Evaluation of Rodent Bait Containing Imidacloprid for the Control of Fleas on Commensal Rodents in a Plague-Endemic Region of Northwest Uganda

JEFF N. BORCHERT,[1,2] RUSSELL E. ENSCORE,[1] REBECCA J. EISEN,[1] LINDA A. ATIKU,[3] NICHOLAS OWOR,[3] SARAH ACAYO,[3] NACKSON BABI,[3] JOHN A. MONTENIERI,[1] AND KENNETH L. GAGE[1]

J. Med. Entomol. 47(5): 842–850 (2010); DOI: 10.1603/ME09221

ABSTRACT In recent decades, the majority of human plague cases (caused by *Yersinia pestis*) have been reported from Africa. In an effort to reduce the risk of the disease in this area, we evaluated the efficacy of a host-targeted rodent bait containing the insecticide imidacloprid for controlling fleas on house-dwelling commensal rodents in a plague-endemic region of northwestern Uganda. Results demonstrated that the use of a palatable, rodent-targeted, wax-based bait cube was effective at reducing the prevalence of fleas on commensal rodents and flea burdens on these animals at day 7 postbait exposure, but lacked significant residual activity, allowing flea populations to rebound in the absence of additional bait applications. Our results indicate the use of a palatable host-targeted bait block containing imidacloprid was an effective technique for quickly reducing flea numbers on rodents in northwest Uganda and, thus, could be useful for lowering the potential risk of human flea bite exposures during plague outbreaks if applied continuously during the period of risk.

KEY WORDS *Rattus rattus*, plague, flea control, imidacloprid

Plague, a highly virulent bacterial and primarily flea-borne zoonotic disease, is thought to be transmitted by at least 80 different flea species and can infect many species of vertebrate hosts (Pollitzer 1954, Gage and Kosoy 2005). Bubonic plague is the most common manifestation, and is typically associated with rodents and their fleas (Gage 1998). Flea-infested rodents, such as commensal rats (*Rattus* spp.) that dwell within homes, are particularly important sources of human *Yersinia pestis* (Lehmann and Neumann) van Loghem infection in many regions of the world, especially those areas that are poverty stricken and experience heavy rat infestations in human dwellings (Gage 1998). Africa usually reports the highest yearly percentage of plague cases in the world, as well as the largest number of human deaths as a result of the disease (WHO 2004). In northwestern Uganda, the Arua and Nebbi Districts have consistently reported human plague cases over the past half century. From 1999 through 2008, for example, clinics from these districts reported to the Ugandan Ministry of Health an average of ≈206 (range: 69–462) suspected human cases per year (Centers for Disease Control and Prevention, unpublished data).

In East Africa, rat fleas (*Xenopsylla cheopis* Rothschild, *X. brasiliensis* Baker) associated with commensal and field rodent hosts are thought to play a crucial role in plague epizootics (Hopkins 1949, Pollitzer 1954, Kilonzo et al. 1992). These fleas readily feed on humans when encountered (Verjbitski 1908, Kwochka 1987), and are efficient vectors of *Y. pestis* in laboratory studies (Pollitzer 1954, Gage and Kosoy 2005, Eisen et al. 2007). Previous research in the West Nile region indicated that *Rattus rattus* L. was the most frequently captured rodent in both peridomestic areas and inside huts, and the majority of fleas acquired from *R. rattus* were *X. cheopis* or *X. brasiliensis* (Orach 2003, Eisen et al. 2008; Centers for Disease Control and Prevention, unpublished data).

Invasive *R. rattus* appear to have been introduced into Uganda early last century, but apparently remained absent from the northwest portion of the country until sometime after 1939 (Hopkins 1949). As in other regions in East Africa, these rats were reported to inhabit the grass roof of indigenous homes and, along with two other rodent species, *Mastomys natalensis* Smith and *Arvicanthis niloticus* Desmarest, were significant pests of stored and growing crops (Hopkins 1949, Smyth 1986, Fielder 1994). Their suspected role in the ecology of plague in Uganda was described as early as the 1920s (Thorton 1930). As the

[1] Bacterial Diseases Branch, Division of Vector-Borne Infectious Diseases, Centers for Disease Control and Prevention, 3150 Rampart Road, Fort Collins, CO 80522.

[2] Corresponding author: Centers for Disease Control and Prevention, Division of Vector-Borne Infectious Diseases, Bacterial Disease Branch, 3150 Rampart Road, Fort Collins, CO (e-mail: gqx1@cdc.gov).

[3] Uganda Virus Research Institute, P.O. Box 49, Plot 51-59 Nakiwongo, Entebbe, Uganda.

fleas of *R. rattus* represent possible bridging vectors to transmit the disease from rats to humans, this host-flea complex represents a potential target for plague control measures in this region.

In Africa, plague control targeting rodents and their fleas has focused on dusting of human dwellings and rodent burrows with insecticidal dusts, trapping and removal of rodents, use of rodenticide baits, bounty schemes intended to result in rodent depopulation, and the burning of dwellings to destroy rats and fleas, as well as their peridomestic habitats (Kumaresan et al. 1991, Kilonzo 1994, Shangula 1998, Kilonzo 1999, Ratovonjato et al. 2003). In this region, plague control is performed reactively, not proactively, often because of lack of resources for surveillance (Govere and Dürrheim 1999). Previous attempts to control plague by applying pesticide products in and around traditional housing (via spraying or dusting) in Uganda (and elsewhere in East Africa) have produced only limited success at best, often failed to control outbreaks, and were not economically sustainable (Kilonzo and Komba 1993, UMoH 1997). Host-targeted control of fleas, through the use of rodent baits containing systemic insecticides, may be possible, and such control could reduce plague transmission between rodents and from rodents to humans. These methods could also prove more economical and practical than areawide application of insecticides. Flea control, done in the absence of rodenticides, also could leave the rodents in place, which could minimize the likelihood that untreated flea-infested rats would immigrate into home environments that had been treated previously. In laboratory and field studies, other authors have described the use of insecticides formulated into rodent bait for the control of fleas on rodents. These insecticides have been used alone or in combination with rodenticides and without, but low bait consumption has been cited as a barrier for applying this method of flea control to field situations (Mbise 1994, Mbise et al. 1995, Larsen and Lodal 1997).

When delivering systemic insecticides to rodents using rodent bait, the importance of bait palatability cannot be overstated. As the inert food base proportion of a prospective rodent bait has the greatest influence on its consumption by the target rodent (Mbise et al. 1995), any bait targeting rodents must be attractive enough to lure these animals away from their usual food items. Others have noted that rodent baits are often ignored when other, more attractive alternative food supplies exist and are available in ample quantities (Gratz and Arata 1975, Cowan et al. 2003). Differences in rodent bait intake often can be seen within the same species in different localities (Gratz and Arata 1975). In rodenticide trials, the availability of alternative foods had the greatest influence on the effectiveness of the bait for controlling rats, and treatment failures are often attributed to lack of consumption (Quy et al. 1996, Corrigan 2001).

This work describes an investigative trial to determine the feasibility of using palatable rodent baits containing the systemic insecticide imidacloprid for the control of fleas on commensal rodent hosts, particularly *R. rattus.* Imidacloprid (1-[(6-chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine) is a nicotinic insecticide with efficacy against fleas when applied topically and systemically (Metzger and Rust 2002, Franc and Yao 2007). Our approach was to target flea populations on the rodent hosts while allowing existing rats to remain in these areas because rodent-focused plague control in tropical Africa, using rodenticides, has often been met with only transitory success, and because rodenticide use has the potential to cause only temporary drops in rodent numbers with rapid replacement through either the reproduction of survivors or immigration from surrounding areas of the commensal rodent populations. It should also be noted that some rats, especially immigrants from surrounding plague-endemic areas, could potentially be infected with plague bacteria and transport infectious fleas to the treated area (Gratz and Arata 1975). For these reasons, our approach was to target flea populations on the rodent hosts while allowing existing rats to remain in these areas, thus minimizing the likelihood that new flea-infested and potentially *Y. pestis*-infected rats will be introduced in the area. Although reduction of rodent host numbers remains desirable, this will be the subject of later studies intended to evaluate sustainable methodologies for long-term management of rodent populations.

Materials and Methods

Study Areas. Field studies were conducted in northwestern Uganda in the Arua and Nebbi Districts. This area is located in the subhumid zone typified by a bimodal rainfall pattern and is characterized by annual mixed cropping and banana/coffee/cattle agro-ecological systems (Mwebaze 1999).

The Arua District is characterized by intense agriculture, dense human population, and highly fragmented land use, with 96% of the households dependent on subsistence farming as their principal source of income. The average rural family cultivates two- to three-acre farms using mixed cropping systems. The major food crops include cassava, beans, groundnuts, sesame seeds, millet, and maize. Tobacco, the major cash crop, is also the main source of livelihood for the majority of the population in the district. Rainfall typically ranges from 90 to 150 cm per year (MAYAN 2005).

The Nebbi District is characterized by family plots surrounded by mixed woodland and fragmented landscape, with over 85% of the district population engaged in subsistence farming. The main crops grown are cotton, coffee, simsim, sorghum, millet, sweet potatoes, beans, cassava, maize, and vegetables (MAYAN 2005).

Village homes consisted of square and round traditional structures constructed of mud bricks and waddle with a grass, thatched roof. Floors were dirt and often smeared with a combination of mud and animal feces, creating a hardened surface after drying. Peridomestic areas contained mixed crop beds and indigenous plants.

Three treatment and three control villages were selected as follows: two pairs of villages in the Arua District and one pair in the Nebbi District. Treatment villages were matched (paired) as closely as possible with control villages with respect to location, elevation, geographical extent of the village, human population size, agricultural practices, and housing construction type. The efficacy trial was implemented January–March 2008 during the dry season.

Bait Cube Formulation. Based on pilot study results, a modified, wax-based bait cube was chosen to deliver an oral dose of the insecticide to rodents. Bait was formulated by pulverizing the commercial bait formulation (Scimetrics, Ltd., Wellington, CO), adding 10% powdered dry fish (purchased at a local market), remelting the formulation using a double-boiler system heated to ≈100°C, and then recasting the new bait formulation in premade molds. The circular bait blocks (≈5 cm diameter × 2 cm) were constructed to include a hole in the center that allowed them to be secured inside the bait boxes. Two baits were formulated, one containing the insecticide (treatment bait) and one without the insecticide (control bait). The reformulated bait material was analyzed to determine the concentration of imidacloprid using a high performance liquid chromatography method based on previously published methods (Baskaran et al. 1997, Liu et al. 2005). Relative bait consumption was determined as a percentage of the amount of bait originally placed in the field after 7 d of exposure.

Capturing and Processing Rodents. Periodic trapping was conducted to evaluate the efficacy of the insecticidal bait against rodent fleas. To assess the effect of the bait on parasitizing fleas, rodent collections were performed 7 d before baiting and on days 7 and 14 postbaiting. The first day of baiting was defined as day 0. In both treatment and control villages, 100 traps (48.3 × 17.1 × 17.1 cm; Tomahawk Trap, Tomahawk, WI) were set inside 50 randomly selected huts (two traps/house) per village. One trap was placed on the ground against the inside of wall and, whenever possible, the second trap was secured in an elevated position (i.e., on top of exposed wall or inside beam). If the second trap could not be placed in an elevated position, it was placed on the ground, parallel to the wall in a manner similar to that described for the first trap. Traps were collected the next morning. Upon capture, animals were euthanized by inhalation of halothane, identified to species based on morphological appearance and measurements (e.g., length of body, tail, right hind foot, and ear) (Delany 1975), and thoroughly combed with a small pocket comb to recover fleas (Gage 1999). All animal-handling procedures were performed according to protocols approved by the Centers for Disease Control and Prevention, Division of Vector-Borne Diseases (ACUC 07-014). All fleas collected from rodents were stored in individual microcentrifuge tubes containing 70% alcohol and later identified to species following published taxonomic keys (Hopkins 1947, Haselbarth 1966, Smit 1973). Voucher flea specimens were submitted to the Centers for Disease Control and Prevention, Division of Vector-Borne Diseases (Fort Collins, CO). Voucher specimens for small mammals were submitted to Makerere University (Kampala, Uganda) for verification of species identification.

Application of Bait. For treatment and control villages, commercial, rat-sized bait stations (Protecta, Bell Laboratories, Madison, WI) were baited by placing two bait blocks on each of two metal retaining rods in each station, resulting in four bait blocks per station. One bait station was placed on the ground against the inside of wall, and the second bait station was secured (using wire) in an elevated position (i.e., on top of exposed wall or inside beam). To determine whether the presence of the bait station itself would affect total flea population on rodents in the control villages, we placed two bait stations in 50% of the village homes (every other hut as technicians proceeded through the village). All huts in the treatment villages received two bait stations. The bait stations were placed in homes for 7 d. Bait stations were evaluated at day 4. If necessary, additional bait was added.

Statistical Analysis. Bait consumption between treatment and control villages was compared using nonparametric Wilcoxon rank sum tests, and bait consumption comparisons between elevated and ground bait stations were compared using a Wilcoxon signed rank test. Nonparametric Kruskal-Wallis or Wilcoxon rank sum tests were used to compare median numbers of fleas collected, and Fisher exact test was used to compare the percentage of rodents infested at each trapping session. All statistical comparisons were run using JMP statistical software (SAS Institute, Cary, NC), and results were considered significant if $P < 0.05$. Percentage of control of the insecticide bait effectiveness against fleas, taking into account changes in flea populations on paired control sites, between days 0 and 7, was determined using Henderson's formula as modified by Mount et al. (1976): % control = $100 - (T/U \times 100)$, where T = the posttreatment flea index divided by the pretreatment flea index in the treated site, and U = the posttreatment mean divided by the pretreatment mean in the control site.

Results

Bait Application and Consumption. The average weight of each cube of bait was 34.3 ± 2.4 g ($n = 40$). The total bait applied (kg) to each treatment plot was 48.2 kg on Olli/Yapi, 42.0 kg on Jiki, and 33.5 kg on Ocungulir/Godrombo. The percentage of day 7 feed consumption on treatment plots was 10.3% (3.7% ground, 6.6% elevated) on Olli/Yapi, 29.6% (11.3% ground, 18.3% elevated) on Jiki, and 31.8% (17.0% ground, 14.8% elevated) on Ocungulir/Godrombo. Day 7 feed consumption on control plots was 22.1% (11.3% ground, 10.8% elevated) on Olli, 25.1% (11.2% ground, 13.9% elevated) on Jiki/Paganza, and 22.4% (10.4% ground, 12.4% elevated) on Jupakonja. During the study, there were no observations of mold or deterioration of the bait, but insects were observed in some stations. The concentration of imidacloprid in the reformulated bait block was determined to be

Table 1. Flea infestation data for rodents collected inside traditional housing in northwestern Uganda

Flea Species	Village	Rodent hosts							
		R. rattus		*A. niloticus*		*M. natalensis*		*Other*[a]	
		Mean no. fleas	Hosts (*n*)	Mean no. fleas	Hosts (*n*)	Mean no. fleas	Hosts (*n*)	Mean no. fleas	Hosts (*n*)
X. cheopis	Olli/Yapi (T)	0.31	99	0.00	2	0.33	3	1.00	1
	Olli (C)	0.08	128	0.33	3	NA	0	0.00	1
	Jiki (T)	0.08	156	NA	0	0.00	5	NA	0
	Jiki/Paganza (C)	0.08	144	0.00	4	1.57	7	NA	0
	Ocungulir/Godrombo (T)	0.10	114	0.43	21	0.07	14	NA	0
	Jupakonja (C)	0.12	112	0.00	1	0.38	8	0.00	1
X. brasiliensis	Olli/Yapi (T)	0.16	99	0.00	2	0.00	3	1.00	1
	Olli (C)	0.29	128	0.00	3	NA	0	0.00	1
	Jiki (T)	0.14	156	NA	0	1.4	5	NA	0
	Jiki/Paganza (C)	0.23	144	0.00	4	0.71	7	NA	0
	Ocungulir/Godrombo (T)	0.54	114	2.38	21	1.29	14	NA	0
	Jupakonja (C)	0.91	112	0.00	1	2.13	8	0.00	1
D. lypusus	Olli/Yapi (T)	0.10	99	0.05	2	0.67	3	0.00	1
	Olli (C)	0.05	128	0.33	3	NA	0	0.00	1
	Jiki (T)	0.08	156	NA	0	0.00	5	NA	0
	Jiki/Paganza (C)	0.15	144	0.00	4	0.14	7	NA	0
	Ocungulir/Godrombo (T)	0.11	114	0.33	21	0.36	14	NA	0
	Jupakonja (C)	0.03	112	1.00	1	0.00	8	3.00	1
Ct. bacopus/Ct. calceatus c.	Olli/Yapi (T)	0.03	99	1.00	2	0.00	3	0.00	1
	Olli (C)	0.01	128	0.33	3	NA	0	0.00	1
	Jiki (T)	0.01	156	NA	0	0.60	5	NA	0
	Jiki/Paganza (C)	0.05	144	1.25	4	0.00	7	NA	0
	Ocungulir/Godrombo (T)	0.05	114	0.38	21	0.14	14	NA	0
	Jupakonja (C)	0.00	112	0.00	1	0.00	8	0.00	1
Other[b]	Olli/Yapi (T)	0.01	99	0.00	2	0.00	3	0.00	1
	Olli (C)	0.02	128	0.00	3	NA	0	0.00	1
	Jiki (T)	0.00	156	NA	0	0.00	5	NA	0
	Jiki/Paganza (C)	0.08	144	0.00	4	0.14	7	NA	0
	Ocungulir/Godrombo (T)	0.11	114	0.14	21	0.14	14	NA	0
	Jupakonja (C)	0.13	112	0.00	1	0.00	8	1.00	1
All fleas	Olli/Yapi (T)	0.62	99	1.50	2	1.00	3	2.00	1
	Olli (C)	0.44	128	1.00	3	NA	0	0.00	1
	Jiki (T)	0.31	156	NA	0	2.00	5	NA	0
	Jiki/Paganza (C)	0.47	144	1.25	4	2.57	7	NA	0
	Ocungulir/Godrombo (T)	0.93	114	3.67	21	2.00	14	NA	0
	Jupakonja (C)	1.24	112	1.00	1	2.50	8	4.00	1
	All treatment	0.58	369	3.49	23	1.86	22	2.00	1
	All controls	0.71	384	1.13	8	2.53	15	3.00	2

T, treatment; C, control.
[a] Other rodent species: *T. validi*, *P. jacksoni*, and *A. kaiseri*.
[b] Other flea species: *Xenopsylla* spp., *Afristivalus torvus* Rothschild (syn. *Stivalus torvus* in Hopkins 1947), *Afristivalus* spp., *Libyastus* spp., *Leptopsylla aethoipica* Rothschild, *Ctenocephalides felis* Bouche, and *Echidnophaga gallinacea* Westwood.

196.7 ± 7.8 mg of imidacloprid/kg bait (ppm). There was no difference between the consumption of bait on treatment and control plots ($\chi^2 \geq 0$, df = 1, $P > 0.05$), but rodents consumed significantly more bait from elevated bait stations than bait stations placed on the ground ($P < 0.001$).

Domestic Rodent Collection. In total, 824 small mammals representing six species were collected from traditional homes in the six field sites. Roof rats (*R. rattus*) comprised 91.4% (n = 753) of captured animals. Nile grass rats (*A. niloticus*) and multimammate rats (*M. natalensis*) comprised 3.8% (n = 31) and 4.5% (n = 37) of the sampled rodents, respectively. *Aethomys kasseri* Noack, *Praomys jacksoni* de Winton, and *Tatera validi* Bocage comprised the remainder of the captures (each 0.1%, n = 1) (Table 1).

Field-Derived Evaluation of On-Host Flea Infestations. A total of 663 fleas, representing 11 species, was collected. Table 1 lists the mean number of fleas and diversity of hosts and fleas captured throughout the study for both pretreatment and posttreatment trapping periods. Two flea species, *X. cheopis* and *X. brasiliensis*, represented 73.6% (n = 488) of fleas collected from commensal rodents (Table 1). *Dinopsyllus lypusus* Jordan and Rothschild was the next most commonly encountered flea, representing 13.0% (n = 86) of fleas collected. *Ctenophthalmus bacopus* Jordan and *Ct. calceatus cabirus* Jordan and Rothschild (syn. *Ct. cabirus* in Hopkins 1947) each represented 3.2% (n = 21) and 2.7% (n = 18) of fleas collected, respectively.

The percentage of commensal rodents infested (having at least one flea) with fleas decreased significantly on the three treatment areas when comparing pretreatment and day 7 flea infestations (Table 2). Differences in the proportion of rodents infested with fleas did not differ significantly for any control villages when comparing pretrapping and days 7 and 14, but significant increases in this parameter were noted at day 14 on the Jiki/Paganza plot and at day 7 on Jupakonja.

Table 2. The percentage of rodents infested with fleas collected in commensal areas in Arua and Nebbi Districts

Village	Treatment/Control	% rodents infested with fleas (no. examined)		
		Pretreatment	7 d	14 d
Olli/Yapi	Treatment	48.3 (29)	23.5 (34)*	26.2 (42)
Olli	Control	37.8 (37)	29.5 (44)	21.6 (51)
Jiki	Treatment	34.0 (53)	0 (51)***	24.6 (57)
Jiki/Paganza	Control	22.6 (53)	25.5 (51)	47.1 (51)**
Ocungulir/Godrombo	Treatment	44.0 (50)	13.2 (53)**	54.3 (46)
Jupakonja	Control	42.2 (45)	76.4 (34)**	46.5 (43)

Comparison with pretrap (Fisher's exact test). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Considering only rodents captured in control villages, there were no differences in the median number of flea on rodents captured from homes receiving bait stations versus rodents captured in homes without bait stations ($\chi^2 \geq 2.50$, df = 1, $P > 0.05$). Therefore, control data from rodents collected in both of the above sets of homes were pooled for comparison of time points. Consistent with the percentage of commensal rodents infested with fleas on treatment sites, comparisons of the median number of fleas per host between pretreatment and day 7 periods indicated a significant reduction of fleas in the three treatment villages, as follows: Olli/Yapi ($\chi^2 \geq 4.50$, df = 1, $P < 0.05$), Jiki ($\chi^2 \geq 20.54$, df = 1, $P < 0.001$), and Ocungulir/Godrombo ($\chi^2 \geq 12.49$, df = 1, $P < 0.001$) (Table 3). Comparisons of median number of fleas per host between pretreatment and day 14 periods indicated a significant reduction of fleas in the Olli/Yapi treatment village ($\chi^2 \geq 4.50$, df = 1, $P < 0.05$), but not in the Jiki and Ocungulir/Godrombo treatment areas. The median number of fleas per host was not significantly reduced for any control villages when comparing pretreatment and day 7 or pretreatment versus day 14, but was significantly increased at day 14 on the Jiki/Paganza plot and at day 7 on Jupakonja.

Considering only commensal *R. rattus*, comparisons of the median number of fleas per host between pretreatment and day 7 periods indicated a significant reduction of fleas in two treatment villages, as follows: Jiki ($\chi^2 \geq 19.07$, df = 1, $P < 0.0001$) and Ocungulir/Godrombo ($\chi^2 \geq 12.49$, df = 1, $P < 0.001$) (Table 4). Differences of the median number of fleas per host were not significantly decreased for any treatment villages when comparing pretrapping and day 14. Differences of median number of fleas per host were not significantly reduced for any control villages when comparing pretrapping results with those observed on day 7 or 14, but were significantly increased at day 14 on the Jiki/Paganza plot and at day 7 on Jupakonja.

Using the mean number of fleas per rodent host (Table 5) and Henderson's formula for the effectiveness of an insecticide, the percentage of control of fleas on treatment plots on day 7 was 0% or less (negative percentages can occur because of a decrease of fleas on the control site) on Olli/Yapi, 100% on Jiki, and 93.9% on Ocungulir/Godrombo.

Discussion

In this study, a host-targeted, palatable bait containing wax, cereal flours, fish powder, and imidacloprid was demonstrated to be effective in reducing the burden of fleas on commensal rodents in northwest Uganda, as well as the flea burden specifically associated with commensal *R. rattus.* Ground and elevated bait stations appeared to be effective at bait delivery, with more bait being consumed at elevated stations on treatment sites. Based on the consumption of the bait observed in this study, the lower bait consumption on the Olli/Yapi treatment site (10.3%) may have contributed to the reduced level of flea control on both commensal rodents and *R. rattus* alone. Treatment plots where bait consumption was ≥29.6%, as indicated by the Jiki and Ocungulir/Godrombo treatment sites, offered better control of fleas on rodents.

The addition of ground fish into the rodent bait formulation appeared to overcome palatability problems encountered in unpublished pilot studies in the same area. This finding is consistent with other studies in which fish was added to the inert base of rodent baits, thereby increasing the bait palatability (Mbise et al. 1995, Pervez 2007). Probably because of the inclusion of wax into the formula, there was no observed molding (and, therefore, potential decreased palat-

Table 3. Median and range of no. of fleas of rodents collected in commensal areas in Arua and Nebbi Districts, Uganda

Village	Treatment/Control	Median (range) no. fleas recovered		
		Pretreatment	7 d	14 d
Olli/Yapi	Treatment	0 (0–4)	0* (0–8)	0* (0–5)
Olli	Control	0 (0–5)	0 (0–2)	0 (0–4)
Jiki	Treatment	0 (0–4)	0***	0 (0–8)
Jiki/Paganza	Control	0 (0–6)	0 (0–8)	0** (0–10)
Ocungulir/Godrombo	Treatment	0 (0–28)	0*** (0–4)	1 (0–20)
Jupakonja	Control	0 (0–5)	2** (0–11)	0 (0–7)

Comparison with pretrap (Mann-Whitney *U* or Kruskall-Wallis test with χ^2 approximation). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 4. Median and range of no. of fleas of *Rattus rattus* collected in commensal areas in Arua and Nebbi Districts, Uganda

Village	Treatment/Control	Median (range) no. fleas recovered		
		Pretreatment	7 d	14 d
Olli/Yapi	Treatment	0 (0–4)	0 (0–8)	0 (0–5)
Olli	Control	0 (0–5)	0 (0–2)	0 (0–4)
Jiki	Treatment	0 (0–4)	0***	0.3 (0–4)
Jiki/Paganza	Control	0 (0–6)	0 (0–8)	0* (0–7)
Ocungulir/Godrombo	Treatment	0 (0–11)	0*** (0–4)	0 (0–8)
Jupakonja	Control	0 (0–5)	2.0*** (0–11)	0 (0–7)

Comparison with pretrap (Mann-Whitney U or Kruskall-Wallis test with χ^2 approximation). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

ability) of the bait, described as problematic in other tropical areas (Gratz and Arata 1975). The timing of bait application may have influenced the consumption of the bait. This study was performed in the dry season when crops were already harvested and the amount of stored grains increased. As the amount and type of resources available to the rodent vary throughout any given year, rodents often will switch foraging preference and strategy in response to such changes (Witmer 2007). During the period of this evaluation, our rodent bait was most likely competing with stored grains, suggesting that the formulation containing the ground fish is likely to be consumed in all seasons. This study also showed that bait box usage among rodents is high. Other studies have used passively applied topical insecticides (both liquid and powder) via rodent bait stations, to control fleas (Beard et al. 1988, Gage et al. 1997, Bronson and Smith 2002, Ratovonjato and Duchemin 2001). It is possible that incorporating a passively applied topical insecticide that has appropriate residual activity into the bait box would increase the length of extended flea control.

In commensal areas, *R. rattus* was by far the most common rodent captured in this study and represented the target rodent of this bait. This finding is similar to other studies in Africa investigating commensal rodents (Orach 2003, Eisen et al. 2008; Centers for Disease Control and Prevention, unpublished data). As the primary flea species found on rodents captured in this study were *X. cheopis* and *X. brasiliensis,* baits that target rats and incorporate a systemic insecticide offer a promising tool for use in integrated plague control programs in Uganda. The appearance of *A. niloticus* and *M. natalensis* inside huts is not surprising. *A. niloticus* is semidomestic, diurnal, and can inflict crop damage (Hoffman et al. 2006, Abdel Rahman Ahmed 2008). Likewise, *M. natalensis* can cause serious crop damage, is nocturnal, commensal, and was previously considered the dominant rodent species found in Ugandan huts (and those found in nearby eastern Democratic Republic of the Congo) before the invasion of *R. rattus* (Thorton 1930, Fiedler 1994, Janssens 1997, Nowak 1999).

This study used rodent trapping with removal of these hosts to assess flea index. This method was chosen, instead of a mark-recapture study, because of reluctance among village leaders to allow the release of captured animals. Therefore, we admit this bias because of removal trapping, and realize that the study might not have fairly assessed the residual action of imidacloprid against fleas, which appeared to be almost nil at 14 d posttreatment. It is possible that as rats were removed from the population, other rats (untreated and parasitized) filled the void created by their absence. The rats most likely to have consumed the bait were also the rats most likely to be trapped at the day 7 collection. Rodent bait containing imidacloprid was shown elsewhere to control fleas on rodents for at least 29 d, and it is possible that we would have been able to observe similar results on animals that had consumed the bait, but later released (Borchert et al. 2009).

Baits of this nature could be used for plague control in certain situations either alone or in combination with a rodenticide. Although the imidacloprid-containing bait used in our study effectively controlled fleas for short periods, baits of this type might be cost prohibitive for use by local plague control programs in developing countries without financial assistance from national governments or donors. Clearly, a considerable need exists for rodent control in developing na-

Table 5. Percent control and mean no. of fleas recovered on rodents collected in commensal areas in Arua and Nebbi Districts, Uganda

Village	Treatment/Control	Mean no. fleas recovered			Percent control
		Pretreatment	7 d	14 d	
Olli/Yapi	Treatment	1.1	0.6	0.4	0
Olli	Control	0.7	0.3	0.4	—
Jiki	Treatment	0.6	0	0.5	100
Jiki/Paganza	Control	0.4	0.5	1.2	—
Ocungulir/Godrombo	Treatment	2.1	0.3	2.0	93.9
Jupakonja	Control	0.9	2.1	1.1	—

% Control = 100 − (T/U × 100); T = posttreatment flea index divided by the pretreatment flea index in the treated site, and U = the posttreatment mean divided by the pretreatment mean in the control site.

tions, but research on this topic is highly underfunded (Gratz and Arata 1975, Smyth 1986, Witmer 2007). The addition of a slow-acting rodenticide to the formulation described in this study would allow rapid flea control while resulting in the death of the rodent host after its fleas have died. In the current study, the initial bait formulation was a commercial formulation of bait purchased in the United States. Despite the need for flea control, without financial assistance from national governments or donors, baits of this type may be cost prohibitive for use in plague foci in developing nations. A bait containing both a rodenticide and insecticide would allow effective rodent control and afford protection from flea-borne diseases. Preferably, baits could be formulated and mixed locally, which could reduce costs and increase the likelihood that baits will be used.

Our study suggests that plague control programs should continue to focus on reducing the abundance of the region's two rat fleas (*X. cheopis* and *X. brasiliensis*), both of which have been suggested elsewhere to be important plague vectors elsewhere in Africa (Kilonzo et al. 1997, Eisen et al. 2008). To improve targeting of these baits and to gain a better understanding of human plague risks in northwestern Uganda, further studies are needed on the reservoir competency of rodents and transmission efficacy of major flea species collected. For example, although our study indicated that *R. rattus* was the rodent most commonly found in the huts in our study areas (91.4%), five (8.6%) other species of rodents were captured. Among the noncommensal rodents captured in our study, only *M. natalensis* has been evaluated for its susceptibility to *Y. pestis* infection (Isaäcson et al. 1983, Shepherd et al. 1986). Although the plague susceptibility has not been investigated under laboratory conditions, *A. niloticus* is thought to be involved in the ecology of plague (Hopkins 1949, Kilonzo and Mhina 1983, Gratz 1999) elsewhere in East Africa and was the most commonly encountered noncommensal rodent species collected in our study. Yet, even though laboratory strains of this rodent are available (Katona and Smale 1997, Nixon and Smale 2007), evaluations of their susceptibility of *Y. pestis* infection and their ability to act as sources of flea infection are lacking. Likewise, although 13% of fleas found on hut-dwelling rodents were *D. lypusus,* a species that is thought to be a competent vector of plague (Kilonzo et al. 1997), laboratory investigations to support this belief are largely lacking. Regardless, flea control efforts targeting *Xenopsylla* fleas will most likely have an impact on other flea species as well.

In conclusion, our study demonstrates the feasibility of using an insecticide-containing bait for controlling plague vectors. Future studies, now underway by our group, will compare the efficacy of host-targeted baits with indoor residual insecticide sprays, a technique widely used for malaria control in Africa (Beier et al. 2008).

Acknowledgments

We express our gratitude to Santos Angualia, Joshua Andiku, Sebi Ali, Robert Kibenga Banjo (Uganda Virus Research Institute, Arua, Uganda), and Richard M. Poché (Scimetrics, Ltd.) for helpful discussion and assistance with this study. This work was supported in part by the appointment of Jeff N. Borchert to the Research Participation Program at the Centers for Disease Control and Prevention, Division of Vector-Borne Infectious Diseases, administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the United States Department of Energy and the Centers for Disease Control and Prevention. This work was also supported by the Centers for Disease Control and Prevention, National Center of Zoonotic, Vector-Borne and Enteric Diseases, Division of Vector-Borne Infectious Diseases Emerging Infectious Disease Project 37723, and Bioterrorism Project 6665.

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Received 25 August 2009; accepted 30 April 2010.