Sulfluramid Resistance and Vapor Toxicity in Field-Collected German Cockroaches (Dictyoptera: Blattellidae)

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J. Med. Entomol. 29(2): 207–215 (1992)

ABSTRACT The toxicities of Raid Max Roach Bait (sulfluramid) and COMBAT Roach Control System (hydramethylnon) to susceptible and field-collected German cockroaches were examined. In all field-collected strains, a variable fraction of the population exhibited tolerance to Raid Max. In some strains, few males were killed in the first 5 d of exposure to Raid Max and some lived for up to 123 d when provided Raid Max only. Field-collected males that were given access to Raid Max for only 3 h following a 45-h starvation exhibited a 22-fold delay in mortality of 50% of the population compared with males that were continuously exposed to Raid Max. Males exposed to COMBAT for 3 h exhibited a similar pattern of mortality as males continuously exposed to this bait. Field-collected males provided COMBAT with or without rat chow exhibited identical patterns of mortality. However, males that were offered Raid Max along with rat chow exhibited significantly delayed mortality compared with males given Raid Max alone. A direct comparison of 1% hydramethylnon and sulfluramid, the active ingredients in COMBAT and Raid Max, respectively, in rat chow showed that physiological resistance to sulfluramid was involved; field-collected males consumed both baits equally on the first day, but whereas 100% of the males that were fed hydramethylnon-containing chow died within 5 d, only one of 25 males fed sulfluramid-baited rat chow died during this period, and males continued to consume large amounts of food. This suggested that, in the presence of alternate foods, the effective dose of sulfluramid was diminished, resulting in reduced mortality in males fed Raid Max. These results suggest that relatively high levels of resistance to sulfluramid are pervasive in field populations of the German cockroach. Experiments in which cockroaches were exposed to vapors of Raid Max or sulfluramid without direct contact showed that both acted as fumigants. The Raid Max bait remained lethal without direct contact for at least 170 d of continuous aeration in a fume hood. A headspace analysis revealed that sulfluramid was present in airborne collections of both technical sulfluramid and the Raid Max bait.

KEY WORDS Insecta, resistance, *Blattella germanica*, baits

RESISTANCE TO INSECTICIDES is common in field populations of the German cockroach, *Blattella germanica* (L.). Varying levels of resistance to organochlorine, organophosphate, and pyrethroid insecticides have been documented, resulting in reported control problems (Rust & Reierson 1978; Cochran 1982, 1989; Schal 1988). Cross-resistance, particularly to structurally unrelated compounds, frequently accompanies resistance to specific insecticides, but it is poorly documented in field populations of this cockroach mainly because application records are rarely accurate, hindering a clear distinction between cross- and multiple-resistance. The best documentations of cross-resistance involve insects that had been collected before the target insecticide was available commercially. Nelson & Wood (1982) and Barson & Renn (1983) reported significant resistance to bendiocarb in field populations that apparently had not been exposed to this chemical.

Recently, there has been increased emphasis on bait formulations for cockroach control (see Schal & Hamilton 1990). This was encouraged in part by environmental and public health concerns and the resultant regulations, by the availability of new toxicants that are more effective as stomach poisons, and by the relatively good performance of newer baits compared with conventional sprays. COMBAT Roach Control System (The Clorox Co., Pleasanton, Calif.) contains hydramethylnon (1.65% [AI] tetrahydro-5,5-dimethyl-2(1*H*)-pyrimidinone [3-[4-(trifluoromethyl)phenyl]-1-[2-[4-(trifluoromethyl)phenyl]ethenyl]-2-propenylidene] hydrazone; American Cyanamid, Princeton, N.J.) and represents a new class of amidinohydrazone insecticides that depress respiration by acting as inhibitors of mitochondrial electron transport (Hollingshaus 1987). Since it was introduced in 1985, its effectiveness has been amply documented in laboratory and field tests against cockroaches (e.g., Milio et al. 1986, Appel 1990). Raid

Max Roach Bait (S. C. Johnson & Son, Racine, Wis.) contains sulfluramid (1.0% [AI] *N*-ethyl perfluorooctane sulfonamide; Griffin Corp., Valdosta, Ga.). It appears to act as an uncoupler of oxidative phosphorylation in isolated rabbit renal cortical mitochondria (Schnellmann & Manning 1990). Appel & Abd-Elghafar (1990) showed that, in field trials, both 1% and 1.5% (AI) sulfluramid-containing baits (presumably Raid Max) performed equally well and as well as COMBAT.

In routine comparisons of the efficacy of household baits for cockroach control that were initiated in 1988, I found that field-collected German cockroaches survived prolonged exposure to sulfluramid baits. The study reported herein was undertaken to describe the incidence of this apparent resistance in various field-collected strains. In addition, preliminary results suggested that sulfluramid vapors caused mortality in nonresistant laboratory cockroaches. The present investigation describes this previously unknown phenomenon.

Materials and Methods

Cockroach Strains. The laboratory nonresistant strain was from an American Cyanamid (Princeton, N.J.) stock. The Rutgers strain was collected in a Rutgers University cafeteria (Piscataway, N.J.) in 1984. All other strains were obtained from D. Cochran (VPI & SU); their resistance spectra are detailed in part by Cochran (1987, 1989, 1990) and Scott et al. (1990). The Kenley strain was collected in a house (Kenley, N.C.) in 1984, the Easton strain was collected in 1988 in a house (Holly Springs, N.C.), the Forest Green strain in an apartment (Gainesville, Fla.) in 1989, the Navy strain was collected on a ship (Norfolk, Va.) in 1987, the Jacksonville strain in an apartment (Jacksonville, Fla.) in 1988, and the Reddick strain was collected in a house (Smithfield, N.C.) in 1986.

All cockroaches were maintained at 27°C, variable humidity (35–60%), a photoperiod of 12:12 (L:D), and were provided Purina rat chow #5012 and water ad lib. Colonies were maintained in tightly sealed plastic containers (11.3 liters) with fine-mesh brass screens soldered into the lids. The sides of the dishes were coated with Fluon AD1 (Northern Products, Inc., Woonsocket, R.I.) to prevent cockroaches from escaping; paper cups were provided as shelters.

Chemicals and Bioassay. The two insecticide baits, Raid Max and COMBAT, were purchased in local markets. The baits were carefully removed from their plastic tray containers and each bait block was divided into quarters.

Approximately 20 male German cockroaches of unknown ages (except where noted) were placed into plastic disposable dishes (15 by 2 cm) whose rims had been coated with petroleum jelly (vaseline). Food (rat chow) and water were provided ad lib. After a 3-d acclimation to these dishes at 27°C, the food was removed and immediately replaced with one of the two baits. Mortality was monitored until all cockroaches died. At least 40 males (40–121, 2–6 dished) were used for each strain–bait combination. Mortality was defined as the inability of an insect to right itself. This was unambiguous in insects poisoned by sulfluramid. Insects intoxicated by hydramethylnon exhibit increased activity before death followed by general lethargy, and many die dorsal side up. To increase the resolution of the assay, insects that appeared to be knocked down were turned ventral side up and considered dead if they did not right themselves within 10 min. Insects were not removed from the dishes until all leg and antennal movements ceased. Data were analyzed by probit analysis (SAS Institute 1985) using time as the dosage variable (see Schal 1988, Cochran 1989). Respective LT_{50} or LT_{90} values were considered significantly different if the 95% fiducial limits did not overlap.

One modification of this standard bioassay involved brief exposures of insects to the baits. Baits were offered to susceptible and Jacksonville males that had been starved (with access to water) for 45 h. After 3 h, the baits were removed and replaced with rat chow. Another modification was designed to evaluate the effect of alternate food on mortality. Either bait was presented along with a pellet of rat chow. Susceptible and Rutgers males were tested. Mortality was assayed as above.

To control for differences between the baits in terms of concentration of AIs and bait formulation, technical grade hydramethylnon (American Cyanamid, Princeton, N.J.) or sulfluramid (3M, St. Paul, Minn.) was diluted in diethyl ether/methanol (2:1 vol/vol) and incorporated into finely ground rat chow. Daily consumption by five Reddick males (replicated five times) was measured gravimetrically, and mortality was recorded.

Volatility. Preliminary assays indicated that control insects (fed rat chow) experienced high mortality in an incubator containing Raid Max. To test the possibility that they succumbed to airborne insecticide, I conducted four tests. In the first, Raid Max or COMBAT baits (2.0 g each) were placed into Petri dishes 6 by 1.5 cm with tightly fitting lids. A fine-mesh brass screen was soldered onto a hole (3 by 3 cm) in the cover. This prevented cockroaches from contacting the baits. Each Petri dish was placed into a 2-liter glass jar housing 27–83 susceptible 14-d-old male German cockroaches. Rat chow and water were provided ad lib. Mortality of males was monitored until all males died. The males were then removed, the jar was aerated in a fume hood, and the test was repeated with the same bait-containing dish to evaluate the persistence of this effect. This procedure was repeated three times.

In the second test, this procedure was repeated with technical sulfluramid or hydramethylnon. After all males died, the Petri dish containing the insecticide was removed, the glass jar was aerated in a fume hood for 3 d, and mortality of 14-d-old susceptible males was monitored to determine whether residual insecticide was present in the jar.

The third test examined gravimetric changes in a glass Petri dish containing 11.3151 g of technical sulfluramid. The dish was placed in a 35°C sand bath in a fume hood and weighed frequently to the nearest 0.1 mg.

I also conducted a head-space analysis of sulfluramid and Raid Max. One g of bait or 200 mg sulfluramid was placed on a watch glass on the bottom of a 473-ml Mason jar. Air (dry grade) was further filtered through Tenax before it was introduced into the Mason jar and trapped on 500 mg of activated charcoal (Carbotrap 20/40, Supelco, Pa.). Air flow was 30 ml/min for 3 h. The charcoal was desorbed with 7 ml ethyl acetate, and 2 μg n-docosane was added as an internal standard. Analysis was performed with a gas–liquid chromatograph (HP 5890, FID) interfaced with a digital integrator. Samples were introduced by splitless injection into a SPB-5 column (15 m by 0.53 mm) (Supelco, Belefonte, Pa.). The oven was maintained at 50°C for 2 min, then programmed at 10°C/min to 200°C. Sulfluramid was quantified relative to the internal standard.

Results and Discussion

Exposure Tests

Although mortality data were routinely transformed to probit values to improve the resulting dose–response model, mortality data are nonetheless presented graphically as percentages in Fig. 1–6 to illustrate mortality patterns in populations containing cockroaches that survived for extended periods. The toxicities of Raid Max and COMBAT to susceptible (American Cyanamid) male German cockroaches are shown in Fig. 1. Raid Max caused significantly faster mortality than COMBAT. The LT_{50} and the LT_{90} values on Raid Max were 0.64 and 0.90 d, respectively, compared with 1.45 and 1.70 d for the respective values on COMBAT (Table 1).

Field-collected strains of the German cockroach died as readily as the susceptible strain upon exposure to COMBAT. For most strains, the 95% fiducial limits for the LT_{50} and LT_{90} values did not overlap with the respective limits for the susceptible strain, suggesting significant differences. However, the LT_{50} or the LT_{90} levels for field-collected strains were always below 1.5- and 1.7-fold of the respective values in non-

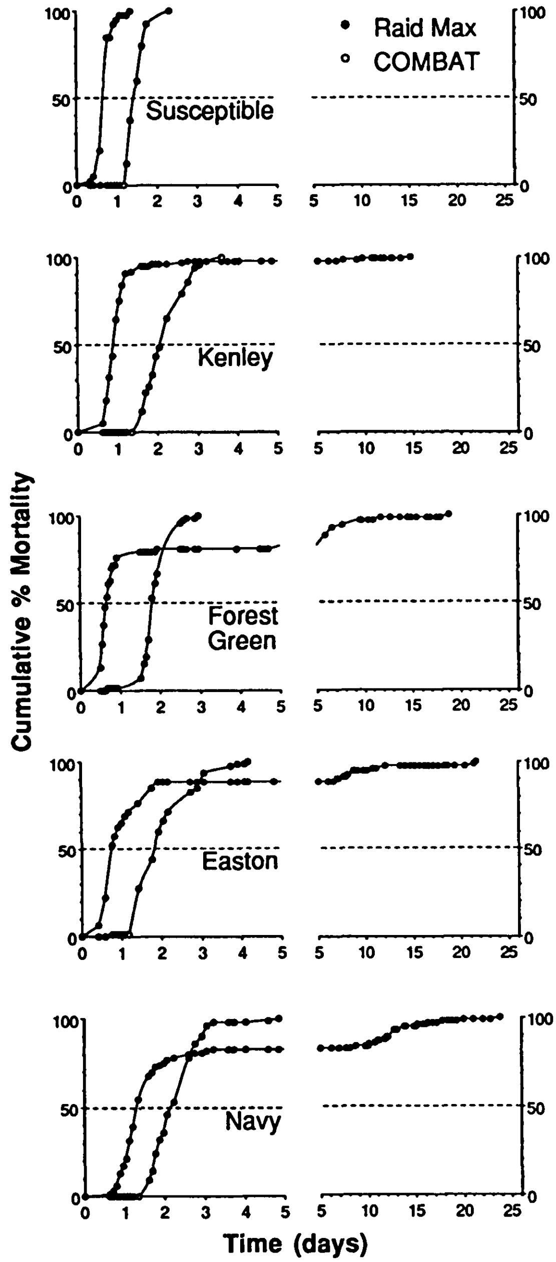

Fig. 1. Cumulative mortality of susceptible males and males of four field-collected German cockroach strains fed either COMBAT or Raid Max baits. n = 40–121 for each test.

resistant males (Tables 1 and 2). The slopes for all strains were very steep (6.95–15.06), and the LT_{90} values were no more than 1 d greater than the respective LT_{50} values (Table 1).

Conversely, Raid Max tolerance was variable but common among field-collected strains. Fig. 1 and 2 are sequenced to show a gradual shift in the shape of the time–mortality curves for Raid Max. It is clear that in some strains (Forest Green, Kenley, Easton, Navy), most of the males

Table 1. Toxicity of COMBAT (1.65% [AI] hydramethylnon) and Raid Max (1% [AI] sulfluramid) baits to susceptible cockroaches and to various field-collected strains in continuous and 3-h exposure tests or in the presence of alternate foods

Strain and treatment[a]	COMBAT[b]				Raid Max[b]			
	n	Slope ± SD	LT_{50} (95% CI)	LT_{90} (95% CI)	n	Slope ±SD	LT_{50} (95% CI)	LT_{90} (95% CI)
Susceptible	40	18.58 ± 0.054	1.45 (1.41–1.48)	1.70 (1.64–1.78)	40	8.62 ± 0.116	0.64 (0.60– 0.68)	0.90 (0.86– 0.97)
3-h exposure	80	13.67 ± 0.073	1.66 (1.60–1.71)	2.06 (1.99–2.17)	80	9.59 ± 0.104	0.59 (0.46– 0.68)	0.80 (0.70– 1.06)
Bait + chow	79	13.77 ± 0.073	1.82 (1.77–1.86)	2.25 (2.18–2.34)	80	5.75 ± 0.174	0.72 (0.62– 0.81)	1.20 (1.05– 1.47)
Kenley	120	10.24 ± 0.098	2.08 (2.05–2.12)	2.78 (2.71–2.86)	121	2.98 ± 0.336	0.75 (0.52– 0.97)	2.06 (1.68– 2.73)
Forest Green	72	9.25 ± 0.108	1.80 (1.44–2.19)	2.48 (2.08–4.78)	67	1.46 ± 0.684	0.61 (0.48– 0.74)	4.61 (3.88– 5.68)
Easton	80	6.95 ± 0.144	1.87 (1.81–1.93)	2.86 (2.73–3.00)	80	1.48 ± 0.676	0.66 (0.52– 0.80)	4.86 (4.27– 5.61)
Navy	100	9.70 ± 0.103	2.16 (2.11–2.20)	2.92 (2.84–3.02)	99	1.78 ± 0.563	1.60 (1.33– 1.87)	8.41 (7.20–10.10)
Rutgers	100	14.84 ± 0.067	1.66 (1.63–1.69)	2.02 (1.98–2.08)	100	1.28 ± 0.780	1.26 (1.09– 1.43)	12.57 (11.40–13.95)
Bait + chow	80	19.87 ± 0.050	1.79 (1.75–1.82)	2.07 (2.03–2.14)	80	1.18 ± 0.845	1.95 (1.55– 2.37)	23.64 (18.84–31.36)
Jacksonville	79	11.77 ± 0.085	1.95 (1.90–2.00)	2.50 (2.42–2.61)	80	1.69 ± 0.592	5.20 (4.92– 5.49)	29.84 (28.46–31.35)
3-h exposure	80	14.24 ± 0.070	1.65 (1.61–1.68)	2.03 (1.97–2.09)	80	1.79 ± 0.559	12.96 (11.16–14.85)	67.45 (56.93–82.34)
Reddick	40	15.06 ± 0.066	1.90 (1.84–1.96)	2.31 (2.21–2.47)	45	4.09 ± 0.244	9.97 (9.52–10.42)	20.50 (19.48–21.68)

[a] Unless otherwise stated, the standard bioassay involved continuous exposure to baits with no other food.
[b] LT_{50} and LT_{90} values are expressed in days.

Table 2. Resistance levels of various field-collected strains to COMBAT (1.65% [AI] hydramethylnon) and Raid Max (1% [AI] sulfluramid) baits

Strain and treatment[a]	COMBAT[b]		Raid Max[b]	
	RR_{50}	RR_{90}	RR_{50}	RR_{90}
Kenley	1.43	1.63	1.17	2.29
Forest Green	1.24	1.46	0.95	5.12
Easton	1.29	1.68	1.03	5.40
Navy	1.49	1.72	2.50	9.34
Rutgers	1.14	1.19	1.97	13.97
Bait + chow	0.98	0.92	2.71	19.70
Jacksonville	1.34	1.47	8.12	33.15
3-h exposure	0.99	0.98	21.97	84.31
Reddick	1.31	1.36	15.58	22.78

[a] Unless otherwise stated, the standard bioassay involved continuous exposure to baits with no other food.
[b] RR_{50} and RR_{90} values are expressed as the respective LT value of the field-collected strain divided by the LT value of the susceptible strain in the same assays.

died in the first 2–3 d, well before most of the males that fed on COMBAT (Fig. 1). The Forest Green strain had the lowest level of resistance to Raid Max at the LT_{50} level; it exhibits high resistance to pyrethrins and various pyrethroids, moderate to high resistance to carbamates, and moderate resistance to organophosphates (D. G. Cochran, personal communication). However, a variable component of the population (usually <10% of the males) survived, and some lived for

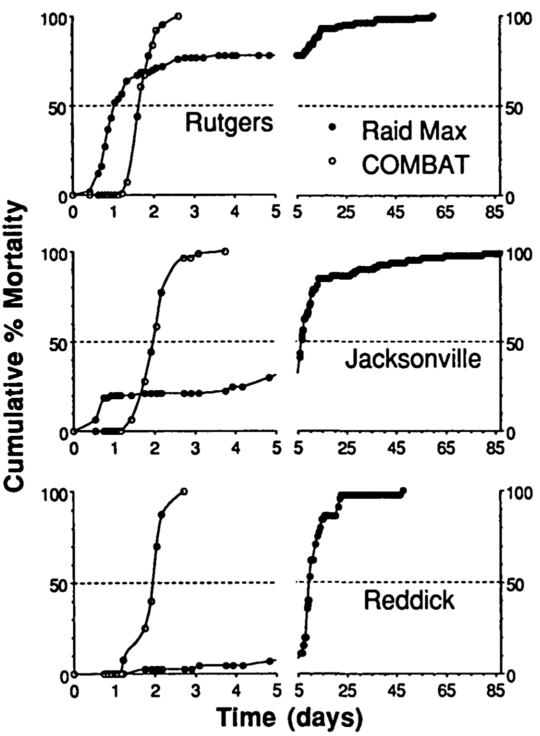

Fig. 2. Cumulative mortality of three field-collected German cockroach strains fed either COMBAT or Raid Max baits. Mortality patterns of susceptible males are presented in Fig. 1. n = 40–100 for each test.

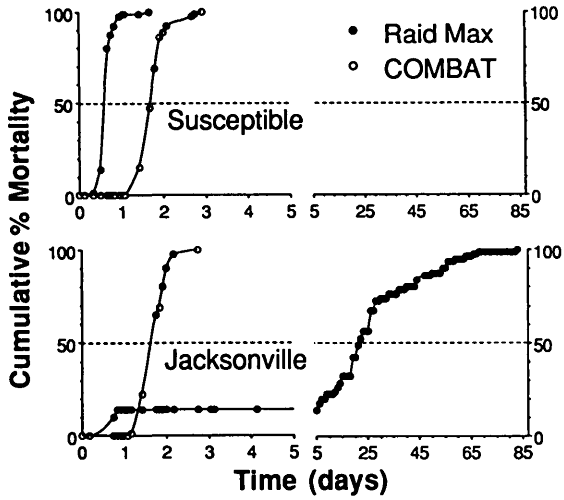

Fig. 3. Cumulative mortality of susceptible and Jacksonville German cockroach males that were starved for 45 h, provided with either Raid Max or COMBAT for 3 h, then fed rat chow. n = 80 for each test.

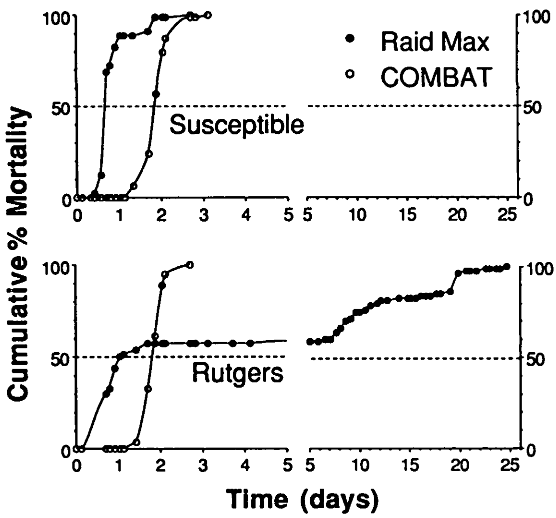

Fig. 4. Cumulative mortality of susceptible and Rutgers German cockroach males that were provided either Raid Max or COMBAT along with rat chow. n = 79–80 for each test.

up to 22 d. This heterogeneity within the population was apparent at the LT_{90} level and by the flattening of the time–mortality curves (Table 1), indicating incipient resistance.

In other strains (Rutgers, Jacksonville, Reddick), only a minor proportion of the males died within the first 5 d (Fig. 2), and both the LT_{50} and LT_{90} were significantly greater than in the susceptible strain (Table 1) resulting in high resistance ratios (Table 2). The greatest resistance at the LT_{50} level was exhibited by the Reddick strain (15.58-fold), which also has been shown to be highly resistant to bendiocarb, propoxur, malathion, pyrethrins, and allethrin (Cochran 1989). It was not uncommon for males of these strains to survive for several weeks; the last male in the Jacksonville strain died after 123 d of continuous exposure to Raid Max with no other food available. Because males of unknown ages were used in these assays, it appears that some field-collected males might have died of natural causes.

In the modified bioassay in which susceptible and Jacksonville males were starved for 45 h, then provided either COMBAT or Raid Max baits for 3 h and subsequently given rat chow only, all susceptible males that fed on Raid Max or COMBAT died within 2.9 d (Fig. 3). The LT_{50} and LT_{90} values of susceptible insects on either bait were similar to the respective values in susceptible males with continuous exposure to the respective baits (Table 1). Similarly, Jacksonville males provided with COMBAT exhibited a mortality pattern identical to that in control males. However, the LT_{50} for Jacksonville males that fed on Raid Max for only 3 h was significantly greater (22-fold) than the LT_{50} for males that were continuously exposed to the same bait (Fig. 2 and 3, Tables 1 and 2). The resistance ratio at the LT_{90} level was 84 (compared with 33 for continuous exposure), indicating that in some field-collected insects, continuous exposure to Raid Max is needed to achieve rapid mortality. The Jacksonville males that were continuously exposed to Raid Max lived significantly longer (last male dead after 123 d) than similar males exposed to this bait for only 3 h (last male dead after 83.1 d) (Fig. 3). This may indicate a chronic effect of the 45-h starvation or, more likely, differences in the ages of approximately 5% of the males in the respective experiments (as noted above). Although quantitative measures of consumption were not conducted, it was evident from direct observations that both sets of starved males fed on the baits.

In the previous assays, cockroaches were exposed to baits without access to alternate food. When offered either of the two baits in conjunction with rat chow, susceptible males exhibited slightly delayed patterns of mortality compared with exposure to baits alone (Fig. 1 and 4). Rutgers strain males provided COMBAT with or without rat chow exhibited similar patterns of mortality over time (Fig. 2 and 4, Table 1). However, Rutgers males that were offered Raid Max along with rat chow exhibited significantly delayed mortality, especially at the LT_{90} level, compared with males given Raid Max alone. By day 5, only approximately 60% of the males died in the former test compared with 80% in the continuous exposure tests described above, and the LT_{90} values doubled. This may indicate either a behavioral avoidance of the bait or an effective dilution of the AI by the alternate food.

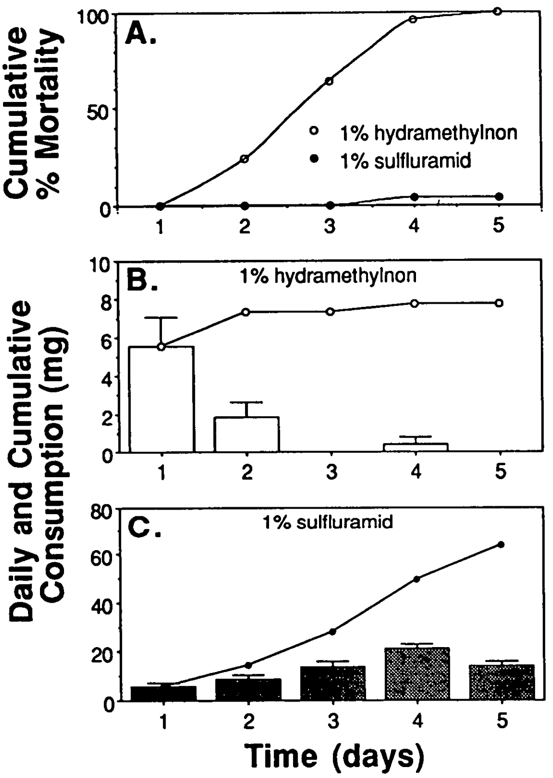

Fig. 5. Cumulative mortality (A) and daily (bars) and cumulative (lines) consumption of Reddick German cockroach males that were fed either 1% hydramethylnon in rat chow (B) or 1% sulfluramid in rat chow (C). n = 25 in five groups of five males for each test.

The difference in the time to 100% mortality between the two bioassays is likely due to different ages of the Rutgers males used in the assays.

A direct comparison of the 2 AIs (1%) in rat chow was conducted with males that were acclimated to eating rat chow to determine whether lack of feeding (e.g., repellent or deterrent effects) or physiological–metabolic resistance were of major importance in resistance to sulfluramid. That physiological resistance was involved was evident from the observation that Reddick males consumed both baits equally on the first day (Fig. 5). However, whereas 100% of the males that were fed hydramethylnon-containing chow died within 5 d, only one male (n = 25) fed sulfluramid-baited rat chow died during this period, and the remaining 24 males continued to consume large amounts of food (Fig. 5). Moreover, because most starved cockroaches died within 20 d (unpublished observations), this clearly indicates that some cockroaches fed Raid Max or sulfluramid bait must have consumed and assimilated the bait to survive for up to 110 d (Fig. 2). This was also readily evident from the fact that new blocks of Raid Max had to be added to dishes in which males survived for long periods. This suggests that in the presence of alternate foods, the effective dose of sulfluramid is reduced, resulting in diminished mortality in males fed Raid Max, as was also shown in Fig. 4.

Reid et al. (1990) showed that sulfluramid caused more rapid mortality in nonresistant cockroaches (topical application) than did hydramethylnon. They suggested that this may offer advantages in the control of German cockroaches in the field. My feeding assays confirm the observations that sulfluramid-containing baits are faster acting on laboratory nonresistant cockroaches. However, such inferences are confounded by at least two major caveats: First, hydramethylnon-treated insects are destined to die after relatively short exposure to the bait and before any overt signs of intoxication are obvious (Hollingshaus & Little 1984). This was also demonstrated by a short 3-h exposure in the present study (Fig. 3, Table 1) and by the fact that consumption decreased dramatically after the first day of exposure to toxic baits (Fig. 5). Thus, the speed at which mortality occurs (within the first few days of exposure) should play little role in efficacy in the field, particularly when determinations of field efficacy are made 2 or 4 wk after treatment. Second, and more importantly, field-collected strains clearly exhibited delayed and reduced mortality when fed Raid Max compared with COMBAT. Delays in mortality on Raid Max of up to several weeks or months will have profound effects on the long-term efficacy of this bait in the field.

Some of the field-collected strains tested in the present investigation were collected before the approval of sulfluramid for commercial use against cockroaches and all were collected at sites where Raid Max had not been used. They exhibit broad profiles of resistance to a variety of insecticides (Cochran 1989, 1990; Scott et al. 1990; D. G. Cochran, personal communication), although several of the strains were collected randomly with no association with reported control failures. This suggests that broad cross-resistance to sulfluramid is common. It is not clear, however, which of the commonly used conventional insecticides might confer cross-resistance to sulfluramid. All strains exhibited moderate to high resistance to pyrethrins and carbamates, but because the Kenley and Forest Green strains are highly resistant to pyrethrins (D. G. Cochran 1989, personal communication; Scott et al. 1990) but only moderately resistant to sulfluramid, carbamate cross-resistance appears to be more likely. This is supported by two findings: First, most of the tested strains exhibited moderate to high resistance to bendiocarb or propoxur, although resistance levels to the latter are confounded by the testing method (see Scott et al. 1990). Second, a propoxur (Baygon)-selected laboratory strain that originated from the same susceptible population as I used in this study exhibited significant cross-resistance to both technical sulfluramid and to Raid Max (unpublished results). Carbamate resistance is widespread in various geographical locations in the United States (Cochran 1989) and elsewhere (e.g., Barson & Renn 1983), strongly suggesting that many field populations of the German cockroach may be cross-resistant to sulfluramid. The use of sulfluramid-containing baits may represent long-lasting sublethal exposure which should result in rapid selection of highly resistant cockroaches in the field.

An alternative explanation for sulfluramid resistance is that it developed in response to exposure of the German cockroach to various xenobiotics, including household and industrial chemicals. Brattsten (1987) and others have hypothesized that in phytophagous insects, naturally occurring detoxification mechanisms which are inducible by phytochemicals may predispose insects to tolerate certain synthetic pesticides. Indeed, allelochemicals in plants, which induce detoxifying enzymes, also decrease the toxicity of some insecticides (e.g., Yu 1983). Conversely, insecticide (cyclodiene)-resistant German cockroaches are also resistant to picrotoxinin, a plant-derived neuroexcitant (Kadous et al. 1983). This hypothesis may be extended to household and industrial chemicals in relation to the German cockroach. In its association with humans, this cockroach is routinely exposed to numerous surfactants, cleaners, solvents, lubricants, various oils, waxes and stains, food additives, and potentially even mammalian hormones and metabolites in food and sewage. It is possible that field populations of the German cockroach have developed broad tolerance to many such chemicals. Fluorocarbons such as sulfluramid are used as surfactants, surface active agents in textiles, and in a variety of specialty chemicals requiring thermal and chemical stability. They are thus used in various industrial and household applications. Resistance to sulfluramid may, therefore, represent a case of cross-resistance to either pesticides or to common household chemicals, or to both.

Volatility and Vapor Toxicity. It was noticed that control insects that were housed in an incubator containing Raid Max and fed only rat chow died within 20 d. Because the insects were separated from the bait by at least 1 m, it appeared that an airborne insecticide was responsible. Susceptible males that were denied contact with, but with access to, vapors from either Raid Max baits (2.0 g) or sulfluramid (0.265 g), died within 13 d (Fig. 6). Mortality occurred in some males after 3 d of continuous exposure to sulfluramid vapors, and all males died within 8 d. The Raid Max bait remained lethal without direct contact for at least 170 d of continuous aeration in a fume hood (Fig. 6). Interestingly, males died faster

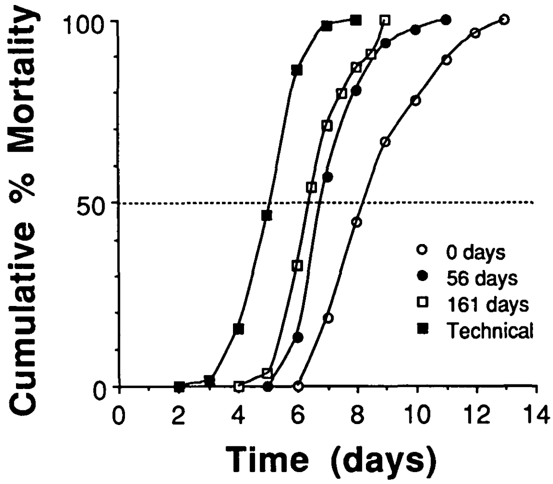

Fig. 6. Cumulative mortality of susceptible German cockroach males exposed to 2 g of Raid Max bait or 265 mg of technical sulfluramid. The males were separated from the insecticides with a fine-mesh brass screen. The bait was aerated for the specified number of days before the assay was conducted. n = 27–83 for each test.

when exposed to the Raid Max vapors after 161 d of aging of the bait than in earlier studies, suggesting that either more sulfluramid became airborne with time or that the glass jar became contaminated with sulfluramid residues. The latter hypothesis was examined by bioassay.

Because sulfluramid is a rather large molecule (MW = 527) with a boiling point of approximately 110°C at 2 mm Hg (3M "Fluorad" FX-12 Product Information 1985) and a vapor pressure of 4.3×10^{-7} mm Hg at 25°C (GX-071 Material Safety Data Sheet, Griffin Corp., Valdosta, Ga.), I hypothesized that a "flowing" or "creeping" phenomenon involving its low surface tension might occur. The technical material and the baits used (Fig. 6) were removed from the glass jars, the jars were aerated for 2 d, and new males were bioassayed in the jars with food and water. No males died in either jar in 20 d of observations, suggesting that vapors rather than residual insecticide on the surface were responsible for this mortality. Furthermore, technical sulfluramid incubated in a 35°C sand bath lost weight over time. Ten days after monitoring was initiated, 10% of the original 11.3151 g was lost. After 100 d, 21.1% of the sulfluramid was lost, indicating significant sublimation.

A headspace analysis was conducted to determine whether sulfluramid could be recovered from airborne collections. Because the efficiency of the charcoal trap, air speed, extraction procedure, and the GLC analysis were not optimized, and the adsorbed compounds were not subjected to mass spectrum analysis, I regard this a preliminary qualitative investigation. Based on GLC retention times, sulfluramid was clearly present in airborne collections from both technical sulfluramid and from Raid Max baits. I did not elucidate the identity of minor components which were found in the technical material and were trapped on charcoal. COMBAT bait and hydramethylnon did not exhibit vapor toxicity in similar tests in which males were observed for at least 30 d.

Vander Meer et al. (cited as unpublished results in Vander Meer et al. 1985) concluded that various sulfluramid analogs, including the one tested herein, did not exhibit fumigant action against the red imported fire ant, *Solenopsis invicta* Buren. My results suggest that either fumigant action can play a substantial role in causing *B. germanica* mortality in laboratory assays, or that impurities in both the technical material and the formulated commercial bait may act as fumigants. Contact toxicity in the absence of feeding has also been observed in baits containing conventional insecticides, such as chlorpyrifos (Rust & Reierson 1981); Reierson & Rust (1984) suggested that detection of toxic residues by foraging cockroaches may result in avoidance of baits. Reid et al. (1990) showed that 0.1% sulfluramid in rat chow was not deterrent to last-instar nymphs of *B. germanica,* but Appel & Abd-Elghafar (1990) noted that sulfluramid-containing baits (1 and 1.5% [AI]) as well as residual deposits exhibited dose-dependent repellency similar to that of baits containing chlorpyrifos. It is not clear whether the vapor toxicity described herein plays a role in such repellency. My consumption study indicates that COMBAT and Raid Max are consumed equally on the first day, but comparative studies of the relative repellency–attractancy of the Raid Max bait in the presence of alternate foods are clearly needed, especially if the amount of AI is increased in efforts to ameliorate resistance.

Roush & McKenzie (1987) concluded that field strains provide the most rigorous tests of various management approaches, and they argued that new insecticides should be tested against such strains. The results presented herein, and my hypothesis that unrelated household and industrial compounds might predispose cockroaches to tolerate new insecticides, highlight the importance of the thorough testing of new and novel insecticides before they are commercialized, not only in the laboratory but also against field-collected insects.

Acknowledgment

I thank Ann-Shyn Chiang, Richard Cooper, Lou Vasvary, and an anonymous reviewer for valuable comments on the experiments and manuscript, and D. Cochran (Virginia Polytechnic Institute & State University) for sharing several cockroach strains and associated resistance data. The research was supported in part by a grant from USDA-CSRS (90-34103-5413). A contribution of the New Jersey Agricultural Experiment Station (publication D-08928-04-91) supported by State funds and by the U.S. Hatch Act.

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Received for publication 15 February 1991; accepted 4 September 1991.