Characteristics of *Cimex lectularius* (Hemiptera: Cimicidae), Infestation and Dispersal in a High-Rise Apartment Building

CHANGLU WANG,[1] KURT SALTZMANN,[2] EVA CHIN,[2] GARY W. BENNETT,[2] AND TIMOTHY GIBB[2]

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ABSTRACT Bed bugs, *Cimex lectularius* L. (Hemiptera: Cimicidae), are a fast-growing urban pest of significant public health importance in the United States and many other countries. Yet, there is very little field research on the ecology of this pest due to its near absence in the United States and most developed nations for several decades. We investigated characteristics of the bed bug infestation and dispersal in a 223-unit high-rise apartment building through visual inspections, intercepting devices, and resident and staff interviews between December 2008 and April 2009. The following results were obtained: 1) 101 apartments (45% of the high-rise building complex) experienced bed bug infestations (within 41 mo of the first confirmed introduction), 2) 78% of the bed bugs trapped were nymphs, 3) an average of six bed bugs were detected dispersing through apartment entry doors every 4 wk, 4) adult bed bugs were 9 times more likely to disperse than nymphs, 5) 53% of apartments adjacent to infested apartments also were infested, and 6) 50% of the interviewed residents who had infestations were unaware of the bed bugs in their apartments. In addition to active dispersal, several passive bed bug dispersal mechanisms were observed: bringing bed bug-infested furniture into the building, travel, resident turnover, resident visits, and use of a bed bug-infested wheelchair in building common areas. These findings validate an urgent need for public education, early detection, and adoption of more effective bed bug monitoring and intervention programs to curb the exploding problem of bed bug infestations.

KEY WORDS *Cimex lectularius*, bed bug, dispersal, monitoring

Bed bug, *Cimex lectularius* L. (Hemiptera: Cimicidae) infestations are on the rise across the United States (Gangloff-Kaufmann et al. 2006). They have been found in diverse settings such as single family homes, multi-unit dwellings, hotels, schools, hospitals, shelters, and public transportation. Bed bug resurgence has been reported in Canada, Australia, and some European countries (Boase 2004, Hwang et al. 2005, Doggett and Russell 2008, Kilpinen et al. 2008). Although evidence of disease transmission by bed bugs is lacking (Goddard 2009), they are important public health pests as their bites can cause significant discomfort and anxiety (Reinhardt and Siva-Jothy 2007). As a result, bed bugs have recently become the subject of significant media attention.

Despite intense interest in curbing the global bed bug resurgence, there are few recent field studies on bed bug biology and ecology. The scarcity of bed bugs in recent decades has contributed to a lack of current practical applied information available to citizens plagued by these insects. Scattered field observations and research reports imply that increased international travel, insecticide resistance, and lack of effective chemical control tools may have led to the bed bug resurgence (Doggett et al. 2004, Potter 2005, Romero et al. 2007). Until present, there is no systematic investigation on how bed bugs spread and how infestations increase rapidly in many communities.

Bed bug dispersal is known to be closely related to human activities such as travel and using infested furniture, but little information is available on bed bugs' active dispersal behavior. Doggett and Russell (2008) reported that the number of bed bug-infested units in a 320-room medical facility increased from 1 to 68 rooms in 50 mo, suggesting that bed bugs have the potential to spread within a building once introduced. If detected early, bed bug infestations can be contained and eradicated, but once established in multiple apartments in a building, bed bugs are much more difficult to eliminate. Thus, understanding bed bug dispersal behavior and factors contributing to bed bug spread is critical to developing effective bed bug control programs and curbing the spread of bed bug infestations.

During 2006–2008, rapid spread of bed bug infestations occurred in a high-rise apartment building in Indianapolis, IN. The explosive occurrence and spread of bed bugs in the building presented a significant financial burden (furniture replacement, increased laundry expenses, professional bed bug control costs) to the residents and the management office. The build-

[1] Corresponding author: Department of Entomology, Rutgers University, New Brunswick, NJ 08901 (e-mail: cwang@aesop.rutgers.edu).
[2] Center for Urban and Industrial Pest Management, Department of Entomology, Purdue University, West Lafayette, IN 47907.

Fig. 1. Interceptors placed in apartments for detecting bed bugs and their dispersal between apartments: (A) an interceptor under a bed leg, (B) two interceptors in the hallway beside an apartment door, and (C) an interceptor behind the entry door.

ing managers, staff, and the pest control provider implemented both nonchemical and chemical tools to manage the bed bugs. In addition, chemical (Wang et al. 2007) and integrated pest management (IPM) (Wang et al. 2009a) programs were implemented by researchers from Purdue University. Yet, many infested apartments were always present in the building. As a part of our long-term goal of developing more effective and sustainable bed bug management programs, we investigated the characteristics of bed bug infestation and dispersal in the building during December 2008–April 2009. We attempted to answer the following questions: What factors contributed to the spread of bed bugs? How often do bed bugs disperse from infested apartments? How effective is the bed bug control program currently in place?

Materials and Methods

Study Site. The study site was a 15-story apartment building located in Indianapolis, IN. The building had 223 one-bedroom apartments occupied by low-income elderly or disabled people. Each apartment had a bedroom, a living room, a kitchen, and a bathroom (total 45 m^2 per apartment). According to the management office's records, the bed bug infestation in this building is thought to have originated from a single resident who moved into a unit on the 12th floor of the building. The bed bug infestation was not detected and reported to the building management until >10 apartments were infested. The building was serviced monthly by a pest control contractor who used a variety of chemical pesticides including pyrethroids, chlorfenapyr, alcohol, and diatomaceous earth in an effort to control the pests. Upon request from residents, the housing authority staff applied hot steam directly to bed bug harborage areas using a Ladybug XL2300 Steam Vapor Cleaner (Advanced Vapor Technologies, Edmonds, WA). In addition, C.W. and T.G. treated 24 infested apartments during 2007–2008 and delivered a seminar and an educational brochure to residents.

Survey of Bed Bug Infestations. A list of the apartments with reported/suspected bed bug infestations was obtained from the management office in December 2008. This was immediately followed by visual inspections and resident interviews (if residents were available) about the history of the infestation, past bed bug control efforts, and resident awareness of bed bugs in their apartments. Conducting resident interviews allow us to detect any discrepancy between visual inspections and resident reports as well as other useful information on bed bug infestations. The beds, sofas, other upholstered furniture, wheelchairs, perimeter of the floors, curtains, and boxes stored under the beds or in the closets were closely inspected by C.W., K.S., and E.C. with the aid of flashlights. Beds were disassembled if possible for inspection. Each apartment was inspected for ≈20–30 min (or 0.7–1.5 person hours). All bed bugs (except the egg stage) were hand-removed with forceps during inspections.

Monitoring Bed Bug Populations. Immediately after visual inspection in each apartment, CLIMBUP Insect Interceptors (Susan McKnight, Inc., Memphis, TN), referred to hereafter as "interceptors," were installed under legs of the beds, sofas, and upholstered chairs (Fig. 1A). Interceptors are an effective tool for detecting low-level bed bug infestations and for evaluating the effectiveness of bed bug management programs (Wang et al. 2009a,b). The inside surfaces of the interceptors were coated with a light layer of talcum powder to make the traps slippery and prevent trapped bed bugs from escaping. A 10-cm-diameter, 5-cm-tall polyvinyl chloride (PVC) pipe was placed in the center of each interceptor to support beds or sofas that did not have legs or if the furniture footer was too big for the interceptors. The exterior and interior surfaces of the PVC pipes were lightly coated with talcum powder to prevent trapped bed bugs from climbing back onto the furniture. The number of trapped bed bugs were identified by location in the interceptor (inner well or outer well) and developmental stage approximated with the aid of a 10× handheld magnifier according to the key of Usinger (1966). Interceptors were placed in a total of 64 apartments and were inspected and cleaned every 2–3 wk after installation for a maximum of 15 wk.

After an apartment was identified as having bed bugs, the two adjoining units and the two units immediately across the hallway from the infested unit were also inspected. If no bed bugs were found, the apartments were inspected again 1–3 mo later to confirm the absence of bed bugs. Residents from ≈15% of

the apartments declined the inspection services, citing their belief that bed bugs were not present.

Monitoring Bed Bug Dispersal Among Apartments. We hypothesized that bed bugs frequently move to the entry door area of an apartment and from there disperse into adjacent apartments via the hallways. To test this hypothesis, we placed a pair of interceptor traps baited with a lure provided by Bedoukian Research Inc. (Danbury, CT) in the hallways beside the entrance doors of five bed bug-infested apartments (Fig. 1B). The lure was formulated as a slow-release block and was placed in the center of the interceptors. Laboratory studies revealed the lure was attractive to bed bugs from short distances (<30 cm) (our unpublished data).

Because of esthetic concerns from the management office, the interceptors were removed from the hallways 7 d after installation. Interceptors were then placed behind the entry doors in eight infested apartments (Fig. 1C). The distance from the interceptor traps to the upholstered furniture in the living rooms or the bedrooms was 3–4.8 m. Among the eight apartments, interceptors were installed within 1 wk after visual inspection in five apartments, 2 wk after visual inspection in one apartment, and 2 mo after visual inspection in two apartments. The interceptors were examined every 2–3 wk for 15 wk. The lures were replaced at 4–6-wk intervals and each lure had minimum expected life of 30 d based on laboratory test results from the manufacturer.

Data Analysis. Regression analysis was used to evaluate the relationship between trap counts from interceptors and visual inspections. Analysis of variance (ANOVA) was used to compare logarithmic transformed interceptor counts and infestation levels determined by visual inspections. This was followed by Tukey's honestly significant difference test to separate the means. ANOVA also was used to compare the logarithmic transformed counts from interceptor inner wells and outer wells. All analyses were performed using SAS software (SAS Institute 2003).

Results

Bed Bug Infestations. The only species of bed bug encountered during this study was *C. lectularius.* Based on visual inspections, bed bugs from interceptor traps, resident and staff interviews, and records from the management office, 101 known apartments experienced bed bug infestations as of April 2009 (within 41 mo of the first confirmed infestation). This number represented 45% of the apartments in the building. Visual inspections revealed 53 active infestations, each with 64.5 ± 15.8 (mean ± SEM) bed bugs. Relative location of these infested apartments was characterized as the following two categories: adjoining apartments on same floor, 53% and apartments across the hallway, 45%.

Residents in 40 apartments with previously reported bed bug infestations were interviewed to determine their level of awareness of bed bugs in their apartments. Among them, only 12 were aware of bed bug activity in their apartments. Visual inspection alone in these 40 apartments revealed 24 active infestations, indicating that bed bugs' cryptic nature can lead to significant disparity between resident reports and visual inspections. The fact that some people show no visible, dermal reaction (based on resident self-examination) nor cite pain or pruritus after bed bugs take a bloodmeal contributes to some infestations going unnoticed.

The maximum number of bed bugs trapped in interceptors placed under furniture legs (in a single apartment) was 551 within a 4-wk period. In addition, 25 bed bugs were intercepted immediately behind the entry door of this apartment within a 5-wk period. This resident was unaware that the apartment was infested and misinterpreted the red welts as symptoms of an allergic reaction to underarm deodorant.

Twenty bed bug-infested apartments were chosen to compare the effectiveness of visual inspections and interceptors for estimating bed bug numbers. After hand removal of all the bed bugs found by visual inspections, the interceptors further detected bed bugs in 17 apartments. Mean visual count and interceptor count (12-wk period) were 45 ± 18 and 67 ± 16, respectively. Therefore, visual inspections missed a large number of bed bugs. The apartments were grouped by level of infestation: low (1–10 bed bugs per apartment), medium (11–100 bed bugs per apartment), or high (>100 bed bugs per apartment) based on visual inspections before installation of interceptors. Mean number of bed bugs from interceptors were: 21 ± 8, 96 ± 32, and 155 ± 33, respectively. Apartments with medium and high infestation levels yielded significantly more bed bugs in interceptors than those with low infestation levels ($F = 7.7$; df = 2, 17; $P = 0.004$).

Bed Bug Treatment Methods. Among the 40 surveyed residents, 40% used chemicals to control bed bugs themselves, 35% discarded furniture, and 20% purchased synthetic pyrethroid sprays or insecticide foggers from stores or internet vendors. Other chemicals used by residents included alcohol, bleach, and boric acid dust. Nonchemical control methods used by residents included washing clothes and bedding materials, covering cracks on walls with tape, placing blankets under the doors and installing encasements on mattresses and box springs. Fifty percent of the surveyed residents indicated they had received treatment for bed bugs from a pest control contractor hired by the housing authority that manages the building.

Bed Bug Population Structure and Dynamics. Dynamics of the bed bug numbers as detected by interceptor traps were recorded in 20 infested apartments (Fig. 2). Data from other infested apartments were not reported here because of resident turnover, disposal of furniture by residents, or incomplete data. Visual counts of bed bugs before interceptor installation ranged from 1 to 345. The mean bed bug counts decreased 77% from sampling period 0–4 wk to 9–12 wk (Fig. 2). At 12 wk, bed bugs were still present in 11 of the 20 apartments, demonstrating that in this case

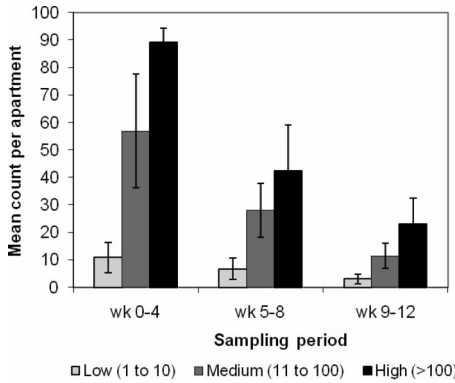

Fig. 2. Dynamics of bed bug counts (mean ± SEM) from interceptors placed under furniture legs. The apartments were grouped into low (1–10 bed bugs per apartment, n = 10), medium (11–100 bed bugs per apartment, n = 7), and high (>100 bed bugs per apartment, n = 3) infestation levels based on visual inspections before installation of interceptors.

contractor pest control efforts were ineffective in eliminating the bed bug infestations.

In total, 1,540 trapped bed bugs were examined for their developmental stage and location in the interceptors. Among them, 78% were nymphs and 89% were found in the outer well of the trap (suggesting movement into the trap from the room). Significantly more bed bugs were in the outer well than those in the inner well (F = 11.97; df = 1, 128; P = 0.001). Thus, most of the bed bugs missed by visual inspections were not on the furniture. Nymphs accounted for 81 and 77% in inner well and outer well, respectively. Greater than 98% of the bed bugs trapped in the interceptors were dead at the time traps were checked.

Bed Bug Dispersal Between Apartments. Three of the five pairs of interceptors placed in the hallways trapped two bed bugs per pair after 1 wk, supporting our hypothesis that bed bugs used hallways as a route for dispersal. The mean visual counts from these five apartments before placing the interceptors were 196.4 ± 58.7 per apartment. The average number of bed bugs detected at entry doors over 4 wk period was 6 ± 2 (n = 8) and the maximum was 42. Among the 138 bed bugs examined that were caught at entry doors (dispersing), 30% were nymphs, including first instars. Some of the first instars were from eggs laid by trapped adult females as evidenced by the presence of empty eggs in interceptors. The difference between the proportion of nymphs at entry doors versus under furniture indicates that adult bed bugs were 9 times more likely to disperse than nymphs.

The total number of bed bugs from interceptors placed at entry doors were positively correlated with the visual counts (F = 16.5; df = 1, 5; P = 0.01; R^2 = 0.74.) but were not correlated with the counts from interceptors under furniture legs (F = 0.62; df = 1, 5; P = 0.47). The mean visual counts and counts from interceptors (4 wk period) placed under furniture legs were 96 ± 34 and 112 ± 30, respectively. Most of the neighboring apartments of these sampled apartments were either not infested or had much lower bed bug populations than the sampled apartments. We therefore considered the bed bugs trapped in the interceptors at entry doors as dispersing from, not moving into, the sampled apartments.

The interviews and field observations revealed the following additional bed bug dispersal mechanisms: bringing in infested furniture, using an infested wheelchair in the building common areas, improper removal of infested furniture (e.g., not wrapping infested furniture in plastic before removal from the building), resident visits to infested apartments or common areas, and visits by guests harboring bed bugs on their clothing or belongings.

Discussion

Several important characteristics of bed bug infestation and dispersal were observed in this study. First, bed bug infestations have potential to spread into many rooms within a building after introduction. Second, bed bugs frequently disperse through entry doors to the hallways. Third, a large percentage of residents may be unaware of extant bed bug infestations in their apartments. Fourth, bed bug control efforts by either residents themselves or by a contracted pest control professional are often ineffective in eliminating bed bug infestations. Fifth, bed bug interceptors are an effective tool in estimating bed bug populations and evaluating the effectiveness of bed bug management programs.

Bed bugs were frequently intercepted beside entry doors of the infested apartments. Although chemical lures were used in the interceptors to detect bed bug dispersal, a separate study in nine apartments indicated that the presence of lures did not significantly increase the number of trapped bed bugs (our unpublished data). Thus, we considered the counts from interceptors placed at entry doors or in the hallways to be random catches of bed bugs that were passing through those areas. Furthermore, it is likely that more bed bugs dispersed through the doors and hallways without being detected. Besides doorways, bed bugs may disperse through common walls of adjacent units. This study was not designed to investigate the presence and frequency of these dispersal venues. However, we found bed bugs hiding in electrical outlets, corners of ceilings, and behind baseboards on the floors. When pathways to the neighboring units exist from these sites, bed bugs can migrate into the neighboring units (on the same floor level, immediately above or below the infested unit) through walls or ceilings. Because bed bugs will disperse to the hallways and their dispersal frequency is positively correlated with bed bug population levels, building-wide bed bug monitoring and treatment programs must be in place to effectively eradicate bed bugs in a building. Simultaneous treatment will reduce bed bug dispersal and help achieve building-wide bed bug elimination.

This study confirmed that interceptors are an effective tool for detecting bed bug infestations, evalu-

ating the effectiveness of bed bug management programs, and providing peace of mind to concerned residents that they do not have bed bugs in their apartments (Wang et al. 2009a,b). Visual inspections alone were not reliable for estimating bed bug numbers. Examining interceptors is rapid and more efficient than visually inspecting an apartment (a few minutes versus hours per apartment). For full effectiveness of the interceptors, it is necessary to install them properly and clean them regularly. Although all residents who received interceptors welcomed the device, some of them did not try to keep their bed sheets or blankets from touching the walls or floors. Thus, bridges were formed between the beds and the floors or walls. Bed bugs could climb to the beds through these bridges. In addition, excessive dust was brought into the interceptors by resident activities in some apartments. In cases where bed bugs entered dust-covered interceptors, it is possible some of the insects could escape by crawling out of the interceptors.

The dynamics of the interceptor counts showed that the contractor's pest control practice (monthly application of pesticides in reported apartments) was inadequate and less effective compared with the IPM program conducted in the same building (Wang et al. 2009a). Interceptors not only helped determine the effectiveness of the bed bug management program but also served as a nonchemical tool for killing bed bugs because the trapped bed bugs could not escape and a majority of the trapped bed bugs died when examined at 2–3-wk intervals. The high mortality of bed bugs in the interceptors was at least partially due to the existence of talc powder in the interceptors. Replacing talc powder with fluoropolymer resin (DuPont Polymers, Wilmington, DE) can significantly reduce the mortality (our unpublished data). When the number of bed bugs in an apartment is small, the advantage of installing interceptors is even more pronounced as they catch the few bed bugs present, reduce the risk of population build-up, and could reduce the need for application of pesticides.

Each resident in the building received a bed bug educational brochure and were invited to an educational seminar on bed bugs, before this study. Yet, 50% of the residents in infested apartments were unaware of their infestations. These residents were either not sensitive to bed bug bites, had no dermal reaction based on their description, or mistakenly thought the bed bug bite symptoms were due to other causes. Five hundred and fifty one bed bugs were trapped in one apartment within a 4-wk period. This resident was a frequent traveler (>4 travel days per week) and was unaware of bed bugs in the apartment. One resident used a bed bug-infested wheelchair in the building common areas on a daily basis and was regularly visited by social workers and friends in his apartment, even though he was aware of the bed bug infestations. One sofa in the common area was found with 10 adult bed bugs on 18 June 2008. The sofa was subsequently treated with hot steam and discarded. Approximately 15% of the residents declined inspection services. They believed their apartments were not infested. However, their observations were not necessarily accurate as revealed by our inspections in other apartments. These cases demonstrate the enormous risks of bed bug spread and the necessity for more aggressive education efforts to detect bed bug infestations in their early stage, and reduce the spread of bed bugs within and between communities.

Although bed bug infestations are not reported to be related to building quality or socioeconomic status of the residents, once introduced, infestations in low-income communities are especially difficult to eradicate. Eliminating bed bugs is a very difficult and expensive task (Doggett and Russell 2008, Potter 2008). Financial constraints from housing authorities and low-income residents prevented them from adopting some important bed bug management options (such as installing mattress encasements, frequent laundering, replacing heavily infested furniture, spending more time on monitoring and control). The large proportion of apartments (45%) that experienced bed bug infestations within a relatively short period after the problem was first reported underscores the importance of concerted effort and greater financial input. Several of the surveyed apartments in this study were infested for more than two years. The active and passive bed bug dispersal mechanisms observed during this study and the rapid spread of bed bug infestations suggest an urgent need for more effective bed bug monitoring and intervention programs to curb the exploding problem of bed bug infestations. Without such efforts, bed bug infestations will continue to spread in our society and likely become much more widespread in low-income housing in the years to come. Bed bugs cause more than discomfort and pain. Bed bug infestations have economic, social, and legal ramifications (Potter 2006). Thus, it is critical to act early to prevent bed bug infestations from becoming chronic and incurring much greater health and economic consequences.

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