Research Article

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Comparison of multiple steam treatment durations for control of bed bugs (*Cimex lectularius* L.)

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Abstract

BACKGROUND: The factors contributing to the current resurgence of bed bug *Cimex lectularius* L. populations across the United States and elsewhere include, among others, the development of resistance to chemical insecticides and population management practices. This has led to the development and attempted refinement of many non-chemical control methods that contribute to an IPM approach to solving the current bed bug population density increase in urban dwellings. One such approach is the use of heat in the form of steam to provide an effective mechanism for controlling localized infestations of bed bugs.

RESULTS: The work reported herein was designed to refine our understanding of the duration of bed bug/steam contact necessary to affect mortality of bed bugs in laboratory trials. Beg bug eggs, nymphs and adults were exposed to three steam treatment exposure periods in these trials. Mean percentage mortality of bed bug eggs was 100% (regardless of duration of exposure), and that of nymphs and adults ranged from 88.0 to 94.0%. Survivorship of nymphs and adults in the trials was the result of experimental protocol restrictions that would not usually be associated with actual pest management efforts.

CONCLUSIONS: The treatment equipment used in these trials is portable and relatively inexpensive and represents a non-chemical means of killing all life stages of bed bugs. While this method would likely be seen as an inefficient means of remediating a mature bed bug infestation within a structure, it does represent a practical component of integrated management of this pest insect.

Keywords: bed bugs; *Cimex lectularius*; steam treatment; IPM

1 INTRODUCTION

After near eradication from the United States during the middle decades of the twentieth century,[1] the recent global resurgence of bed bugs (*Cimex lectularius* L.) has been driven in large measure by bed bug resistance to commonly used insecticides and pest management practices.[2–9] As a result of this resurgence, as well as general movement within the pest control industry towards IPM of urban pest insects,[10] finding alternative means of controlling bed bug populations has gained importance in the development of bed bug population control methods by the global pest management industry.

Control of bed bug populations via exposure to temperatures above their critical thermal maximum has been intensively studied as a potential non-chemical means of suppressing populations of these insects.[11–14] The typical approach to controlling bed bug populations via heat is to raise the temperature of an infested room or entire structure to a temperature in excess of that which bed bugs can tolerate physiologically. Doggett *et al*.[15] reported the lethal maximum temperature range for bed bug populations to be between 44 and 45 °C, while Benoit *et al*.[16] suggested that exposure to 48 °C for 1 h is necessary to achieve complete mortality of experimental bed bug cohorts in laboratory trials, and Pereira *et al*.[17] demonstrated the relationship between temperature and time of exposure when attempting to affect mortality of structure-confined bed bug populations.

Steam treatment for bed bugs is not a novel approach. Potter[7] notes that Fewell[18] documented early (1873) success at controlling these pests in structures with a portable steam-emitting device. While more recent attempts to use steam as a mechanism for controlling bed bugs utilize similar, albeit more sophisticated, equipment[7] relative to that of Fewell,[18] the approach is the same. Steam is applied to visible bed bugs and eggs, as well as to locations that insects are likely to utilize as refugia and oviposition sites. As opposed to the heating of complete structures, steam treatment to control bed bugs requires more precision, time and effort to ensure exposure of the insects to the killing agent. Thus, steam treatment for bed bug eggs, nymphs and adults should be conceptualized as a component of an integrated pest management approach for bed bug population control in human dwellings.

The boiling point of water at 1 atm of pressure (sea level) is 100 °C, well above the documented lethal thermal maximum of bed bugs. Thus, it is clear that exposing bed bugs to steam will result in their mortality. Less clear is the duration of exposure time required to affect mortality of bed bug eggs, nymphs and adults. The objective of the present study was to determine the duration of

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steam exposure necessary to kill bed bugs of all life stages, with the goal of providing more specific recommendations for integrating this method of control into bed bug management practices.

2 EXPERIMENTAL METHODS

2.1 Bed bug source

Bed bugs (adults, nymphs and eggs) for this experiment were purchased from Sierra Research Laboratories (Modesto, CA) and were reared in a 4.57 × 2.44 m walk-in environmental chamber, the conditions of which were maintained at 26.6 ± 5 °C and 75 ± 5% relative humidity (RH) with a 12:12 h light:dark photocycle. The insects used in these trials were of the Sierra Research Laboraroty (SRL) field strain 'Earl'.

2.2 Treatment arenas

Experimental arenas were constructed to simulate actual beds and consisted of 31 × 19 × 9 cm plastic boxes. Mattress material was obtained from the Sealy Mattress Company (Brenham, TX). This material was folded around and stapled to a wooden base and affixed within arenas with caulk (Fig. 1a). This ensured that: (1) bed bugs were exposed to steam treatments; and (2) they were not obscured from view during post-treatment observation periods. Five replicates for each treatment (detailed below) and untreated controls were conducted for this test.

2.3 Egg treatment

Bed bug eggs (Fig. 1b) were shipped to the authors' laboratory affixed to Whatman filter paper discs contained inside tape-sealed petri dishes. Eggs were dislodged with soft-tipped paintbrushes. Ten eggs per replicate (five replicates per treatment and untreated controls) were evenly spaced and affixed along the adhesive side of a 2.54 × 1.5 cm strip of electrician's tape. The tape strips were centered lengthwise in treatment arenas and were treated in an identical fashion as nymphs and adults (see below). After treatment, tape strips were placed in 40 × 12 mm petri dishes which were sealed with Parafilm® and returned to environmental chambers for the remainder of the post-treatment observation period. Observations of egg hatch were made at 1, 2, 3, 4, 5, 10, 15, 20, 25 and 30 days post-treatment. The mean number of hatched eggs was the metric used for statistical comparison via ANOVA and Tukey's honestly significant difference (HSD) means separation test ($P \leq 0.05$).

2.4 Adult and nymph treatment

Twenty bed bugs (ten adults and ten nymphs) were placed in each arena (five replicates per treatment and untreated controls) immediately after being allowed to feed, and were allowed to acclimate to laboratory/arena conditions for a period of approximately 24 h prior to the initiation of trials. After this acclimation period had elapsed, the steam trials were initiated. A J-4000DM Jiffy® steamer (Jiffy Steamer Company, Union City, TN) with a 15.25 cm metal steam head was used to treat insects. During treatment, the steam head rested directly on the mattress tape edge, creating a space of approximately 1 cm between steam head and mattress material below. The treatments consisted of steam treatment along the length of the arena at rates of 10, 20 and 30 s per 30.50 cm. A single operator carried out the treatments, while a second person monitored the treatment time and provided instructions to the operator regarding pace of treatment. Post-treatment observations of bed bug mortality were made at 5, 10, 15 and 30 min, and then at 1, 3 and 7 h post-treatment. Mortality was recorded only if bed bugs failed to respond to mechanical stimuli (probing with a wooden applicator stick). The temperature of the mattress material was measured with a Traceable® infrared thermometer (catalogue No. 06 664 38; Fisher Scientific, Atlanta, GA) prior to and immediately after treatment, as well as during every post-treatment mortality observation. The temperature of the steam head was measured in a similar fashion prior to treatment of each arena. Additionally, in order to determine the amount of water absorption during treatment, the arenas were weighed prior to treatment and at 5, 10, 15 and 30 min, 1, 3 and 7 h and 7 days post-treatment. Mattress arenas were also assessed for the presence of mold after being stored for 30 days post-treatment. Mortality, mattress temperature, arena weight and steam head temperature were compared statistically via ANOVA and Tukey's HSD means separation test ($P \leq 0.05$).

3 RESULTS

3.1 Egg hatch

No treated eggs (Fig. 1c) hatched after exposure to any of the steam treatment durations during the 30 day post-treatment observation. The mean percentage bed bug hatch of untreated controls was significantly greater than that of all treatment groups ($F = 1536.00$; df = 3, 16; $P < 0.01$) (Fig. 2 and Table 1).

3.2 Adult and nymph mortality

The mean mortality of bed bugs (adults and nymphs) in all treatment groups was significantly greater than that of the untreated controls in each post-treatment observation period (Fig. 3), including the 7 h observation ($F = 48.50$; df = 3, 16; $P < 0.01$ and $F = 21.63$; df = 3, 16; $P < 0.01$ for adults and nymphs respectively) (Fig. 3 and Table 1). No mortality was recorded in any of the untreated control replications during any observation period. Additionally, the mean mortality of bed bug adults and nymphs that were exposed to 30 s per 30.50 cm of steam treatment was greater than that of the other two steam treatment durations in each post-treatment observation period, but this was not a statistically significant effect (Fig. 3).

3.3 Trial arena temperature (°C)

There was no significant difference among the treated and untreated control groups regarding the temperature of the trial arena surface during pretrial assessments ($F = 2.09$; df = 3, 16; $P = 0.14$) (Table 2). During steam treatments there was no significant difference between the mean recorded temperatures of treatment arena surfaces. However, the temperature of each treatment arena surface was significantly greater than that of the untreated control arena surfaces ($F = 47.62$; df = 3, 16; $P < 0.01$) (Table 2). Significant differences in trial arena surface temperatures were recorded at 1, 3 and 7 h post-treatment; however, the range of temperature differentials among treatments during the 1, 3 and 7 h post-treatment observation periods was 0.66, 0.70 and 1.86 °C respectively.

3.4 Arena weight (g)

An average weight gain of 0.92, 1.32, 1.44 and 0.00 g was recorded at 5 min post-treatment in the 10, 20 and 30 s per 30.50 cm and untreated control groups respectively. There was no significant difference between treatments and untreated controls regarding the total weight of trial arenas prior to or in the 7 h post-treatment observation period ($F = 0.87$; df = 3, 16; $P = 0.48$ and $F = 0.87$;

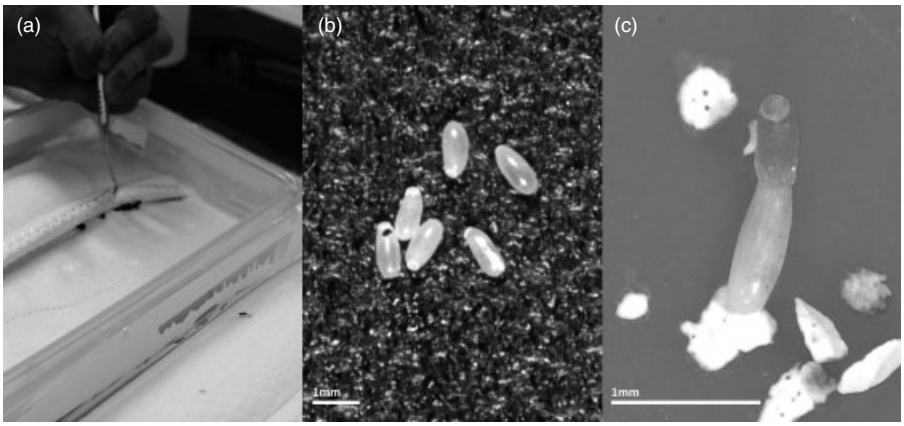

Figure 1. Photos of arenas (a) untreated (b) and steamed (c) bed bug eggs. Note the expelled embryonic tissue extruded from the steam-treated egg (c).

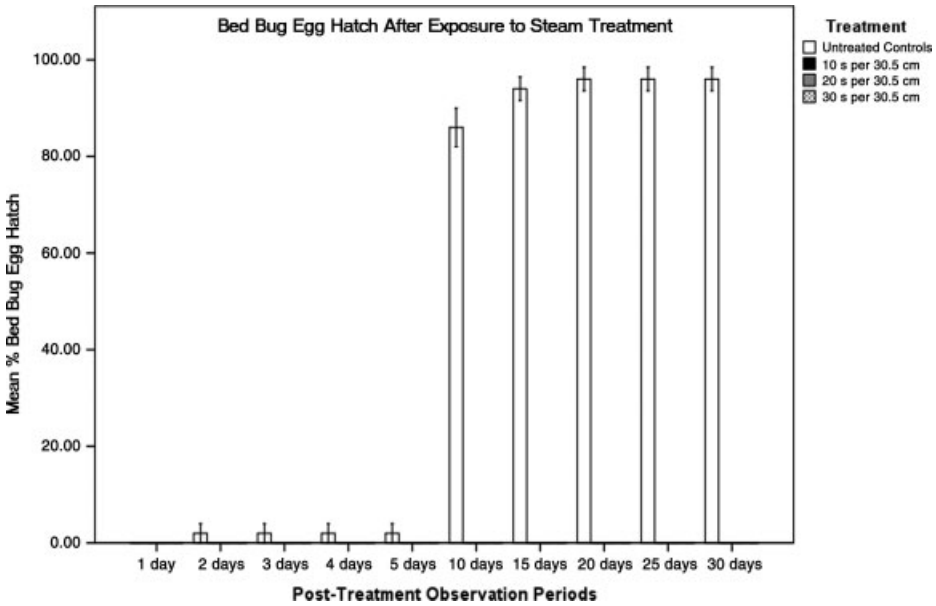

Figure 2. Mean percentage bed bug egg hatch during 30 day post-treatment period. The mean bed bug hatch of untreated controls was significantly greater than that of all treatment groups at 30 days post-treatment ($F = 1536.00$; df = 3, 16; $P < 0.01$).

df = 3, 16; $P = 0.47$ for pretrial and 7 h post-treatment respectively) (Table 2). Additionally, no mold was found on any arenas after being stored for 30 days post-treatment.

4 DISCUSSION AND CONCLUSIONS

Of special interest is the fact that complete mortality of bed bug eggs was observed when using this method, regardless of steam duration. However, it should be noted that in these trials the eggs were confined to a position known to the steam equipment operator. While these results demonstrate the effectiveness of steam treatment on bed bug eggs, field applications would take place without the *a priori* knowledge of the location of eggs. There was no attempt to determine whether, or to what depth, steam penetrates into folds, creases or fissures associated with the substrate in these trials.

Steam treatment effectively killed bed bug nymphs and adults and destroyed eggs when the steam head was placed directly onto the substrate on which the insects were restricted, regardless of the speed of application. Mean mortality rates of nymphs and adults ranged from 84 to 94% during post-treatment observations (all steam durations). While mean mortality in the 30 s per 30.50 cm treatment was consistently greater than mean mortality for the remaining treatment groups, the effect was not significant. This suggests that the shortest steam durations tested in these trials (10 s per 30.50 cm) provided levels of bed bug mortality that were competitive with those of longer steam durations. It is important to note that some bed bugs escaped steam treatment as a result of their lateral position (relative to the steam head) in the arenas. The experimental protocol prevented the operator from making supplemental stream treatments to kill these insects. When engaged in pest management activities, an actual operator/user would not be likewise constricted from killing insects missed during initial treatment. Insects that were directly exposed to steam died almost immediately. While no attempt was made to count the number of bed bugs under the tape edge relative to those that were found in an exposed position during treatment, insects that were harboring under the mattress tape edge were killed as well.

An assessment of possible mortality induced by the 6″ metal steam head attachment itself was also made and should be

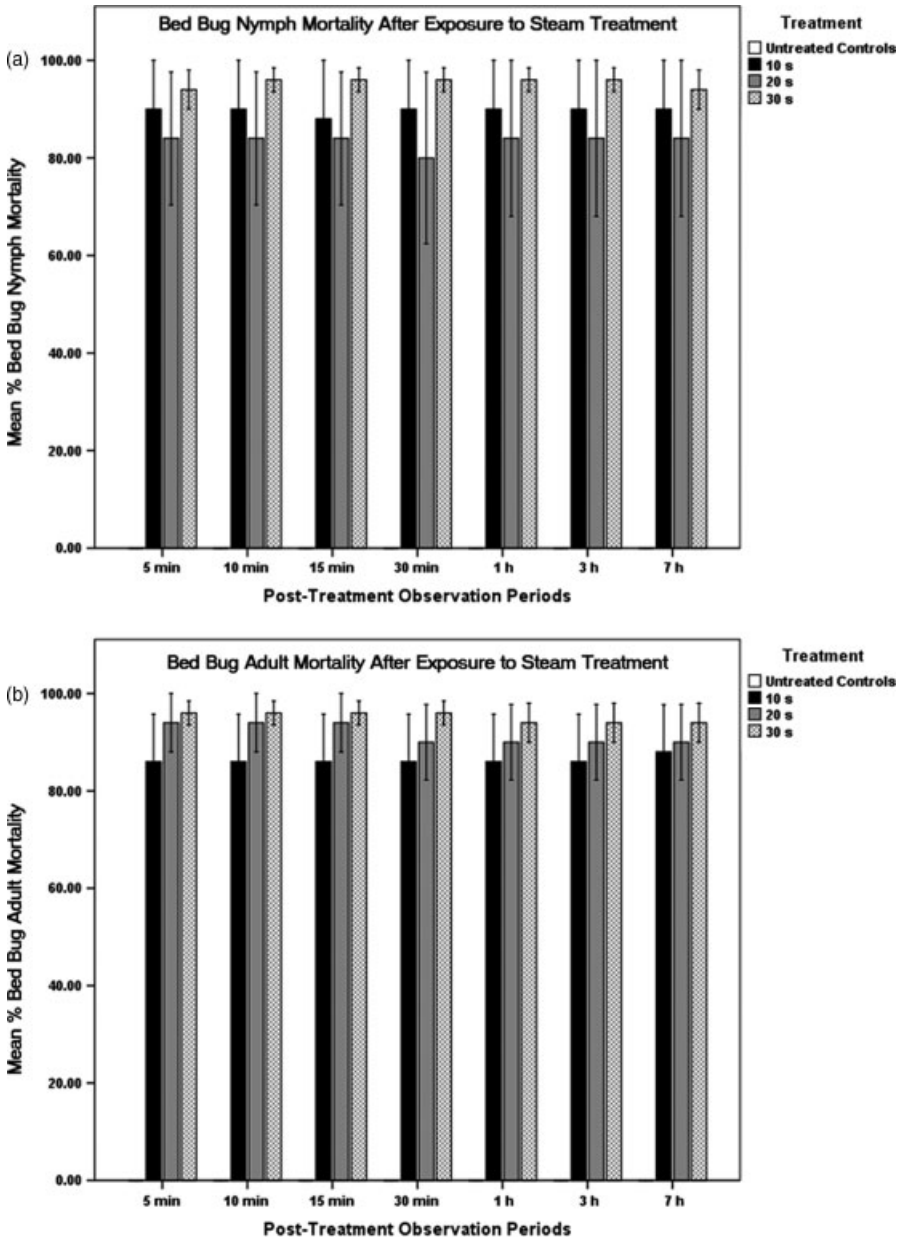

Figure 3. Mean percentage mortality of bed bug nymphs (a) and adults (b) during 7 h post-treatment period. The mean mortality of all steam treatment durations was significantly greater than that of untreated controls during the 7 h post-treatment observation ($F = 21.63$; df = 3, 16; $P < 0.01$ and $F = 48.50$; df = 3, 16; $P < 0.01$ for nymphs and adults respectively).

discussed. After the final post-treatment mortality assessment was recorded, the cool (room temperature) steamer head was moved across the insects in the untreated control arenas in an identical manner to the 30 s per 30.50 cm treatment. No mortality was recorded. Thus, it is clear that it was the temperature of the steam emitted from the J-4000DM Jiffy® steamer with a 15.24 cm metal steam head attachment that was responsible for the bed bug mortality observed in these trials.

Interestingly, the greatest mean temperatures recorded during the trials were associated with the shortest treatment duration. This is likely due to the inability of the steam unit to maintain constant temperature output for the length of time required to accomplish these trials (~2 h). The mean temperature of the treated trial arenas ranged from 67.38 to 73.91 (°C) immediately after treatment. The mean temperature of the steam head immediately prior to treatment was consistent with this finding. That is, the greatest steam head temperatures were associated with the 10 s per 30.50 cm treatments, and the lowest temperatures were associated with the 30 s per 30.50 cm treatments. This suggests that the unit recovers more rapidly and maintains a more consistent temperature when used for shorter durations. While this may present challenges for commercial operators as they conduct actual pest control, the issue can be overcome by simply maintaining two units and alternating between them. It should be noted that only one commercial steamer was tested in these trials, and the temperature maintenance trend observed in this device may not be consistent among other comparable units.

Arena weight change was used as a measure of water absorption during trials. The weight change of trial arenas was negligible and was not significant among treatment and untreated control

Table 1. Mean percentage mortality of bed bug nymphs, adults, and of nymphs and adults combined in 7 h post-treatment mortality observation period, and percentage egg hatch at 30 days post-treatment

	Mean percentage mortality (7 h)			
	Nymphs	Adults	Nymphs and adults	Percentage egg hatch (30 days)
Untreated controls	0.00 (b)	0.00 (b)	0.00 (b)	96.00 (a)
10 s per 30.50 cm	90.00 (a)	88.00 (a)	89.00 (a)	0.00 (b)
20 s per 30.50 cm	84.00 (a)	90.00 (a)	87.00 (a)	0.00 (b)
30 s per 30.50 cm	94.00 (a)	94.00 (a)	94.00 (a)	0.00 (b)
P-value	<0.01	<0.01	<0.01	<0.01
F-value	21.63	48.50	32.41	1536.00
df	3, 16	3, 16	3, 16	3, 16
N	20	20	20	20

[a] Analysis of variance (ANOVA) at $P < 0.05$.
[b] Means followed by the same letter(s) are not significantly different using Tukey's HSD *post hoc* analysis at $P < 0.05$ (SPSS for Windows, v.16.0).
[c] Ten nymphs and ten adult bed bugs were exposed to treatment in each arena. These data have been separated into life stage for comparison.

Table 2. Arena temperatures and weights during pre-trial and 7 h post-treatment observations

	Arena temperature (°C)		Arena weight (g)	
	Pre-trial	During treatment	Pre-trial	7 h post-treatment
Untreated controls	19.61 (a)	19.73 (b)	580.44 (a)	573.56 (a)
10 s at 30.50 cm	19.65 (a)	73.91 (a)	592.16 (a)	592.46 (a)
20 s at 30.50 cm	19.54 (a)	67.38 (a)	573.54 (a)	574.08 (a)
30 s at 30.50 cm	19.54 (a)	73.43 (a)	584.48 (a)	585.02 (a)
P-value	0.14	<0.01	0.48	0.47
F-value	2.09	47.62	0.87	0.87
df	3, 16	3, 16	3, 16	3, 16

[a] Analysis of variance (ANOVA) at $P < 0.05$.
[b] Means followed by the same letter(s) are not significantly different using Tukey's HSD *post hoc* analysis at $P < 0.05$ (SPSS for Windows, v.16.0).

groups in any post-treatment observation period. Additionally, arenas were stored in an exposed air-conditioned environment (simulating a home) for a period of 30 days post-treatment. At the end of this period of time, mattress material in the arenas was inspected for the formation of mold/mildew. None was noted, and the mattress material in trial arenas did not appear to be physically affected by steam treatment. This is an important aspect of this treatment methodology, and it is clear that actual applications of steam to control bed bug populations can be accomplished without the threat of moisture damage to personal belongings.

Steam treatment proved to be a very useful and effective tool for killing bed bugs, and, as with the heat control work of Pereira *et al*.[17] and Kells and Goblirsch,[19] should be considered as a tool that can be used along with residual pesticides to control bed bug populations. When the insects are found in exposed situations, the steamer equipment represents a non-chemical method for control of bed bug adults, nymphs and eggs. It is not clear whether it will be equally effective at killing these insects when they are hiding in less conspicuous situations (i.e. inside mattresses, within furniture joints and in/under carpeting). Thus, it is suggested that future studies regarding steam treatment effects on bed bugs incorporate these aspects of natural bed bug behavior and biology.

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