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Review Article: Bed Bug Detection: Current Technologies and Future Directions

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Abstract. Technologies to detect bed bugs have not kept pace with their global resurgence. Early detection is critical to prevent infestations from spreading. Detection based exclusively on bites is inadequate, because reactions to insect bites are non-specific and often misdiagnosed. Visual inspections are commonly used and depend on identifying live bugs, exuviae, or fecal droplets. Visual inspections are inexpensive, but they are time-consuming and unreliable when only a few bugs are present. Use of a dog to detect bed bugs is gaining in popularity, but it can be expensive, may unintentionally advertise a bed bug problem, and is not foolproof. Passive monitors mimic natural harborages; they are discreet and typically use an adhesive to trap bugs. Active monitors generate carbon dioxide, heat, a pheromone, or a combination to attract bed bugs to a trap. New technologies using DNA analysis, mass spectrometry, and electronic noses are innovative but impractical and expensive for widespread use.

INTRODUCTION

The common bed bug, *Cimex lectularius* L., is an obligate blood-feeding ectoparasite that preferentially feeds on humans. Global bed bug infestations were common into the 1930s and 1940s until the advent of synthetic pesticides that were commonly used to control bed bugs and other urban pests. From World War II to the 1960s, dichlorodiphenyltrichloroethane (DDT) proved to be an inexpensive, toxic, and effective residual treatment against many arthropods, including bed bugs,[1,2] and bed bugs were thought to be eliminated from human habitations in the United States.[3,4] In the past two decades, populations of *C. lectularius* have increased in North America, Europe, and Australia.[5–7] Although peer-reviewed studies on the resurgence of bed bugs are generally lacking, industry surveys[8] report a 100-fold increase in calls for bed bug control, and almost all pest control operations currently respond to bed bug problems. Explanations for this resurgence include but are not limited to increased international travel, changes in pest control practices for other urban pests, increased trade in secondhand furniture, and widespread bed bug resistance to most commercially available pesticides registered for use against this blood-sucking insect.[2,9,10]

Public health importance. All stages of the bed bugs feed on blood and require a blood meal to molt (nymphs) and reproduce (adults). Although many pathogens have been isolated from bed bugs, including hepatitis B virus and antibiotic-resistant bacteria, to date, no laboratory evidence supports the role of bed bugs as biological vectors of any virus, bacteria, or protozoa.[11–18] Bed bug bites are annoying, and the clinical manifestations of their bites can vary from little (if any) irritation to both immediate and delayed immune reactions of varying degrees to severe allergic hypersensitivity.[6,19–23] Heavy infestations of bed bugs with repeated bites can also result in the patients presenting with anemia.[24–26] Because bed bugs have not been shown to transmit pathogens, the reaction to their bites has generally been considered of minor medical importance. However, studies revealing the underlying immunological responses to bed bug bites are emerging,[27,28] and a better understanding of the salivary components that likely play a role in the immune response is also being revealed.[29–31] The histological features associated with certain severe reactions to the bites reflect a localized but destructive inflammation of blood vessels.[32] The clinical features of bed bug bites have been recently reviewed.[6]

Mental health is an aspect of public health, and there are numerous reports in the lay media of a variety of mental health issues associated with bed bug infestations. The few peer-reviewed articles on this subject document the effects of bed bugs as psychosocial stressors that can result in nightmares, insomnia, anxiety, depression, social isolation, and even suicidal thoughts.[33,34] Delusional parasitosis, a mistaken belief that one is infested with a parasite or parasites, may also present.[34]

The US Centers for Disease Control and Prevention (CDC) and the US Environmental Protection Agency (EPA) consider bed bugs a pest of "significant public health importance" and an emerging public health problem across the United States.[35] The CDC has also documented 111 cases of poisoning associated with pesticide misuse by individuals attempting to rid themselves of bed bugs.[36]

Financial impact and societal concerns. The overall economic impact of bed bug infestations is difficult to document and may range from thousands of dollars to control infestations and replace bedding and furniture to millions of dollars because of negative publicity and lawsuits by people who encounter bed bugs in apartments, hotels, and workplaces. A 2006 Australian survey conservatively estimated the financial impact of bed bugs to that country at AU$100 million, a figure that likely doubled by 2011.[37] In the United States, the revenue generated in 2011 by the pest control industry specific to bed bug detection and control was estimated at $409 million.[38] A separate, although related, issue is the cost of litigation involving the resolution of bed bug encounters.[39–41] The National Pest Management Association has compiled and made available a list of state bed bug laws, many of which detail tenant/landlord issues concerning bed bugs.[42]

The bed bug problem is exacerbated for disadvantaged and low-income people who may not have resources to treat infestations, thereby allowing them to both expand within properties and act as a reservoir for new infestations elsewhere. Several comprehensive web-based references directly address bed bug infestations in these environments,[43,44] and management strategies for these environments are beginning to emerge.[45] The control of bed bugs in different

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socioeconomic groups is being regarded by some as an issue of social justice.[46,47]

The goal of this review is to discuss current detection techniques for bed bugs, including new information about canine inspection, and examine new opportunities for detection technologies.

CURRENT TECHNOLOGIES

Early detection of bed bug infestations is problematic, because bed bugs are cryptic and spend most of their lives in harborages consisting of cracks, crevices, or similarly concealed areas. Moreover, reactions to insect bites are often non-specific and easily misdiagnosed. Because bed bug bites may not cause a reaction or the reaction is misdiagnosed, infestations can reach a relatively large size before being noticed. The intensity of an infestation is also subjective; there are no standard industry definitions for light, medium, and heavy infestations. In addition, finding insect debris in the bedroom or surrounding areas does not necessarily mean that bed bugs are present, because other insects, such as fleas or carpet beetles, could be mistaken for bed bugs by the untrained eye. Interviews with tenants are unreliable; many people do not realize that they have bed bugs, or they are unwilling to report infestations, because they feel ashamed or anxious about intrusive control strategies. Therefore, the basis of all control strategies starts with an inspection to determine if bed bugs are present and the extent of the infestation. The need to detect an infestation as early as possible is summarized by the statement "that when bed bug infestations reach a certain size, even the best, most aggressive actions often fail to meet expectations."[48]

Several methods are commonly used to identify a bed bug infestation, including (1) visual inspection, (2) passive and active monitoring devices, (3) canines trained to find bed bugs, or (4) a combination of these methods. All of these methods have advantages and disadvantages when time, cost, and effectiveness are considered, and a disadvantage may be magnified in low-level infestations, where only a few bed bugs and their eggs exist. The following sections discuss these different inspection methods.

Visual inspection. The internet can be a good source of information in this regard, and there are numerous websites that discuss the bed bug life stages and signs that indicate an infestation.[4,43,49–51] Individuals should be thoroughly familiar with this information before undertaking a personal inspection of their dwelling or business. Although live bed bugs can be difficult to find in small infestations because of their cryptic behavior, it is possible to identify an infestation by finding signs that bed bugs are present. Shed exoskeletons, known as exuviae, left behind by the immature stages after molting or spotting that results from fecal droplets deposited by all stages during and after blood feeding indicate a bed bug infestation. Visual inspection may be a low-cost alternative, requiring little more than a flashlight and magnifying glass, but it can also be time-consuming—especially when the inspection extends beyond the bedroom—and unreliable, significantly underestimating the intensity of an infestation. Visual inspection to detect bed bugs is covered in detail in the work by Pinto and others.[52]

Active and passive monitoring. There are numerous traps, lures, and monitors available to homeowners, tenants, and pest management professionals to detect bed bugs (Table 1). Passive monitors are essentially traps that use the sleeping human host as bait without a separate heat source or a chemical deemed to be an attractant. Passive monitors are placed behind a bed or sofa, beside furniture, or under furniture legs, where bed bugs might be expected to traverse while seeking a host. Their design often includes an adhesive or lubricant that prevents bed bugs from escaping. Passive monitors tend to be less expensive than active monitors, which use heat, a chemical attractant, or both. In a recent study, passive interceptor devices were more effective than visual inspection alone in identifying bed bug infestations and could play a role in integrated pest management programs.[53] For example, plastic bowls placed under the legs of sofas and beds trapped six to seven times as many bed bugs than were detected visually, thus simultaneously detecting and controlling bed bugs.[54]

Because chemical attractants are used in many active detectors and traps, a brief discussion of chemical terminology may prove useful. Chemical signals that transmit information between individuals form the basis of chemical ecology,[55] and chemical signals mediate most aspects of bed bug behavior. The word pheromone was first coined in 1959 by the German biochemist Peter Karlson and the Swiss entomologist Martin Lüscher to describe a chemical released by one individual that triggers a specific behavioral response in another individual of the same species.[56,57] Pheromones are characterized by the behavior that they elicit. For example, sex pheromones attract one sex to the other, whereas alarm pheromones alert members of the same species to potential danger. Alarm pheromones of bed bugs have been known since 1964, when the seminal work by Schildknecht and others[58] identified (*E*)-2-hexenal and (*E*)-2-octenal as bed bug-defensive secretions. This work was built on by Collins[59] and a series of papers by Levinson and Bar Ilan,[60] Levinson and others.[61,62] The buggy odor of *C. lectularius* was described in the early 1900s,[63] although this work preceded any mention of the odor's behavioral action or the identification of the compounds responsible. The resurgence of bed bug populations has resulted in a renewed interest in the chemical ecology of these pests, which in turn, has led to the discovery of two new alarm pheromones and new insights into how bed bugs use them.[64–67] Although alarm pheromones have been incorporated into some trapping or monitoring devices, they have also been used as part of a control strategy,[68] and alarm pheromones may play a role in canine detection of bed bugs (discussed below).

Aggregation pheromones are another type of chemical signal used for intraspecific communication, and evidence for these pheromones contributing to the gregarious behavior of bed bugs is increasing.[69–71] The chemical mixtures seem to be more complex, consisting in excess of 10 compounds, although the two alarm pheromones, (*E*)-2-hexenal and (*E*)-2-octenal, have been identified as part of the aggregation blend by at least one research group.[70] The unequivocal identification of a compound or blend of compounds that constitutes a definitive aggregation pheromone would represent a significant advance in the detection and possible control of bed bugs.

Pheromones belong to a larger group of biologically active chemicals now referred to as semiochemicals.[72,73] In addition to pheromones, semiochemicals include important chemical

TABLE 1
A comparison of active and passive monitors for bed bug detection

Device	Active or passive (principle behind the technology)	Approximate cost	Duration of use	Training and ease of use	Website
Catchmaster Bedbug Detection System (BBEDS)	Passive: Mimics harborages, traps bed bugs in adhesive	$0.70–1.00	30–90 days	Portable, discreet, uses adhesive. No special training. Requires handling dead bugs.	http://www.catchmaster.com/bbeds/bbeds.php
BuggyBeds	Passive: Textured, clear plastic tray; glue trap purportedly "lures bedbugs into the trap," although no specific attractant is named	$11.99 for a 4-pack; $28.99 for a 12-pack	"After a bed bug or other insect is found or after six months of use"	Portable, discreet, non-toxic glue trap. No special training. Requires handling dead bugs. Independent verification lacking.	http://www.buggybeds.com/
Trapper Monitor Insect Trap TM2600 by Bell Laboratories	Passive: Glue trap for monitoring bed bugs and other domestic pests	$0.25–0.50	Unknown	Portable, 7″ × 3.5″ cardboard trap adheres to surfaces. Not specific to bed bugs.	http://www.belllabs.com/product_details/south-africa-trapper-monitor-and-insect-trap
ClimbUp Insect Interceptor	Passive: coaster trap coated with talcum powder is placed under the legs of furniture; can be converted to an active monitor by adding dry ice	$34.00–80.00 for a pack of 12	Minimum of 7 days; may be left indefinitely	No chemicals; may require lifting heavy furniture; needs to be serviced periodically. Likelihood of handling live bugs might be objectionable.	http://www.insect-interceptor.com/
Bed Bug Alert (BB ALERT)	Passive: Small crevices mimic harborages; white border reveals fecal droplets	$21.08	Up to 1 year	No moving parts or consumables. No special training; must be able to identify bed bug fecal droplets.	http://www.bedbugsalert.com
	Active: Warmth and CO_2 emission	$29.96	Two nights over a 3- to 5-day period	Should be used overnight, between 6 and 9 p.m. Requires visual inspection of live bugs or their feces.	http://www.bedbugsalert.com
CDC3000 (no longer produced)	Active: Uses 45-g cartridges of CO_2, warmth, and a "synthetic attractant chemistry blend of pheromones and other bed bug attractants"	$999.00 (includes the device, three single-use CO_2 cartridges, and three single-use capture slides)	One CO_2 cartridge lasts 10 hours	About the size of a suitcase. Requires separate purchase of a "capture slide" or plastic insert with adhesive. The capture slide must be discarded after every use. Trapped bed bugs are contained within the unit; must open the device to see the bed bugs.	http://www.sternenvironmental.com/products/cdc-3000.php
NightWatch (no longer produced)	Active: Pitfall trap design combining CO_2 and a "patented thermal heat source"	$400.00–600.00 (includes the device, reusable pitfall traps, and four chemical lures); must purchase CO_2 cylinder separately	10 hours per day for up to 1 week	Bed bugs are captured and visible in wells attached to outside of the device.	http://www.biosensory.com/nightWatch-bedbug-monitor.cfm
Bed Bug Beacon by PackTite	Active: Pitfall trap with CO_2 and mineral oil to trap the bugs	$50.00	5 days	Must run monitor for at least 5 days or it will not attract recently fed bed bugs. Recommended not to sleep in the room while using this monitor. Three units recommended for an average-sized bedroom.	http://www.sternenvironmental.com/bedbugs/bedbug-beacon.php
FMC Verifi	Active: CO_2, kairomone, and aggregation pheromone	$30.00; replacement cartridges $7.00	90 days	Nontoxic, portable, discreet, silent. One technician, no tools required.	http://www.fmcprosolutions.com/BedBugs/Home.aspx

messengers called kairomones that elicit behavioral changes in species different than the emitter species, and the reader is referred to discussions of these semiochemical classes.[74,75] Many active bed bug monitors use compounds considered kairomones, such as carbon dioxide or other host odors that are components of human sweat or breath like proprionic acid, butyric acid, valeric acid, lactic acid, and octenol.[76] Carbon dioxide and heat have proven to be the two most effective attractants used for bed bug monitoring,[76,77] and human odor in the absence of carbon dioxide and heat seems to have a very weak influence on bed bug behavior.[78] Two active monitors, the CDC3000 (Stern Environmental Products, Secaucus, NJ) and the NightWatch (BioSensory, Inc., Putnam, CT), along with a homemade dry ice trap were evaluated for their ability to trap bed bugs.[79] In the study, the ClimbUp Insect Interceptor (Susan McKnight, Inc., Memphis, TN), a passive monitor, was used to estimate bed bug numbers before and after the use of the active monitors.[79] The work by Wang and others[79] concluded that the homemade dry ice trap was superior to commercial traps and that the passive monitor operating for 7 days trapped as many bed bugs as the homemade monitor in 1 day.[79] An active monitor baited with carbon dioxide, heat, and a proprietary kairomone blend was used to evaluate the population structure in two locations deemed heavily infested with bed bugs.[80] The work by Schaafsma and others[80] concluded that their trapping methodology caught a disproportionate number of first-instar nymphs.

A device has been patented that would generate infrared radiation and volatilize a cocktail of bed bug pheromones, including nonanal; decanal; (*E*)-2-hexenal; (*E*)-2-octenal; (*E,E*)-2,4-octadienal; benzaldehyde; benzyl alcohol; (+)-limonene; (–)-limonene; and sulcatone. To date, there has been no independent evaluation of the efficacy of this particular device.[81] The use of semiochemicals in monitoring and controlling bed bugs has recently been reviewed.[82,83]

Canine inspection. Because of the problems associated with visual inspections, pest control companies and individuals have incorporated canines in their inspection efforts.[52,84] Trained bed bug dogs were able to detect live bed bugs and eggs and distinguish bed bugs from other urban insect pests.[85] The keen canine sense of olfaction has previously been used in human search and rescue operations and detection of drugs, explosives, and foodstuffs.[86] Although the underlying chemical basis for these latter detections has been examined,[87–89] little or no information was available in this area regarding bed bug dogs. The report by Pfeister and others[85] that a solvent extract of live bed bugs was recognized by trained dogs as a bed bug scent piqued our interest in this area, particularly in light of our research on bed bug semiochemicals.[64,90,91] Using a dog trained on live bed bugs and bed bug eggs and used by a pest control firm to detect live bed bugs under field conditions, we conducted a proof of concept study to determine any role that bed bug semiochemicals might play in bed bug detection by canines.

Various amounts of two predominant bed bug alarm pheromones, (*E*)-2-hexenal and (*E*)-2-octenal (1:1, weight:weight; Bedoukian Research Inc., Danbury, CT), were applied in acetone to 47-mm filter paper disks to yield final concentrations ranging from 10 pg/cm^2 to 100 μg/cm^2. The two major cuticular hydrocarbons, *n*-nonacosane and *n*-hentriacontane (4:3, w:w; Sigma-Aldrich, St. Louis, MO) were applied to other filter paper disks, yielding concentrations of 10 and 100 μg/cm^2.

TABLE 2
Canine detection of bed bug semiochemicals*

Concentration (μg/cm^2)	Alarm pheromone†	Hydrocarbons‡
10^2	A§	NA
10^1	A	NA
10^0	A	–
10^{-1}	A	–
10^{-2}	A	–
10^{-3}	A	–
10^{-4}	A	–
10^{-5}	A	–
Live bed bugs (n = 6)	A	A
Control (acetone)	NA	NA

*Filter papers treated with chemicals (in acetone) were hidden without the knowledge of the handler or dog. Live bed bugs and acetone-treated filter paper acted as positive and negative controls, respectively. Search area ranged from 60 to 300 ft^2.
†(*E*)-2-hexenal + (*E*)-2-octenal (1:1, weight:weight) in acetone was applied to a filter paper disk and allowed to dry, yielding a final concentration expressed as micrograms per centimeter squared.
‡*n*-Nonacosane + *n*-hentriacontane (4:3, weight:weight) in acetone was applied in the same way as described above.
§A = positive alert (occurred when the dog sat and pawed the area); NA = no alert (occurred when the dog did not detect a specific sample); – = not attempted.

Because cast skins of immature bed bugs contain both alarm pheromones in their dorsal abdominal glands and cuticular hydrocarbons,[64,91] they were also used in our testing (N = 1–6; cast skins < 2 weeks old). Filter paper disks were treated with acetone and allowed to dry, and live bed bugs served as negative and positive controls, respectively. Treated paper disks, cast skins, and live bed bugs were hidden in offices and open spaces from 60 to 300 ft^2, and the locations in each trial were unknown to both the dog and the handler. The dog was able to detect live bed bugs and all concentrations of alarm pheromone, including 10 pg/cm^2 (the lowest concentration tested) (Table 2). However, the dog did not alert to the disks treated with cuticular hydrocarbons or acetone controls (Table 2). The dog used in this study also alerted on as few as one cast skin. Based on these findings, it is reasonable to conclude that a dog trained on live bed bugs will also alert to items other than live bed bugs, albeit items that contain a mixture of the two major bed bug alarm pheromones. The dog used in our study alerted to live bed bugs, filter paper treated with alarm pheromone, and cast skins 100% of the time. However, it is important to understand that our study was conducted in a semicontrolled environment—office spaces and rooms that were relatively uncluttered and did not have people present (handler and observer remained at the door threshold while the dog worked off leash). A recent study, using several dogs examining apartment complexes in several buildings, reported a lower and more variable success rate.[92] Studies involving the training and handling of scent detection dogs, in general, can also be found in the literature.[93,94] These studies show that the handler interaction with the dog is crucial and can have a profound influence on the reliability of subsequent detections.

FUTURE DIRECTIONS

Several new technologies to detect bed bug infestations have been discussed in the literature; most technologies require a laboratory equipped with sophisticated and expensive equipment for at least part of the analyses. For instance, a molecular diagnostic technique has been developed to distinguish bed bug fragments and parts from other insects that may be found in the same environment.[95] This technique, however, requires the extraction of DNA and the use of specialized molecular biology equipment. Another method, using solid-phase extraction techniques to sample air in a room infested with bed bugs, has been used combined with gas chromatography/mass spectrometry to detect and identify airborne chemicals associated with bed bug infestations.[96] The major bed bug alarm pheromones have been detected by this method, although specialized laboratory equipment is needed. A patent[97] and a patent application[98] exist on detection of residual bed bug antigens or antigens from digested human blood voided in bed bug feces. These molecules could act as specific biomarkers to detect infestations. One possible concern about technologies that detect residual pheromones or fecal droplets, however, is the likelihood of false positives in rooms that had bed bug infestations at one time but have since been treated with pesticides or heat.

Technologies that have been used to detect other insect species may eventually find use in a bed bug detection program. Electronic noses are instruments that detect volatile odor compounds at relatively low concentrations, and they have been used for the food industry and environmental monitoring.[99,100] A commercially available handheld product, the Cyranose 320 (Smiths Detection Inc., Pasadena, CA), has been shown to detect stink bug (Heteroptera: Pentatomidae) pests in crops under defined laboratory conditions.[101,102] Instrumentation that relies on acoustic detection to detect stored grain insect pests has also been examined for its efficacy in detecting bed bugs.[103] Finally, wasps have been trained to detect a fungal volatile chemical,[104] and the technology has been proposed for bed bug detection, although no commercially available product currently exists.

SUMMARY

Differential diagnosis of bed bug bites is difficult and insufficient to determine the presence of bed bugs or the extent of an infestation. Visual inspection is tedious and unreliable, and it requires too much time and training to be sustainable in large-scale multiperson housing such as an apartment or hotel. Canine inspections are increasingly popular, but they are expensive and may generate false positives or negatives depending on the expertise of the handler and the training/reward system used for the dog. In addition, canine inspections unintentionally advertise a bed bug problem, and dogs might offend certain religious groups. Passive monitors have no objectionable smell, and they are usually small and discreet enough for widespread use. Pitfall traps, as opposed to glue traps, might also be incorporated into a detection/control program. Evaluating the efficacy of passive monitors in light versus heavy infestations will be helpful, but these relative levels of infestation need to be defined. The most common complaints from pest control operators regarding active monitors are their cost, including purchase and maintenance, their cumbersome size, the constant sound of carbon dioxide dispersal, mechanical problems with carbon dioxide release, and the buggy odor of the pheromones. Some of the newer technologies—including molecular techniques, gas chromatography, and infrared sensors—are still impractical for widespread use by pest control operators and homeowners, and their efficacy needs to be evaluated empirically. None of these strategies are completely reliable, and a combination of different techniques may be necessary to detect early infestations. As with any detection or monitoring device, the development, commercialization, and subsequent use for bed bugs will be driven by cost, convenience, and efficacy.

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