug interceptors and become trapped. The bed bug interceptor provided both protection of humans from bed bug bites and detection of bed bugs. In addition, the interceptor design allows for determination of relative number of bed bugs traveling to the furniture and from the furniture.

The furniture legs had various shapes, and some sofas rested directly on the small bowls of the bed bug interceptors. Some sofas had loose flaps of fabric that touched the large bowl. In addition, some residents placed clothes or bed linens against the wall, forming bridges for bed bugs to access the bed or sofa from the floor to the furniture. These conditions impaired the full effect of the interceptors and may have contributed to the reappearance of bed bugs on furniture.

Another interesting finding from this study is that there were many more bed bugs from off the bed and sofa than previously thought. Visual inspections in this study and earlier studies in apartments found >85% of the bed bugs were on beds and sofas (Potter et al. 2006, 2008; Wang et al. 2007). By comparing results of both visual inspection and bed bug interceptors in this study, we found only 56% of the bed bugs were on beds and sofas. The actual distribution on furniture might be even lower because the insecticides and hot steam might have killed much more bed bugs in the room than those counted by visual inspections. This finding implies that pest management professionals must pay equal attention to furniture and other areas (such as baseboards, dressers, and clutter around the beds and sofas) in an infested room when conducting inspections and treatments.

All live bed bugs found during inspection were removed or killed with hot steam. However, many more bed bugs were trapped in bed bug interceptors afterward, indicating that visual inspection was only a tool for estimating bed bug populations. Bed bugs were found in bed bug interceptors from two of the "eradicated" apartments (based on visual inspections) between weeks 8 and 10 (one and two bed bugs in each apartment, respectively). Thus, bed bug interceptors are very useful for detecting low numbers of bed bugs and eliminating bed bug populations. Furthermore, it is much easier, economical, and less intrusive to install interceptors than to conduct laborious visual inspections.

The IPM programs included mattress encasements and hot steam in an attempt to reduce insecticide use and improve control efficacy. Compared with the chemical-only treatment (pyrethroid dust and spray) conducted in the same apartment complex (Wang et al. 2007), the D-IPM resulted in a similar level of bed bug population reduction ($F = 0.02$; df = 1,43; $P = 0.08$); the S-IPM resulted in significantly lower population reduction ($F = 10.1$; df = 1,43; $P < 0.01$). Interceptors might have had substantial impact on the differences in effectiveness of the two IPM regimens. Potter et al. (2008) reported chlorfenapyr spray alone eradicated bed bugs from one third of the apartments after 12 wk. In our study, a combination of chlorfenapyr and nonchemical tools resulted in eradication from 50% of the apartments after 10 wk.

Compared with the chemical-only treatment (Wang et al. 2007), the D-IPM reduced dust use by 19% and avoided the use of spray. The S-IPM reduced spray use by 30% and avoided the use of dust. Compared with the chemical treatment reported by Potter et al. (2006), the S-IPM reduced insecticide spray (for the initial treatment) by 83%. Compared with chlorfenapyr-alone treatment by Potter et al. (2008), the S-IPM reduced chlorfenapyr use (for the initial treatment) by 62%. More importantly, no chemicals were applied to mattresses and box springs in both IPM programs, thus reducing the risk of human/insecticide exposure. For asthma patients who are allergic to indoor allergens, the encasements and hot steam were anticipated to be helpful in relieving their asthma symptoms by reducing allergens on bed or floors. Additional benefits of installing encasements and applying hot steams were discussed by Pinto et al. (2007).

Even with multiple tools and bi-weekly monitoring and treatments, bed bugs were not eradicated in 50% of the infested apartments after 10 wk. We observed bed bugs covered with diatomaceous earth residues on a very thoroughly treated sofa. We also noticed bed bugs at a corner of an infested bedroom floor after two chlorfenapyr spray applications (4 wk apart). However, pest control companies reported successful control of bed bugs with a combination of chlorfenapyr spray and DE dust or pyrethroid dust (J. Black, personel communication). Field studies evaluating the efficacy of registered bed bug control chemicals are rare. Such studies would be extremely helpful for designing effective bed bug management programs. This study was not designed to compare DE and chlorfenapyr. We were interested in evaluating the effectiveness of two IPM programs. Therefore, we could not draw any conclusions on the relative effectiveness of the two insecticides. How to effectively incorporate residual insecticides, especially low-risk chemicals, into bed bug IPM programs needs to be studied with the goal of rapid bed bug eradication.

This study confirmed that managing bed bug infestations in apartments is a difficult and expensive task.

The cost will be even higher for treating apartments with multiple beds. Follow-up monitoring and treatments are necessary (Pinto et al. 2007, Potter 2008). Residents' attitudes toward bed bug infestations varied greatly. Many of the residents involved in this study were not aware of and/or were not concerned about bed bug infestations. At the end of this study, none of the residents complained about bed bug bites. However, 50% of the apartments still had bed bugs. Thus, relying on resident reporting and interviews will not provide accurate information on bed bug infestations. Many residents did not or were unable to wash bed bug–infested linens and reduce clutter. One resident did not like our frequent visits and treatments, despite her bed bug infestation. She brought in a bed bug–infested chair during our study, which contributed to the eradication failure in her apartment.

Bed bug–infested medical equipment (wheelchairs, walkers) was frequently used by residents in common areas of the building. We found bed bugs in sticky traps placed in the hallways and signs of bed bugs on sofas in the common area of the building. Without a building-wide intensive IPM implementation, including education and remotivation of residents and active staff participation in monitoring and assisting with IPM implementation, any existing bed bug infestation will persist and spread within the community and to other communities.

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