Remote monitoring for bed bugs

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Figure 1. Bed bugs in countersunk screw hole in bed frame.

A global bed bug (*Cimex lectularius*) resurgence has continued throughout the past two decades, following a period of relative absence for most of the world between 1960 and 2000 (Boase, 2001; Reinhardt & Siva-Jothy, 2007). The cause of the modern resurgence is likely to be the result of multiple factors facilitating their survival, reproduction and spread. Insecticide resistance, increased foreign trade and travel, urbanisation and a reduction in the range of products available for bed bug control, have all been cited as likely factors (Doggett et al., 2018).

The negative impacts of a bed bug infestation can be far-reaching. Cutaneous reactions tend to be similar to that of a mosquito bite. This can vary from person to person and may be delayed by up to two weeks from when the bite occurred (Sansome et al., 1992). However, the health impacts extend beyond the cutaneous reaction. Bed bugs are recognised to be a significant source of anxiety and depression. People living with a bed bug infestation often experience severe loss of sleep, due to disturbance fear of being bitten. Many become isolated, either due to the fear of spreading bed bugs or due to the social stigma associated with having them. Bed bug-induced anxiety, isolation and loss of sleep can all contribute to lasting mental health impacts, in some cases triggering a recognised psychological condition, delusional parasitosis, where sufferers believe they are still experiencing an infestation long after the bed bugs have been eradicated.

For the hospitality and housing industries the economic impact of a bed bug infestation can be enormous (Doggett et al., 2018). Aside from the treatment cost, many businesses suffer lost revenue and reputational damage (e.g. when bitten guests post complaints on review websites like TripAdvisor.com). A study in the USA found that >80% of hotels surveyed were treated for bed bugs in 2015, with an average cost (treatment and loss of room) of $6,383 per event. Additionally, 45% of all surveyed hotels have faced litigation due to bed bugs, with an average cost of $23,560 per infestation (Orkin, 2016).

Biology

Bed bugs develop through five nymphal instars, requiring a single blood meal to moult to the next stage. The generation time in warm conditions (25-30^{o}C) may

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be as short as 6 weeks (Usinger, 1966). In cooler environments with no access to a host (e.g. seasonal holiday accommodation), bed bugs become inactive and may survive many months without feeding.

Bed bug foraging behaviour is triggered by the presence of host cues, such as carbon dioxide in exhaled breath. Heat and sebaceous skin secretions are also important directional cues once within range of the host (Reinhardt & Siva-Jothy, 2007).

Feeding typically takes a few minutes, in which time the abdomen becomes completely distended. Adult bed bugs consume between four and five times their body weight in blood in a single feed. The tendency for bed bugs to feed as soon as they climb onto the host's skin, or even from the surrounding fabric, presumably helps them to avoid detection by the host as they feed (Dean & Siva-Jothy, 2012), as well as producing the characteristic "bites in rows" that bitten people often observe.

After feeding, bed bugs seek out sheltered harbourages, usually within close proximity to the feeding site. Suitable harbourages tend to be dark and offer some physical protection, such as counter-sunk screw holes in a wooden bed frame. Bed bugs struggle to climb on smooth surfaces and so exhibit a preference for more textured surfaces, such as sawn wood (Figure 1.).

With time, these sites tend to become heavily soiled with faeces, cast skins and eggs, as well as aggregation pheromones, which help the bed bugs to locate their harbourage when returning from feeding excursions.

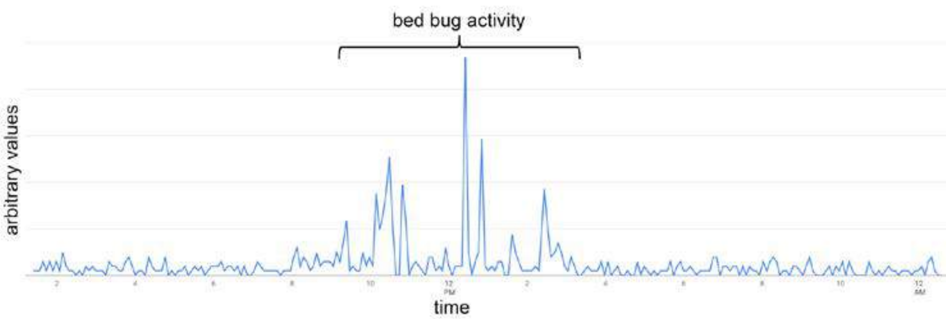

Figure 2. Variation in arbitrary capacitance values caused by activity of one bed bug within the monitoring device.

Monitoring devices:

Bed bugs often hide deep within the bed or headboard structure, so infestations can be difficult to identify in routine inspections. Some hotels employ the services of trained scent detection dog teams to identify infestations before they have a chance to spread. But many hotels simply rely on guest complaints to alert them to a bed bug issue when it arises. By this time, it may be too late to avoid the losses associated with brand damage and compensation claims. Because bite-reactions are often delayed, many guests do not realise they have been bitten until after they have left the hotel. Therefore, infestations often go undetected for some time, allowing them to spread to other parts have complained. In the domestic sector, monitors can be helpful for confirming treatment success and providing peace of mind for people anxious about bed bugs.

Monitoring devices for bed bugs have been developed to exploit several different aspects of their feeding/hiding behaviour. Some monitors mimic host cues, such as human skin secretions (e.g. ActivVolcano, SenSci, USA), carbon dioxide (e.g. Bed Bug Beacon, PackTite, USA), body heat (e.g. BB ALERT Active, Brandenburg UK Ltd.; Silvatronic Bug Dome, Silvandersson AB, Sweden), or a combination of the above (e.g. NightWatch Active Bed Bug Trap, BioSensory Inc, USA) to attract foraging bed bugs that are searching for a host. Other monitors mimic harbourage cues by emitting natural or synthetic cocktails of bed bug aggregation pheromones. These may take the form of a pitfall trap (e.g. Nattaro Scout, Nattaro Labs AB, Sweden; Bed Pod, Spotta Ltd., UK), or a glue board (e.g. Trappit BB Detector Plus, Barrettine, UK).

Passive monitors typically exploit the crevice seeking nature of bed bugs, by providing them with suitable hiding places, usually somewhere in the bed structure (e.g. BB Alert Passive, Midmos Solutions Ltd., UK). Passive monitors benefit from a long service interval as there is no chemical attractant to run out. However, correct positioning of the device is vital for the monitor to be effective. The photophobic nature of bed bugs tends to result in harbourages establishing in the darkest areas of the room, such as behind the head of the bed, where there is minimal light and physical disturbance. As such, these locations are optimal for passive bed bug monitor installation.

based on the passive, "harbourage-style" monitoring approach. Several effective harbourage monitors are based around corrugated cardboard, because the fluting in the cardboard provides the kind of dark shelter that freshly fed bed bugs are searching for, with a surface texture that is easy for them to walk on.

An electronic circuit was developed to detect bed bugs moving around inside a strip of corrugated cardboard. Charged copper electrodes on the upper and lower surface of the cardboard create a capacitive field, which is disrupted by the presence of a bed bug moving around inside the monitor (Figure 2.).

Readings are reported to a server via WiFi. A program running on the server discriminates bed bugs from background noise with simple threshold values. "Triggers" generate an alert to a mobile phone or tablet.

Testing the monitoring device

Testing any bed bug monitoring device raises some unique challenges. Most infestations are treated as soon as they are discovered, so access to active infestations for extended periods for monitor testing, can be challenging. Furthermore, it is virtually impossible to determine the number of bugs present in an active infestation, and therefore make an accurate assessment of the detection success of the monitoring device. Most monitor development is therefore carried out in artificial arenas, which allow for more control of variables, but lack the size and complexity of the bed bug's natural environment.

We constructed two test bedrooms, with beds, carpets and basic furniture, to create a semi-natural test environment

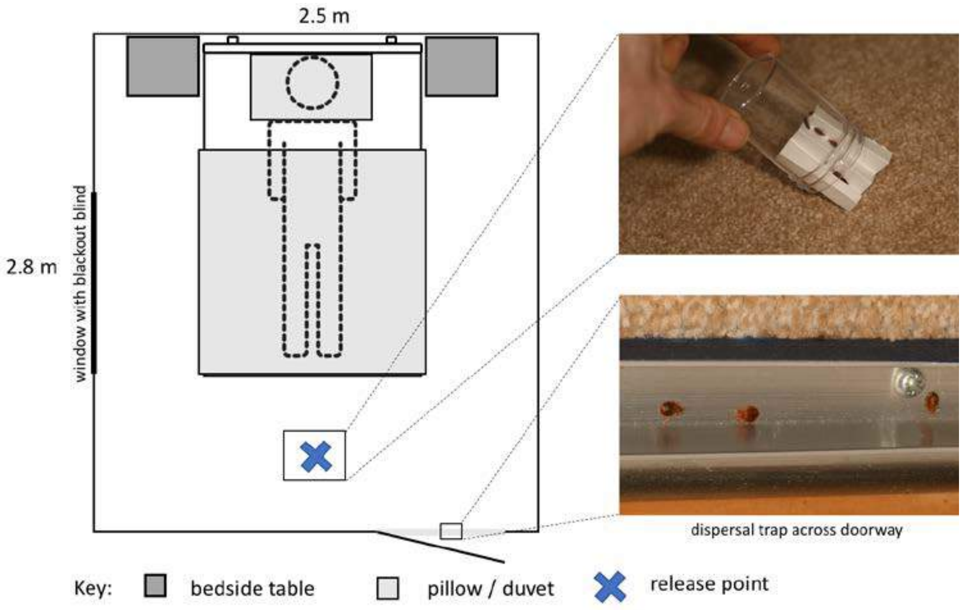

Figure 3. Bed bug monitor test environment.

(Figure 3). A human volunteer (Dr Naylor - Author) slept in the beds, in order to elicit natural foraging and harbouring behaviour (Figure 4.). An aluminium channel was fitted across the doorway to catch bed bugs attempting to disperse out of the room under the door.

Standard release protocol

For each replicate, 10 unfed adult bed bugs (5 male, 5 female) were selected from a culture that had been maintained by Dr Naylor since it was collected in London in 2019. All bed bugs were starved for approximately one week. Prior to the release, bed bugs were transferred to a clean pot, with a 5 x 5 cm square piece of folded filter paper as substrate. The pot was placed on the floor of the test environment and the bed bugs were allowed to settle for approximately 1 hour.

At the start of the scotophase, the piece of filter paper with accompanying bed bugs was carefully transferred out of the pot and onto the floor of the test environment (Figure 3.).

Two hours after the start of the scotophase, the human volunteer got into the bed and remained there for 8 hours. During the subsequent photophase, all bed bugs were located, their sex and feeding status was determined, and their locations were marked on a room plan.

Natural distribution of bed bugs without monitoring

In order to determine the optimum location for installing passive monitors in the test environment, bed bugs were released over 9 replicate nights (10 bed bugs released per night), with no monitoring devices in the room. The cumulative number of bed bugs in each location was plotted on a room plan (Figure 5.). Positions are approximated to reduce the number of location flags.

Figure 4. Single frame from time-lapse camera, illuminated with infra-red light, to monitor bed bug foraging behaviour.

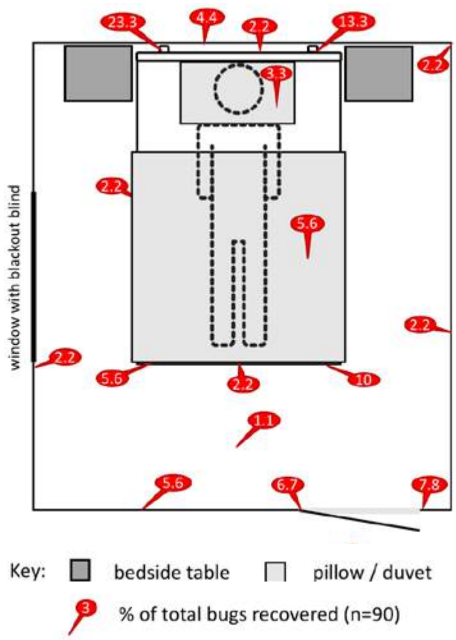

Figure 5. Distribution of bed bugs after one night in an occupied room. Red location flags show the combined percentage of bedbugs recovered at each location for 9 replicate nights.

Of the 90 adult bed bugs released, 47.1% were found harbouring between the headboard and the wall. Of those, 85% were hiding on or adjacent to the wooden headboard supports, suggesting that this may be a good location for positioning monitors. A further 14.5% were found hiding around the door frame, suggesting a possible alternative monitoring location.

Evaluating the devices

The monitoring devices were evaluated in two locations: either side of the headboard, on the wooden supports (Figure 6a), and either side of the doorframe (Figure 6b).

For the first 14 replicates, monitors were only installed on the headboard supports. For the following 4 replicates, monitors were also installed either side of the doorframe. The results are summarised in Table 1.

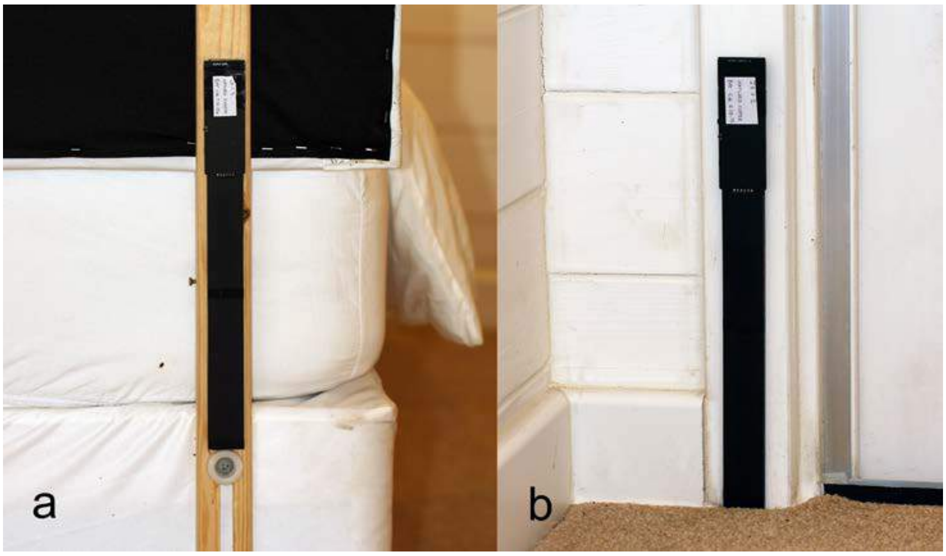

Figure 6. Position of monitors on; a) headboard support, and b) doorframe.

Discussion

Bed bugs seek out dark, sheltered locations, in close proximity to the feeding site. Placed in a suitable location, passive harbourage monitors provide them with a suitable structure in which to establish harbourages.

At least one bed bug was recovered from inside a monitor following every night (n=18) that monitors were installed in the test bedrooms. On average, monitors behind the headboard collected 26% of bed bugs released into the room, while monitors by the door collected 34%. The sample size was insufficient to determine if the difference was significant. However, there was a notable difference in the feeding status of bugs collected from the two monitoring locations. Bed bugs from monitors behind the headboard were all freshly fed, while 79% of bed bugs collected from monitors by the door were unfed.

Placing monitors either side of the doorway may not be sufficiently discrete for the hospitality industry. However, providing suitable harbourage structures in the vicinity of the doorway has the potential to reduce the probability of bed bugs inadvertently dispersing out of the room while searching for shelter, thereby helping to slow the spread of an infestation. ■

All photos: Cimex Store Ltd

TABLE 1

MEAN % ± SD OF BED BUGS RECOVERED AT EACH LOCATION

	BEHIND HEADBOARD	AROUND DOORWAY	ON BED	ON FLOOR	IN BED MONITORS	IN DOOR MONITORS
2 monitors (on headboard)	5.9 ± 8.2	24.3 ± 18.0	15.3 ± 14.8	14.2 ± 3.8	29.3 ± 13.3	
4 monitors (2 on headboard, 2 on doorframe)	9.6 ± 13.5	2.5 ± 5	4.3 ± 5.1	26.8 ± 21.5	23.2 ± 13.9	33.6 ± 12.9

▶ Dr and Mrs Naylor are Managing Directors of Cimex Store Ltd, Mr Jones is Electrical Engineer at Russell IPM and Dr Sampson is Technical Director at Russell IPM. The remote bed bug monitoring device, "i-bug™", was developed by Cimex Store and Russell IPM with support from Welsh Government (1120/ED/1320).

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