〔Med. Entomol. Zool. Vol. 55 No. 2 p. 77–93 2004〕

Insecticide resistance profiles and possible underlying mechanisms in German cockroaches, *Blattella germanica* (Linnaeus) (Dictyoptera: Blattellidae) from Peninsular Malaysia

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(Received: 4 April 2002; Accepted: 24 February 2004)

Abstract: Insecticide resistance and possible underlying mechanisms were studied in 52 strains of the German cockroach, *Blattella germanica* (L.) field-collected from Peninsular Malaysia. These strains were assayed using a lethal time assay at 10x susceptible LC_{95} concentrations of propoxur ($1.10\,\mu g/cm^2$), chlorpyrifos ($18.40\,\mu g/cm^2$), permethrin ($1.70\,\mu g/cm^2$) and deltamethrin ($0.55\,\mu g/cm^2$) using a surface-contact exposure method with reference to the susceptible ICI strain. Results indicated that propoxur and permethrin resistance were highly prevalent (73.0% and 80.2% of LT_{50} RR >10x, respectively) while low prevalence of deltamethrin (29.6%) and chlorpyrifos (4.0%) resistance (RR >5) were detected. Resistance level was partially suppressed in most of the strains when piperonyl butoxide ($100\,\mu g$/insect) and *S,S,S,*-tributylphosphorotrithioates ($30\,\mu g$/insect) were used, indicating possible involvement of elevated monooxygenase and esterase. In addition, altered acetylcholinesterase was also suspected in eight strains. The percentage mortality of field populations were found to be distributed at two extremes when treated topically with deltamethrin at LC_{99} ($0.056\,\mu g$/insect), indicating higher numbers of homogenous susceptible and resistant strains, respectively in those populations tested. Results obtained using topical application (percentage mortality) and surface-contact exposure method (resistance ratio) were not well correlated ($r^2=0.169$, $P=0.023$).

Key words: *Blattella germanica*, insecticide resistance, Malaysia, synergism, resistance mechanism.

INTRODUCTION

The German cockroach, *Blattella germanica* (L.) is an important insect pest to the pest control industry world-wide (Lee et al., 1999a; Lee and Robinson, 2001). One of the major challenges in German cockroach control is insecticide resistance. The first incidence of German cockroach resistance to insecticide was reported by Heal et al. (1953) where a population from Texas, U.S.A. was found to be resistant to chlordane. Since then, insecticide resistance development in the German cockroach has been shown to follow patterns of insecticide usage. It started with organochlorine resistance, followed by carbamate and organophosphate resistance in the 1960s and 1970s (Webb, 1961; McDonald and Cochran, 1968; Collins, 1973; Batth, 1977; Barson and McCheyne, 1979). Pyrethroid resistance was documented in mid to late 1980s (Scott et al., 1986; Cochran, 1987, 1989; Umeda et al., 1988; Zhai and Robinson 1991a). In addition, cross

Table 1. Information on field-collected strains of the German cockroach from Peninsular Malaysia.

Strain	Collection site	Type of kitchen	Collection date
BBR	Hotel kitchen, Penang	Chinese	11 Jan. 1999
BUSM	Cafeteria, Penang	—	20 Nov. 1997
CB	Hotel kitchen, Penang	Malaysian	22 Dec. 1998
CIGO	Restaurant kitchen, Kuala Lumpur	Chinese	28 Dec. 1998
CK	Hotel kitchen, Pahang	Chinese	6 Aug. 1999
Copt	Hotel kitchen, Penang	Chinese	21 Sept. 1999
CP	Hotel kitchen, Penang	Chinese	2 Nov. 1998
CT	Hotel kitchen, Pahang	Chinese	18 Aug. 1999
DHKL	Hotel kitchen, Kuala Lumpur	Chinese	11 Dec. 1998
Emp	Cruise, Penang	—	2 Dec. 1999
FBR	Hotel kitchen, Penang	Malaysian	20 Jan. 2000
GCJB	Hotel kitchen, Johor	Malaysian	29 Dec. 1998
GCPG	Hotel kitchen, Penang	Malaysian	29 June 1999
GL	Hotel kitchen, Pahang	Malaysian	18 Aug. 1999
GT	Hotel kitchen, Pahang	Malaysian	3 Aug. 1999
HT	Food stall, Kuala Lumpur	—	16 Dec. 1998
HUSM	Cafeteria, Penang	—	20 Nov. 1997
IHKL1	Hotel kitchen, Kuala Lumpur	Chinese	7 May 1998
IHKL2	Hotel kitchen Kuala Lumpur	Malaysian	11 Dec. 1998
IHKL3	Hotel kitchen, Kuala Lumpur	Japanese	15 Oct. 1999
Inai	Food stall, Kuala Lumpur	—	16 Dec. 1998
IndahE	Bus, Kuala Lumpur	—	24 May 1998
Ita	Hotel kitchen, Penang	Malaysian	13 Dec. 1999
KG	Hotel kitchen, Pahang	Malaysian	18 Aug. 1999
KTM	Train, Malacca	—	10 Mar. 2000
LHFA	Restaurant, Kuala Lumpur	Chinese	25 June 1998
LHFB	Restaurant, Kuala Lumpur	Chinese	27 June 1998
Maluri	Hotel kitchen, Kuala Lumpur	Chinese	16 Dec. 1998
May	Restaurant, Penang	Chinese	6 Jan. 1999
Mid	Restaurant, Penang	Chinese	30 June 1999
ML	Hotel kitchen, Kuala Lumpur	Malaysian	Dec. 1996
MT	Hotel kitchen, Penang	Malaysian	25 Jan. 1999
MV	Hotel kitchen, Penang	Malaysian	25 June 1998
Nazir	Restaurant, Penang	Malaysian	11 Jan. 1999
Peak	Hotel kitchen, Pahang	Malaysian	9 Aug. 1999
PG	Club, Penang	Malaysian	20 Sept. 1999
PK	Hotel kitchen, Pahang	Malaysian	17 Aug. 1999
PRKL	Hotel kitchen, Kuala Lumpur	Chinese	12 Dec. 1998
PRKT	Hotel kitchen, Terengganu	Malaysian	23 Apr. 1998
PRPG	Hotel kitchen, Penang	Chinese	6 Jan. 1999
Pudu	Hotel kitchen, Kuala Lumpur	Malaysian	28 Dec. 1998
Raja	Resort kitchen, Pahang	Malaysian	18 Aug. 1998
Relau	Apartment, Penang	—	Aug. 1998
Sedap	Food stall, Johor	Malaysian	5 Jan. 1999
Selesa	Restaurant, Johor	Malaysian	5 Jan. 1999
Sun	Restaurant, Penang	Chinese	23 Nov. 1998
SW	Hotel kitchen, Penang	Malaysian	6 Feb. 1998
Tmas	Restaurant, Penang	—	8 Jan. 1999
TOPS	Supermarket, Johor	—	31 Dec. 1998
TS	Grocery store, Kuala Lumpur	—	17 Aug. 1999
Yao	Shopping mall, Kuala Lumpur	—	5 Dec. 1998
ZT	Boutique cum restaurant, Kuala Lumpur	Malaysian	28 Nov. 1999

resistance among different group of insecticides was also reported and indicating possible involvement of multiple resistance mechanisms (Siegfried et al., 1990; Hemingway et al., 1993; Cochran, 1996; Lee et al., 1996; Lee, 1997).

Residual insecticide treatment is still currently the most preferred method against German cockroaches among the pest control professionals in Malaysia, although baiting is gaining popularity (Lee, 1998). Heavy reliance on a particular insecticide until it is no longer effective is a common practice among pest control operators in Malaysia. In the mid 1990s, Lee et al. (1996) reported that twelve field strains showed varying degree of resistance to bendiocarb, propoxur, chlorpyrifos, cypermethrin and permethrin. More recently, Lee and Lee (2002) adopted a discriminating dose technique to determine the prevalence of insecticide-resistant individuals among more than 30 field populations collected. Possible involvement of elevated oxidative and hydrolytic enzymes and target site insensitivity were also suggested (Lee et al., 1997; Lee and Lee, 1998; Lee et al., 1999b, 2000).

In this paper, we report the profiles of insecticide resistance in 53 field populations of the German cockroach, collected between December 1996 and March 2000 from various locations in Peninsular Malaysia. Possible involvement of elevated detoxifying enzymes such as monooxygenases and esterases were also determined using piperonyl butoxide (PBO) and *S,S,S*-tributylphosphorotrithioates (DEF).

MATERIALS AND METHODS

Insects

The ICI susceptible strain used in this study was previously described in Lee et al. (1996). It is a subculture from an original strain that has been reared in Zeneca Agrochemicals in Jealotts Hill, UK for more than 40 years. Information on field-collected strains was shown in Table 1. All strains were reared under laboratory conditions of 28±1℃, 55±5% RH and 12 hours photoperiod with food and water provided *ad libitum*. The collected cockroaches were reared for 1–3 generations to obtain sufficient individuals for the study.

Insecticides

A total of four insecticides were obtained from various manufacturers. Technical grade propoxur (99.5%) (Bayer AG, Germany), chlorpyrifos (95.9%) (Dow Agro Sciences Asia, Malaysia), deltamethrin (96.1%) and permethrin (95.0%) (Aventis Environmental Health, Malaysia) diluted in analytical grade acetone were used in this study. These are the most common insecticides used in pest control operation in Malaysia and usually applied in residual spray formulations.

Surface-contact exposure method

Prior to the insecticide resistance tests, LC_{95} value for each insecticide were generated by exposing 10 adult *males* of the ICI susceptible strain to a series of five known concentrations of the insecticide coated on the base of 0.45 *l* glass jar that caused between 5–95% mortality. After two-hour

Table 2. LC_{95} (DD) of four insecticides tested against ICI susceptible strain.

Insecticide	*n*	LC_{50} (95% FL)[1] ($\mu g/cm^2$)	LC_{95} (95% FL) ($\mu g/cm^2$)	Slope±SE	χ^2 (df)[2]
Propoxur	250	0.027 (0.022–0.032)	0.107 (0.084–0.147)	2.74±0.25	1.7 (3)
Chlorpyrifos	250	0.897 (0.639–1.174)	1.835 (1.345–4.817)	5.29±0.56	8.8 (3)
Deltamethrin	250	0.017 (0.012–0.021)	0.055 (0.049–0.065)	3.84±0.53	5.5 (3)
Permethrin	250	0.093 (0.082–0.110)	0.165 (0.148–0.182)	6.64±0.92	4.0 (3)

[1] 95% confidence interval.

[2] Degree of freedom.

Table 3. Susceptibility of field-collected German cockroaches to propoxur, and synergistic effects of PBO and DEF.

Strain	Propoxur (1.10 μg/cm^2)		Propoxur + PBO (100 μg/insect)		Propoxur + DEF (30 μg/insect)	
	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
ICI	15.1 (14.4–15.7)	—	17.3 (16.3–18.2)	—	13.9 (13.4–14.3)	—
BBR	35.2 (33.2–37.3)	2.3 (2.2–2.5)	29.9 (28.4–31.3)	1.7 (1.6–1.9)	19.6 (17.8–20.9)	1.4 (1.3–1.5)
BUSM	40.6 (37.9–43.5)	2.7 (2.5–2.9)	—	—	348.4 (281.6–436.0)	25.0 (20.2–31.1)
CB	218.5 (123.6–430.5)	14.4 (10.5–19.8)	30.7 (26.9–34.3)	1.8 (1.6–2.0)	76.5 (48.4–110.4)	5.5 (4.5–6.7)
CIGO	—	>280	99.4 (76.1–137.7)	5.8 (4.8–6.9)	463.8 (271.9–973.2)	33.4 (22.5–49.5)
CK	—	>280	—	—	—	—
Copt	—	>280	42.5 (39.6–45.0)	2.5 (2.3–2.7)	27.7 (15.9–34.8)	2.0 (1.7–2.4)
CP	—	>280	2,285 (1,547–3,810)	133 (84.8–208)	497.4 (372.3–707.3)	35.8 (26.2–49.0)
CT	—	>280	—	—	—	—
DHKL	54.8 (21.5–79.5)	3.6 (3.1–4.2)	—	—	—	—
Emp	—	>280	311.6 (236.3–440.8)	18.0 (14.8–21.9)	—	>280
FBR	—	>280	43.2 (34.8–57.9)	2.5 (2.2–2.9)	169 (79.9–600).	12.2 (8.1–18.2)
GCJB	—	>280	—	—	40.2 (27.6–50.8)	2.9 (2.1–3.9)
GCPG	—	>280	—	—	66.1 (51.5–77.1)	4.8 (4.0–5.6)
GL	170.2 (98.7–514.9)	11.4 (7.9–16.1)	69.5 (30.5–105.2)	4.1 (3.3–5.0)	36.4 (14.4–52.0)	2.6 (2.0–3.4)
GT	—	>280	118.3 (71.4–201.6)	7.8 (6.0–10.2)	219.2 (102.0–507.6)	24.6 (12.6–48.3)
HT	—	>280	—	—	—	—
HUSM	15.3 (13.5–16.6)	1.0 (0.9–1.1)	23.3 (21.0–25.4)	1.4 (1.3–1.5)	310.3 (192.6–497.9)	22.4 (17.2–29.0)
IHKL1	26.8 (20.6–31.7)	1.8 (1.6–2.0)	36.6 (34.5–39.0)	2.1 (1.9–2.4)	182.5 (127.0–245.5)	13.2 (10.3–16.7)
IHKL2	30.6 (27.7–33.6)	2.0 (1.8–2.2)	51.8 (48.3–55.1)	3.0 (2.8–3.2)	251.2 (132.6–819.1)	17.9 (11.6–27.9)
IHKL3	—	>280	88.9 (79.4–99.0)	5.2 (4.6–5.7)	—	>280
Inai	—	>280	66.1 (52.3–81.1)	3.8 (3.5–4.2)	155.1 (75.2–548.3)	11.1 (7.3–17.0)
IndahE	15.7 (13.7–17.0)	1.0 (0.9–1.1)	30.6 (29.3–31.9)	1.8 (1.6–1.9)	96.1 (16.0–212.3)	6.9 (2.5–19.4)
Ita	—	>280	52.7 (47.3–58.7)	3.0 (2.7–3.4)	248.4 (116.5–873.0)	17.9 (12.0–26.5)
KG	—	>280	281.9 (228.4–360.3)	16.2 (12.7–20.8)	301.4 (241.5–377.7)	21.7 (17.3–27.2)
KTM	—	>280	—	>280	—	—
LHFA	—	>280	89.0 (79.8–100.6)	5.2 (4.5–5.9)	17.2 (16.3–17.9)	1.2 (1.1–1.3)

Table 3. Continued.

Strain	Propoxur (1.10 $\mu g/cm^2$)		Propoxur + PBO (100 μg/insect)		Propoxur + DEF (30 μg/insect)	
	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
LHFB	34.2 (29.4–38.3)	2.3 (2.1–2.4)	27.1 (25.4–28.7)	1.6 (1.4–1.7)	25.7 (23.4–27.7)	1.9 (1.7–2.0)
Maluri	—	>280	105.2 (93.3–117.0)	6.1 (5.4–6.8)	11.3 (9.8–50.8)	0.8 (0.7–0.9)
May	362.4 (291.4–478.6)	23.9 (18.7–30.6)	81.6 (57.5–117.7)	4.7 (4.0–5.6)	—	—
Mid	—	>280	—	—	967.6 (696.1–1,473)	69.9 (49.2–99.4)
ML	27.4 (25.1–29.7)	1.8 (1.7–1.9)	30.9 (28.7–33.1)	1.8 (1.6–2.0)	31.2 (29.6–33.0)	2.2 (2.1–2.4)
MT	1,957 (592–78,760)	129 (45.6–362)	34.6 (32.1–37.2)	2.0 (1.8–2.2)	194.3 (138.3–293.2)	14.0 (10.4–18.8)
MV	44.0 (34.6–52.9)	2.9 (2.6–3.3)	33.5 (31.9–35.0)	1.9 (1.8–2.1)	25.0 (22.9–27.1)	1.8 (1.7–1.9)
Nazir	4,105 (2,513–8,724)	271 (151–489)	—	—	—	—
Peak	—	>280	—	—	618 (370–1,123)	44.5 (29.6–67.0)
PG	—	>280	—	—	—	>280
PK	—	>280	67.5 (56.3–82.5)	3.9 (3.5–4.3)	133 (59.4–308)	9.8 (6.5–14.8)
PRKL	—	>280	14.5 (13.8–15.2)	0.8 (0.7–0.9)	3,604 (2,268–6,985)	258 (148–452)
PRKT	718.4 (404.0–1,965)	47.3 (31.1–71.8)	44.6 (27.9–58.7)	2.6 (2.3–2.8)	67.1 (49.1–90.9)	4.8 (4.1–5.7)
PRPG	78.7 (70.9–91.6)	5.2 (4.5–6.0)	34.3 (32.7–35.9)	2.0 (1.8–2.2)	41.2 (38.9–48.9)	3.0 (2.6–3.3)
Pudu	—	>280	2,841 (2,318–3,705)	164 (125–217)	1,333 (1,000–1,821)	96.2 (71.1–130)
Raja	—	>280	—	—	15.7 (13.0–18.1)	1.1 (1.0–1.2)
RC	—	>280	—	—	—	—
Relau	23.4 (22.5–24.2)	1.5 (1.4–1.6)	20.6 (19.5–21.6)	1.2 (1.1–1.3)	—	—
Sedap	77.6 (37.6–128.2)	5.1 (3.5–7.6)	—	—	—	>280
Selesa	—	>280	224.5 (184.5–297.6)	13.0 (10.5–16.0)	473.6 (216.1–3,381)	34.1 (19.4–59.9)
Sun	118.3 (71.4–201.6)	7.8 (6.0–10.2)	—	>280	—	>280
SW	23.1 (20.7–25.1)	1.5 (1.4–1.7)	35.6 (32.2–38.2)	2.1 (1.9–2.3)	26.3 (25.0–27.6)	1.9 (1.8–2.0)
Tmas	685.8 (474.6–1,034)	45.1 (30.4–67.0)	—	—	—	—
TOPS	—	>280	127.3 (107.9–161.5)	7.4 (6.2–8.8)	820.9 (471.4–1,828)	59.4 (35.9–98.4)
TS	—	>280	40.3 (34.2–46.2)	2.3 (2.0–2.7)	—	—
Yao	—	>280	283 (136–656)	16.8 (10.5–32.5)	1,071 (780–1,585)	77.3 (53.8–111)
ZT	—	>280	52.9 (48.6–57.2)	3.1 (2.5–3.4)	31.4 (27.7–35.7)	2.3 (2.0–2.6)

exposure, the cockroaches were transferred to a clean petri-dish with food and water provided. The experiment was replicated five times for each insecticide. Mortality of the cockroaches was scored at 48 hours post-exposure. The pooled data were subjected to probit analysis. The generated LC_{95} for each insecticide was multiplied by 10 and served as the concentration used for insecticide resistance tests (Table 2).

For the resistance test, ten adult males from each field collected strain were introduced into an insecticide-coated glass jar with concentrations as described above. The cumulative number of cockroaches killed was recorded at selected time intervals. The test was replicated five times for each strain and data were pooled and subjected to probit analysis.

Synergism studies

Adult males were each topically treated with 1 μl acetone solution of PBO (100 μg/insect) or DEF (30 $\mu g/\mu l$) on the first abdominal segment before they were subjected to surface-contact exposure in glass jars. About two hours after synergist treatment, ten cockroaches were introduced into an insecticide-coated glass jar and mortality was recorded at selected time intervals. There was less than 3% mortality in the control insects that were treated with synergists.

Deltamethrin resistance test using topical application

This study was conducted to determine possible relationship between the resistance ratio generated through surface response method and percentage mortality obtained using topical application of deltamethrin at a discriminating dose of LD_{99} ($=0.056\ \mu g/\mu l$) (Lee et al., 1999b). A total of 27 field collected strains (BBR, CB, CIGO, Copt, CP, FBR, GCPG, GL, GT, HUSM, IHKL1, Inai, IndahE, Ita, LHFA, LHFB, Maluri, May, ML, MT, MV, PK, Selesa, SW, Sun, TOPS and ZT) were tested using 25 adult males per replicate, and each experiment was replicated four times. The percentage mortality of the cockroaches was scored at 24 hours post-treatment.

Data analysis

Data obtained from surface-contact exposure method and synergism studies were pooled and subjected to probit analysis (Finney, 1972) according to the procedure described by Robertson and Preistler (1992), using POLO-PC computer software (LeOra Software, 1997). Resistance ratio at LT_{50} (RR_{50}) and its 95% confidence interval was calculated according to procedure described by Robertson and Preistler (1992). If the 95% confidence interval of the RR_{50} of a field-collected strain included 1.0, it implied it was not significantly different from that of the ICI susceptible strain. Resistance ratio was classified into five categories: ≤ 1=no resistance; >1 to ≤ 5=low resistance; $>5-\leq 10$=moderate resistance; >10 to ≤ 50=high resistance; >50=very high resistance. Resistance ratio of each field-collected strain was grouped into the respective category, and changes in resistance level upon synergist treatment was analyzed using non-parametric median test (Siegel and Castellan, 1988) and compared with χ^2 test at $P=0.05$ (SPSS 9.05, SPSS Inc). Linear regression was used to determine the relationship between percentage mortality upon treatment with LD_{99} of deltamethrin, and resistance ratio generated through surface response method using deltamethrin (SPSS 9.05, SPSS Inc).

RESULTS

Propoxur resistance

Only HUSM and IndahE strains were susceptible to propoxur (Table 3). About 22% of the strains showed low resistance while 73% showed high resistance (Fig. 1). Development of propoxur resistance is prevalent since this insecticide has been used in Malaysia for more than 20 years (Lee et al., 1996). The major proportion

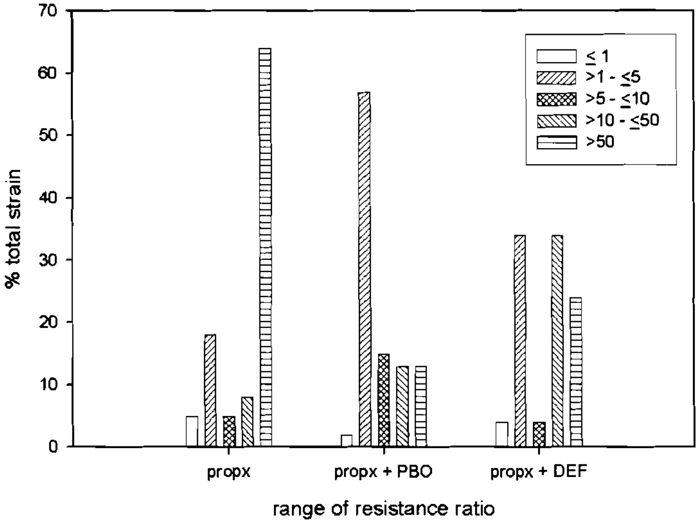

Fig. 1. Propoxur resistance distribution patterns and effects of synergists in field collected strains of German cockroaches when tested using surface contact exposure method.

(62%) of field collected strains shifted significantly from the very high resistance category to low resistance category upon application of PBO ($\chi^2=18.68$, df=1, $P<0.01$) (Fig. 1; Table 3). This suggested the possible involvement of monooxygenase as a resistance mechanism in the majority of these strains. Only about 12.5% were not affected by PBO treatment. This however, does not rule out the involvement of monooxygenase because it has been reported earlier that certain isozymes of monooxygenase were not inhibited by PBO (Yu, 1991).

On the other hand, propoxur resistance was not significantly affected ($P>0.05$) with DEF treatment ($\chi^2=1.61$, df=1, $P<0.20$, Table 3). There were two groups of field strains that were categorized under low and high resistance upon treatment with DEF (Fig. 1). This suggested that propoxur resistance in a number of strains were partially suppressed with DEF treatment, indicating possible involvement of other resistance mechanisms, besides elevated esterase. Propoxur resistance levels for a number of strains (PG, Sun, CP, Emp, IHKL3, KG, Pudu, Selesa, TOPS and Yao) were not affected by either PBO or DEF treatment, thus suggested the involvement of target site insensitivity (altered acetylcholinesterase) as resistance mechanism (Table 3).

Chlorpyrifos resistance

Only two strains (Emp and PRKL) demonstrated moderate resistance to chlorpyrifos (Table 4), while the remaining of the strains (96%) showed low resistance (Fig. 2). Cochran (1989) also reported similar findings when he surveyed 45 strains of German cockroaches collected from various places in U.S.A. that mostly showed low resistant to chlorpyrifos ($RR_{50}=\leq 5x$).

Upon PBO treatment, chlorpyrifos resistance was negated from low to no resistance ($\chi^2=82.12$, df=1, $P<0.001$) (Table 4, Fig. 2). As PBO is a monooxygenase inhibitor, this possibly suggested the involvement of this enzyme group as a resistance mechanism. This was also earlier reflected in Scharf et al. (1999) which reported a common isozyme of cytochrome P450 that contributed to chlorpyrifos resistance in the German cockroach from different geographical locations. On the other hand, the involvement of elevated esterase was also demonstrated in chlorpyrifos+DEF treatment. Chlorpyrifos resistance distribution pattern was shifted

Table 4. Susceptibility of field-collected German cockroaches to chlorpyrifos, and synergistic effects of PBO and DEF.

Strain	Chlorpyrifos (1.10 $\mu g/cm^2$)		Chlorpyrifos + PBO (100 μg/insect)		Chlorpyrifos + DEF (30 μg/insect)	
	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
ICI	50.9 (46.9–54.3)	—	174.4 (158.5–194.8)	—	35.7 (34.3–37.0)	—
BBR	76.5 (70.2–82.6)	1.5 (1.3–1.7)	96.3 (91.1–101.1)	0.5 (0.4–0.6)	57.6 (60.7–65.1)	1.6 (1.4–1.8)
BUSM	58.7 (54.6–62.9)	1.2 (1.1–1.3)	72.6 (67.7–77.6)	0.4 (0.3–0.5)	31.4 (29.5–33.2)	0.9 (0.8–0.9)
CB	100.9 (93.6–108.4)	2.0 (1.8–2.2)	167.8 (154.9–182.4)	1.0 (0.8–1.1)	97.0 (91.1–103.6)	2.7 (2.5–2.9)
CIGO	105.6 (98.2–108.4)	2.1 (1.9–2.3)	139.4 (134.3–145.0)	0.8 (0.7–0.9)	79.2 (73.1–86.5)	2.2 (2.0–2.4)
CK	174.0 (161.0–187.7)	3.4 (2.8–3.8)	—	—	—	—
Copt	202.6 (182.2–227.4)	4.0 (3.5–4.5)	108.6 (103.6–113.8)	0.6 (0.5–0.7)	54.3 (51.1–57.8)	1.5 (1.4–1.6)
CP	136.4 (128.9–143.5)	2.7 (2.4–2.9)	104.3 (97.2–111.1)	0.6 (0.5–0.8)	58.7 (55.1–62.1)	1.6 (1.1–2.5)
CT	158.4 (137.2–178.5)	3.1 (2.9–3.4)	—	—	—	—
DHKL	126.1 (117.6–136.0)	2.5 (2.2–2.8)	179.5 (161.0–207.6)	1.0 (0.9–1.2)	52.7 (49.5–56.1)	1.5 (1.4–1.6)
Emp	343.8 (316.5–377.2)	6.7 (3.4–13.1)	263.1 (221.8–327.5)	1.5 (1.2–2.5)	96.5 (88.5–103.9)	2.7 (1.9–3.8)
FBR	232.1 (217.5–248.9)	4.5 (3.4–6.0)	117.7 (111.2–124.9)	0.7 (0.6–0.8)	81.1 (75.1–88.2)	2.3 (2.0–2.5)
GCJB	149.9 (138.9–162.8)	2.9 (2.2–4.0)	—	—	—	—
GCPG	111.3 (99.6–124.1)	2.2 (0.9–5.0)	72.7 (68.0–77.6)	0.4 (0.3–0.7)	70.5 (65.2–76.3)	2.0 (1.5–3.7)
GL	152.1 (131.1–169.4)	3.0 (1.1–7.9)	79.6 (62.5–93.4)	0.5 (0.3–0.7)	50.5 (41.8–55.7)	1.4 (1.2–1.7)
GT	135.8 (124.6–147.4)	2.7 (1.4–5.0)	—	—	55.4 (51.7–59.1)	1.6 (1.4–1.8)
HT	124.8 (109.3–137.2)	2.4 (2.2–2.8)	86.3 (76.5–96.3)	0.5 (0.4–0.6)	—	—
HUSM	74.9 (71.5–78.3)	1.5 (1.4–1.6)	58.4 (54.1–62.7)	0.3 (0.3–0.4)	33.0 (30.9–35.0)	0.9 (0.8–1.0)
IHKL1	86.7 (83.0–90.3)	1.7 (1.6–1.9)	92.5 (88.1–97.2)	0.5 (0.4–0.6)	64.4 (59.4–69.5)	1.8 (1.6–2.0)
IHKL2	141.8 (134.2–149.7)	2.8 (2.6–3.0)	90.8 (84.5–97.0)	0.5 (0.4–0.6)	44.9 (42.0–47.7)	1.3 (1.2–1.3)
IHKL3	104.2 (99.9–108.6)	2.0 (1.9–2.2)	124.7 (114.3–134.1)	0.7 (0.6–0.9)	93.4 (88.0–99.0)	2.6 (1.5–2.9)
Inai	137.6 (128.4–147.6)	2.7 (2.5–2.9)	125.1 (119.6–131.4)	0.7 (0.6–0.8)	53.3 (49.1–57.5)	1.5 (1.4–1.6)
IndahE	79.6 (76.3–82.7)	1.6 (1.4–1.7)	39.8 (37.3–42.4)	0.2 (0.2–0.3)	32.1 (30.1–33.8)	0.9 (0.8–1.0)
Ita	206.9 (191.1–225.9)	4.1 (3.7–4.5)	116.5 (106.1–125.9)	0.7 (0.6–0.8)	76.9 (73.1–81.0)	2.2 (2.0–2.3)
KG	215.8 (195.8–246.3)	4.2 (2.2–6.7)	95.8 (88.8–102.5)	0.5 (0.4–0.6)	—	—
KTM	108.3 (102.0–114.9)	2.1 (1.3–3.4)	—	—	—	—
LHFA	79.9 (77.0–82.8)	1.6 (1.5–1.7)	103.5 (94.9–113.7)	0.6 (0.5–0.7)	52.2 (48.6–55.9)	1.5 (1.4–1.6)

Table 4. Continued.

Strain	Chlorpyrifos (1.10 $\mu g/cm^2$)		Chlorpyrifos + PBO (100 μg/insect)		Chlorpyrifos + DEF (30 μg/insect)	
	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
LHFB	67.4 (64.7–69.8)	1.3 (1.2–1.4)	110.8 (102.5–119.2)	0.6 (0.5–0.8)	41.6 (38.9–44.1)	1.2 (1.0–1.3)
Maluri	75.8 (70.5–81.4)	2.8 (1.9–3.6)	100.5 (90.3–111.9)	0.6 (0.4–0.8)	56.5 (51.2–61.4)	1.6 (1.3–2.0)
May	64.6 (60.0–68.1)	1.3 (1.2–1.4)	—	—	—	—
Mid	118.6 (106.9–128.6)	2.3 (1.6–3.4)	—	—	70.6 (63.8–76.5)	2.0 (1.2–2.3)
ML	101.5 (97.8–105.3)	2.0 (1.8–2.2)	147.0 (135.9–160.3)	0.8 (0.7–1.0)	35.3 (33.6–36.8)	1.0 (0.8–1.2)
MT	84.6 (77.3–91.9)	1.7 (1.5–1.8)	185.0 (168.7–207.0)	1.0 (0.9–1.2)	95.3 (89.2–102.1)	2.7 (2.5–2.9)
MV	177.6 (167.1–189.9)	3.5 (3.2–3.8)	105.5 (100.6–111.1)	0.6 (0.5–0.7)	48.3 (45.5–51.1)	1.4 (1.3–1.4)
Nazir	129.8 (122.7–138.1)	2.6 (2.3–2.8)	—	—	—	—
Peak	94.5 (59.1–132.3)	1.8 (1.0–3.5)	—	—	55.8 (52.1–59.4)	1.6 (1.0–2.5)
PG	207.3 (182.7–244.8)	4.1 (2.8–5.1)	64.2 (55.3–72.0)	0.4 (0.3–0.5)	132.7 (122.3–144.1)	3.7 (2.0–5.3)
PK	156.0 (145.3–167.9)	3.3 (3.0–3.6)	117.6 (106.3–128.3)	0.7 (0.6–0.8)	—	—
PRKL	378.8 (309.5–466.1)	7.5 (4.2–13.4)	92.0 (80.2–103.4)	0.5 (0.4–0.6)	—	—
PRKT	69.7 (65.8–73.8)	1.4 (1.3–1.5)	102.9 (98.3–107.9)	0.6 (0.5–0.7)	57.7 (54.6–61.0)	1.6 (1.5–1.7)
PRPG	116.3 (107.1–124.3)	2.3 (2.1–2.5)	109.2 (103.7–114.3)	0.6 (0.5–0.7)	71.1 (67.2–75.4)	2.0 (1.9–2.1)
Pudu	273.0 (252.6–296.5)	5.3 (2.3–12.4)	119.1 (109.6–127.7)	0.7 (0.6–0.8)	—	—
Raja	92.2 (84.5–99.3)	1.8 (1.4–2.3)	—	—	50.3 (47.8–52.8)	1.4 (1.3–1.5)
RC	111.1 (90.6–134.0)	2.2 (1.5–3.1)	—	—	—	—
Relau	65.0 (61.0–69.0)	1.3 (1.2–1.4)	132.5 (123.0–144.0)	0.8 (0.7–0.9)	—	—
Sedap	86.1 (81.4–91.6)	1.7 (1.4–2.0)	111.7 (105.8–118.2)	0.6 (0.5–0.7)	44.4 (28.0–57.8)	1.2 (0.9–1.7)
Selesa	148.0 (137.7–157.6)	2.9 (2.3–3.7)	115.2 (111.7–118.6)	0.7 (0.6–0.8)	87.2 (80.1–95.0)	2.4 (2.2–2.7)
Sun	156.5 (137.8–176.8)	3.1 (2.8–3.4)	166.5 (157.0–180.0)	1.0 (0.8–1.1)	43.9 (41.0–46.9)	1.2 (0.6–1.3)
SW	89.9 (86.0–93.5)	1.8 (1.6–1.9)	64.7 (61.0–68.7)	0.4 (0.3–0.5)	51.8 (47.0–55.6)	1.4 (1.0–2.0)
Tmas	145.8 (138.4–153.5)	2.9 (2.4–3.5)	—	—	—	—
TOPS	167.5 (156.0–179.8)	3.3 (3.0–3.7)	110.6 (106.1–115.3)	0.6 (0.5–0.7)	101.1 (93.4–110.1)	2.8 (2.6–3.1)
TS	140.7 (127.4–151.5)	2.7 (2.2–3.4)	—	—	—	—
Yao	152.8 (143.8–163.1)	3.0 (2.7–3.3)	75.4 (71.7–78.9)	0.4 (0.3–0.6)	48.5 (45.5–51.7)	1.3 (0.8–2.4)
ZT	141.5 (127.1–155.2)	2.8 (1.9–3.3)	173.7 (159.6–191.5)	1.0 (0.9–1.1)	47.9 (44.5–51.4)	1.3 (0.6–2.8)

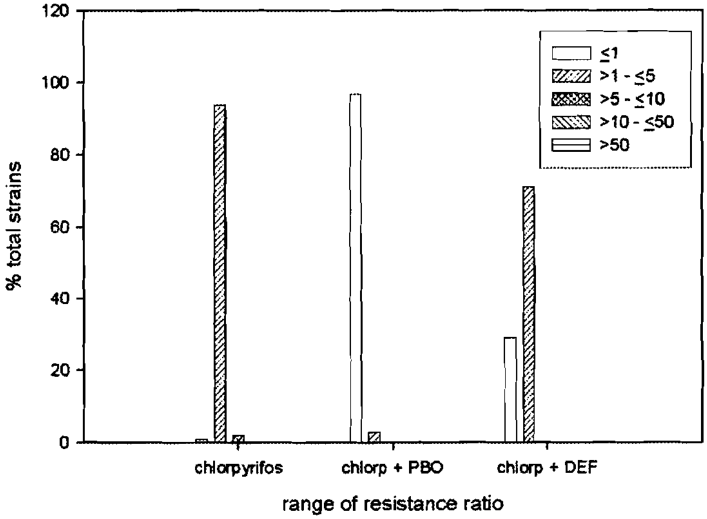

Fig. 2. Chlorpyrifos resistance distribution patterns and effects of synergists in field collected strains of German cockroaches when tested using surface contact exposure method.

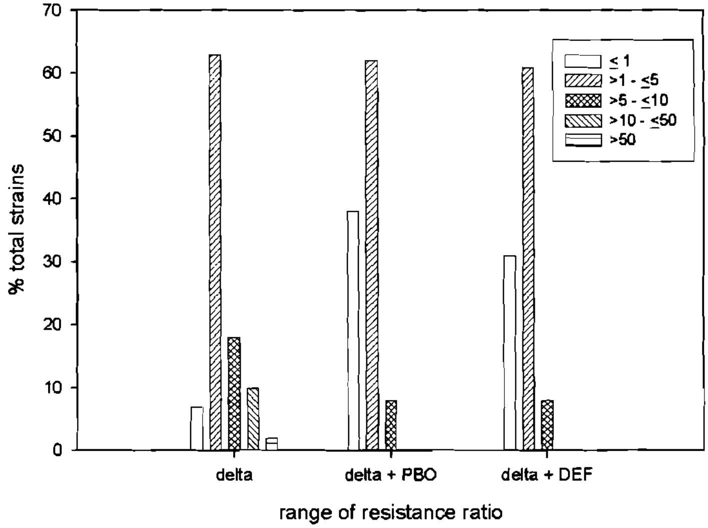

Fig. 3. Deltamethrin resistance distribution patterns and effects of synergists in field collected strains of German cockroaches when tested using surface contact exposure method.

towards low or no resistance upon the synergist treatment ($\chi^2=12.15$, df=1, $P<0.001$) (Table 4, Fig. 2).

Deltamethrin and permethrin resistance

There appeared to be a trend toward development of deltamethrin resistance. A total of 29.6% of the field-collected strains demonstrated resistance of more than five folds (Table 5, Fig. 3). Treatment of test cockroaches with PBO prior to exposure to deltamethrin significantly suppressed deltamethrin resistance to low level (<5x) ($\chi^2=72.18$, df=1, $P<0.001$) (Table 5, Fig. 3), indicating the involvement of monoxygenase as a resistance mechanism. In addition, application of DEF also significantly changed the distribution pattern of resistant populations ($\chi^2=7.79$, df=1, $P<0.01$), where 92.7% of

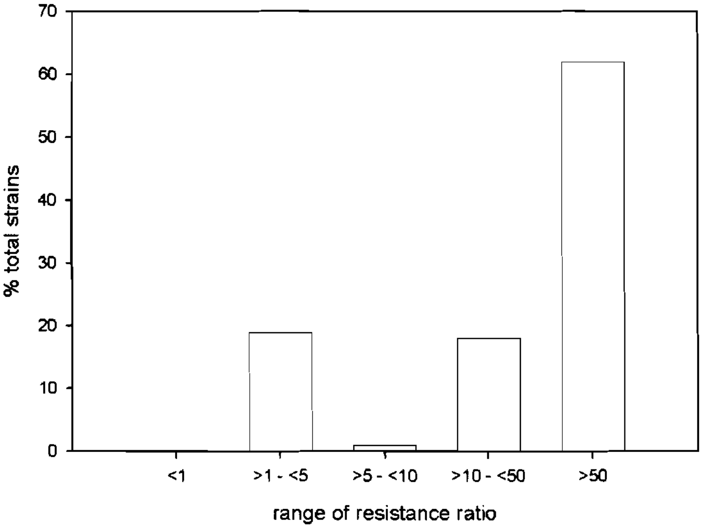

Fig. 4. Permethrin resistance distribution patterns in field collected strains of German cockroaches when tested using surface contact exposure method.

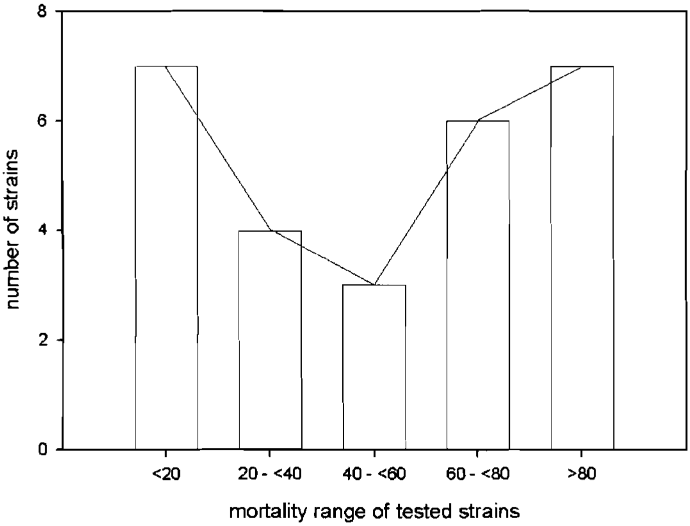

Fig. 5. Mortality distribution pattern upon deltamethrin treatment in field collected strains of German cockroaches when tested using topical application method.

the populations became more susceptible to deltamethrin (Table 5, Fig. 3), suggesting partial involvement of elevated esterases in deltamethrin resistance.

The results obtained above were further supported where 80.2% of the tested field-collected strains demonstrated moderate to very high resistant (>5x) to permethrin (Table 6, Fig. 4). More than 60% of the strains tested showed >50x resistance to permethrin. The observation recorded in this study was not surprising, because pyrethroids in form of residual sprays has been the choice of formulation among pest control operators in Malaysia since the mid 1990s.

Deltamethrin resistance using topical application: When the cockroaches were tested using topical application, we found

Table 5. Susceptibility of field-collected German cockroaches to deltamethrin, and synergistic effects of PBO and DEF.

Strain	Deltamethrin (0.55 $\mu g/cm^2$)		Deltamethrin + PBO (100 μg/insect)		Deltamethrin + DEF (30 μg/insect)	
	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
ICI	6.6 (6.3–7.0)	—	11.3 (10.2–12.3)	—	12.4 (11.8–13.0)	—
BBR	6.7 (6.0–7.3)	1.0 (0.9–1.1)	7.5 (7.0–8.0)	0.7 (0.6–0.8)	8.8 (6.9–10.3)	0.7 (0.6–0.8)
BUSM	8.3 (7.6–9.0)	1.3 (1.1–1.5)	8.6 (8.1–9.1)	0.8 (0.7–0.9)	8.1 (7.3–8.8)	0.7 (0.5–0.8)
CB	20.1 (18.3–22.0)	3.0 (2.7–3.4)	20.0 (15.5–24.4)	1.8 (1.7–1.9)	12.1 (10.9–13.5)	1.0 (0.9–1.1)
CIGO	27.6 (25.8–29.6)	4.2 (4.0–4.4)	16.9 (15.9–17.8)	1.5 (1.4–1.6)	119.4 (90.9–197.8)	9.7 (6.6–14.0)
CK	28.6 (26.9–31.5)	4.7 (4.4–4.9)	—	—	—	—
Copt	12.2 (11.2–13.2)	1.8 (1.7–2.0)	9.7 (8.7–10.6)	0.9 (0.8–1.0)	12.0 (10.5–13.3)	1.0 (0.8–1.1)
CP	70.3 (64.0–77.3)	10.6 (9.5–11.8)	31.2 (29.8–32.5)	2.8 (2.6–3.0)	61.6 (50.3–75.5)	5.0 (4.3–5.8)
CT	29.5 (25.8–33.5)	4.4 (3.9–4.9)	—	—	—	—
DHKL	43.0 (32.6–56.3)	6.5 (5.8–7.2)	18.1 (17.2–18.9)	1.6 (1.5–1.7)	—	—
Emp	236.9 (92.9–888.4)	35.7 (22.0–57.7)	26.2 (15.3–58.8)	2.3 (1.9–2.8)	—	—
FBR	132.8 (108.6–167.2)	20.0 (16.0–25.0)	37.9 (31.1–49.5)	3.4 (2.9–3.9)	31.2 (26.5–36.1)	2.5 (2.3–2.8)
GCJB	18.7 (14.3–23.0)	2.8 (2.4–3.3)	—	—	19.8 (16.5–23.1)	1.6 (1.4–1.8)
GCPG	119.4 (65.6–218.3)	18.0 (11.9–27.2)	17.7 (15.2–20.3)	1.6 (1.4–1.7)	12.2 (9.3–14.8)	1.0 (0.8–1.2)
GL	80.1 (40.3–157.6)	12.0 (7.6–19.2)	14.1 (12.6–15.5)	1.3 (1.1–1.4)	29.6 (20.5–48.3)	2.4 (2.0–2.8)
GT	12.8 (12.0–13.7)	1.9 (1.8–2.1)	18.1 (10.8–24.1)	1.6 (1.5–1.8)	17.6 (15.9–19.4)	1.4 (1.3–1.6)
HT	8.9 (7.5–10.1)	1.3 (1.2–1.5)	—	—	20.6 (14.0–29.1)	1.7 (1.4–2.0)
HUSM	8.2 (7.7–8.7)	0.9 (0.8–1.0)	10.6 (10.1–11.1)	0.9 (0.8–1.0)	9.2 (7.9–10.1)	0.7 (0.6–0.9)
IHKL1	22.8 (20.8–25.1)	3.5 (3.3–3.7)	13.4 (12.8–14.0)	1.2 (1.1–1.3)	20.7 (18.0–23.6)	1.7 (1.5–1.9)
IHKL2	28.8 (23.6–34.8)	4.4 (4.1–4.7)	15.8 (14.5–16.9)	1.4 (1.3–1.5)	26.7 (23.3–30.6)	2.2 (1.9–2.5)
IHKL3	24.6 (11.2–38.0)	3.7 (2.8–4.9)	17.8 (16.1–19.6)	1.6 (1.5–1.7)	29.0 (26.5–32.3)	2.3 (2.0–2.8)
Inai	8.6 (7.8–9.4)	1.3 (1.2–1.5)	10.0 (8.9–11.1)	0.9 (0.8–1.0)	11.6 (10.7–12.4)	0.9 (0.8–1.0)
IndahE	5.7 (4.7–6.5)	0.9 (0.8–1.0)	7.3 (6.4–8.1)	0.7 (0.6–0.8)	8.2 (7.1–9.3)	0.7 (0.6–0.8)
Ita	32.1 (26.5–38.9)	4.8 (4.3–5.3)	12.4 (11.0–13.6)	1.1 (1.0–1.2)	38.9 (34.0–45.3)	3.1 (2.7–3.6)
KG	29.6 (21.2–40.9)	4.5 (4.0–5.0)	—	—	29.5 (25.4–34.4)	2.4 (2.1–2.7)
KTM	19.8 (18.2–21.4)	3.0 (2.7–3.3)	—	—	—	—
LHFA	8.2 (7.5–9.0)	1.2 (1.1–1.3)	7.9 (7.2–8.6)	0.7 (0.6–0.8)	10.7 (10.0–11.3)	0.9 (0.8–1.0)

Table 5. Continued.

Strain	Deltamethrin (0.55 μg/cm^2)		Deltamethrin + PBO (100 μg/insect)		Deltamethrin + DEF (30 μg/insect)	
	LT$_{50}$ (95% FL) (min)	RR$_{50}$ (95% FL)	LT$_{50}$ (95% FL) (min)	RR$_{50}$ (95% FL)	LT$_{50}$ (95% FL) (min)	RR$_{50}$ (95% FL)
LHFB	12.5 (10.1–14.6)	2.0 (1.8–2.2)	8.9 (7.9–9.8)	0.8 (0.7–0.9)	10.9 (9.2–12.3)	0.9 (0.8–1.0)
Maluri	13.7 (12.8–14.6)	2.1 (2.0–2.2)	17.2 (16.4–18.1)	1.5 (1.4–1.7)	9.8 (8.8–10.7)	0.8 (0.7–0.9)
May	9.0 (8.2–9.6)	1.4 (1.2–1.5)	8.1 (7.4–8.7)	0.7 (0.6–0.8)	11.6 (10.7–12.5)	0.9 (0.8–1.0)
Mid	19.5 (16.0–23.2)	2.9 (2.6–3.3)	30.6 (27.9–33.4)	2.7 (2.5–3.0)	—	—
ML	10.9 (8.5–11.5)	1.3 (1.2–1.4)	10.9 (9.8–12.0)	1.0 (0.9–1.1)	10.3 (9.6–10.9)	0.8 (0.7–0.9)
MT	8.7 (7.7–9.5)	1.3 (1.2–1.5)	11.4 (10.7–12.1)	1.0 (0.9–1.1)	15.8 (14.2–16.9)	1.4 (1.2–1.6)
MV	67.5 (59.6–75.4)	10.2 (8.9–11.6)	17.1 (16.2–18.0)	1.5 (1.4–1.7)	19.3 (17.2–21.6)	1.6 (1.4–1.8)
Nazir	806.0 (309.5–6,069)	122 (58.5–358)	—	—	—	—
Peak	45.5 (32.1–90.2)	6.9 (5.4–8.7)	15.9 (14.2–17.7)	1.4 (1.3–1.5)	80.5 (69.4–95.9)	6.5 (5.6–7.5)
PG	26.0 (23.4–28.5)	3.9 (3.5–4.4)	—	—	—	—
PK	138.0 (61.2–342.5)	20.8 (12.5–34.4)	21.7 (16.2–27.3)	1.9 (1.7–2.2)	38.7 (31.1–46.7)	3.1 (2.7–3.7)
PRKL	56.0 (41.4–74.8)	8.4 (6.9–10.3)	13.6 (11.8–15.5)	1.2 (1.1–1.3)	15.4 (13.5–17.3)	1.2 (1.1–1.4)
PRKT	25.6 (24.1–27.2)	3.9 (3.5–4.3)	21.6 (20.6–22.5)	1.9 (1.8–2.1)	15.6 (13.8–17.9)	1.2 (1.1–1.5)
PRPG	22.5 (21.6–23.4)	3.4 (3.2–3.6)	17.1 (16.3–18.0)	1.5 (1.4–1.6)	27.7 (23.2–33.0)	2.2 (2.0–2.6)
Pudu	59.6 (49.7–72.4)	9.0 (7.9–10.2)	29.2 (27.1–31.2)	2.6 (2.4–2.8)	33.9 (24.3–44.7)	2.7 (2.2–3.5)
Raja	25.6 (23.5–28.9)	4.1 (3.8–4.4)	11.4 (10.4–12.4)	1.0 (0.9–1.1)	—	—
RC	52.1 (45.2–60.1)	8.0 (7.6–8.4)	—	—	—	—
Relau	10.2 (7.8–12.0)	1.5 (1.2–1.7)	—	—	—	—
Sedap	16.2 (12.4–20.0)	2.4 (2.1–2.9)	12.3 (10.7–13.7)	1.1 (1.0–1.2)	16.5 (15.4–17.4)	1.3 (1.2–1.4)
Selesa	32.1 (26.9–38.8)	4.9 (4.5–5.4)	36.0 (33.1–39.2)	1.5 (1.4–1.6)	81.1 (71.3–95.3)	6.6 (5.6–7.7)
Sun	53.2 (45.6–61.5)	7.8 (7.2–8.5)	14.1 (13.4–14.8)	1.3 (1.2–1.4)	27.4 (24.7–30.2)	2.2 (2.0–2.5)
SW	8.5 (7.6–9.4)	1.3 (1.2–1.4)	10.9 (10.2–11.5)	1.0 (0.9–1.1)	17.3 (15.3–19.4)	1.4 (1.2–1.6)
Tmas	27.8 (18.4–41.5)	4.2 (3.7–4.8)	12.5 (10.2–14.4)	1.1 (1.0–1.2)	15.1 (13.4–16.8)	1.2 (1.1–1.4)
TOPS	18.3 (17.0–19.6)	2.8 (2.5–3.0)	24.1 (22.1–26.3)	2.1 (1.9–2.4)	46.5 (40.9–53.2)	3.8 (3.3–4.3)
TS	12.5 (9.7–15.2)	1.9 (1.7–2.1)	—	—	22.7 (16.5–30.4)	1.8 (1.6–2.1)
Yao	50.4 (41.5–61.4)	7.6 (6.8–8.2)	—	—	—	—
ZT	222.6 (130.7–484.3)	33.6 (20.8–54.2)	29.4 (25.6–34.1)	2.6 (2.2–3.0)	58.7 (46.1–75.6)	4.7 (3.7–6.1)

Table 6. Permethrin resistance in field populations of the German cockroach at concentration of 1.70 μg/cm^2.

Strain	LT_{50} (95% FL) (min)	RR_{50} (95% FL)
ICI	18.0 (17.3–18.7)	–
BBR	48.3 (5.5–108.2)	2.7 (1.6–4.6)
BUSM	28.5 (26.1–31.3)	1.6 (1.4–1.8)
CB[1]		>280
CIGO[1]		>280
CK[1]		>280
Copt[1]		>280
CP[1]		>280
CT[1]		>280
DHKL[1]		>280
Emp	115.6 (80.0–182.4)	6.4 (4.7–9.6)
FBR	425.0 (274.0–753.9)	24.3 (16.1–39.6)
GCJB	163.4 (115.5–236.3)	9.0 (6.8–12.4)
GCPG[1]		>280
GL	248.0 (114.0–1,477)	14.3 (6.7–77.1)
GT[1]		>280
HT	38.8 (33.9–43.7)	2.2 (2.0–2.6)
HUSM	38.2 (33.9–43.0)	2.1 (2.0–2.3)
IHKL1[1]		>280
IHKL2[1]		>280
IHKL3[1]		>280
Inai[1]		>280
IndahE	28.5 (23.6–34.1)	1.6 (1.4–1.7)
Ita	215.8 (174.5–271.0)	12.1 (10.2–14.5)
KG[1]		>280
KTM[1]		>280
LHFA	194.6 (140.6–278.0)	10.8 (8.7–13.5)
LHFB	142.4 (88.3–271.0)	7.9 (6.3–9.9)
Maluri[1]		>280
May	42.2 (35.1–47.8)	2.4 (2.1–2.7)
Mid	210.5 (158.8–291.4)	11.8 (9.3–15.4)
ML	36.6 (29.5–45.6)	2.0 (1.8–2.3)
MT[1]		>280
MV[1]		>280
Nazir[1]		>280
Peak	381.9 (296.4–519.9)	21.1 (17.4–27.4)
PG[1]		>280
PK[1]		>280
PRKL	72.9 (67.1–78.7)	4.0 (3.7–4.5)
PRKT	3,303 (2,598–4,957)	183 (146–232)
PRPG[1]		>280
Pudu	79.2 (66.6–96.1)	4.4 (3.9–5.1)
Raja	306.0 (212.4–461.4)	16.7 (12.5–24.4)
RC[1]		>280
Relau	35.2 (30.0–40.5)	2.0 (1.8–2.2)
Sedap	148.0 (105.8–204.1)	8.2 (6.5–10.8)
Selesa	432.5 (337.4–589.2)	24.0 (20.1–32.5)
Sun	257.6 (110.9–432.3)	14.4 (7.8–26.4)
SW	38.3 (12.2–74.0)	2.2 (1.8–2.8)
Tmas	197.4 (177.9–223.8)	10.9 (9.1–12.1)
TOPS[1]		>280
TS	126.3 (43.9–280.5)	7.3 (3.1–14.9)
Yao[1]		>280
ZT[1]		>280

[1] Less than 50% mortality achieved after three days of exposure

deltamethrin resistance patterns were heterogenously distributed, with more individuals in both susceptible and highly resistant groups (Fig. 5). The distribution pattern resembled a V-shaped curve ($a = (2.75 \times 1.03^{b})(b^{-1.17})$), where a = population frequency, b = mortality in percentage ($R^2 = 0.87$; $P < 0.05$).

Lastly, we also tested our hypothesis to determine whether strains showing low mortality when tested using topical application will show high resistance on surface contact exposure test. The relationship obtained was weak ($r^2 = 0.169$, $P < 0.05$), thus indicating that response from contact exposure cannot be translated in a similar manner to the results obtained from topical application method.

DISCUSSION

Results for propoxur resistance obtained in this study were different from those reported by Cochran (1989) where 11.1% (total strains tested = 45) of the U.S. strains possessed high resistance (RR > 10x) when subjected to surface contact exposure method. However, the author's conclusion was reached by testing using a propoxur concentration that was five times higher than that of this study. A higher concentration used in the surface contact exposure test may mask the detection of resistance in some strains that showed a moderate resistance level. On the other hand, if a concentration used was too low, it may lead to overestimation of the resistance level (Cochran, 1997; Lee et al., 1999b). Thus, it is of paramount importance to choose an optimal concentration for resistance detection.

None of the field-collected strains showed resistance level to chlorpyrifos of >10x. Cochran (1989) earlier proposed that control failure using chlorpyrifos may possibly be seen in the field in populations showing >3x resistance level. In this study, only seven strains (Copt, Emp, FBR, MV, PRKL, KG & Ita) fell within this category. For German cockroach control in Malaysia, organophosphates are less preferred by the local pest control industry.

Partial inhibition by PBO or DEF on propoxur, chlorpyrifos and deltamethrin resistance indicated possible involvement of both monooxygenase and elevated esterase as resistance mechanisms in most of the field strains collected. However, this did not imply that other resistance mechanisms, particularly target site insensitivity (altered acetylcholinesterase and, sodium channel mediated resistance or previously known as *kdr* [knock-down resistance]) were ruled out. About 18.9% of the field-collected strains were suggested to possess altered acetylcholinesterase as propoxur resistance was not reduced with application of PBO and DEF. However, the occurrence of altered acetylcholinesterase in the German cockroach was relatively lower than metabolic-based resistance and sodium channel mediated resistance. Hemingway et al. (1993) found only one strain showing altered acetylcholinesterase involvement, while Lee et al. (2000) reported four strains that were suspected with the same mechanism. Several strains were suspected to possess sodium channel mediated resistance, especially in those that were not affected by PBO and DEF prior to treatment by deltamethrin. These included the CP, FBR, Pudu and ZT strains of which their resistance levals were only partially suppressed by both synergists.

Topical application is an excellent method to measure physiological-based resistance (metabolic-based mechanism) (Choo et al., 2000), but it is unable to reflect or simulate the natural situation because of possible involvement of behavioural resistance such as avoidance behaviour and insecticide repellency which may occur in insecticide-resistant cockroaches. Earlier, Zhai and Robinson (1991b) and Lee et al. (1996) reported some field-collected German cockroaches became less active upon exposure to insecticide-treated surfaces, thus reducing the pickup of insecticides and insecticide absorption. Thus, surface contact exposure method is still the most reliable method of resistance testing because it takes into consideration of both physiological and behavioral aspects of the test insects.

In summary, broad spectrum resistance profiles and mechanisms were found in most field populations of the German cockroach in Malaysia. Although insecticide resistance has been found to be a major factor for control failure against these insects, other factors such as insecticide repellency (Ebeling et al., 1967) and sublethal effects (Lee et al., 1998) should also be taken into consideration when establishing a feasible pest management program. In this regard, behavioral resistance due to avoidance behavior could also seriously negate the effectiveness of an insecticide, even though the populations may not be physiologically resistant to insecticides. Control strategies such as use of insecticidal baits (Lee, 1998) and integration of residual insecticide and IGR (Lee et al., 1999c) should be seriously considered for better management of insecticide-resistant German cockroach populations in Malaysia.

ACKNOWLEDGEMENTS

We thank Michael E. Scharf (Purdue University) for comments on the manuscript draft, Malaysian Government IRPA program for partial funding of this study (Grant No. 06-02-05-9008), S.Y. Lim for assistance with cockroach rearing, and various Malaysian pest control companies (Flickpest, Rentokil Initial, Ridpest, Pest Dynamics and NLC General Pest Control) for field assistance during cockroach collections. This paper constitutes a portion of the doctoral thesis of the senior author (L.C.L.) submitted to the Graduate School, Universiti Sains Malaysia.

REFERENCES

Barson, G. and McCheyne, N. G. 1979. A test for detecting resistance to bendiocarb in the German cockroach, *Blattella germanica* L. *Intl. Pest Control*, 21: 42–43.

Batth, S. S. 1977. A survey of Canadian populations of the German cockroach for resistance to insecticides. *Can. Entomol.*, 109: 49–52.

Choo, L. E. W., Tang, C. S., Pang, F. Y. and Ho, S. H. 2000. Comparison of two methods for determining deltamethrin resistance in German cockroach (Blattodea: Blattellidae). *J. Econ. Entomol.*, 93: 905–910.

Cochran, D. G. 1987. Effects of synergists on bendiocarb and pyrethrins resistance in the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.*, 80: 728–732.

Cochran, D. G. 1989. Monitoring for insecticide resistance in field-collected strains of the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.*, 82: 336–341.

Cochran, D. G. 1996. Relevance of resistance ratios to operational control in the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.*, 89: 318–321.

Cochran, D. G. 1997. Misuse of the tarsal-contact method for detecting insecticide resistance in the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.*, 90: 1441–1444.

Collins, W. J. 1973. German cockroach resistance. 1. Resistance to diazinon includes cross-resistance to DDT, pyrethrins, and propoxur in a laboratory colony. *J. Econ. Entomol.*, 66: 44–47.

Ebeling, W., Reierson, D. A. and Wagner, R. E. 1967. Influence of repellency on the efficacy of blatticides. II. Laboratory experiments with German cockroaches. *J. Econ. Entomol.*, 60: 1375–1390.

Finney, D. J. 1972. Probit Analysis. 2nd edition. Cambridge University Press, United Kingdom.

Heal, R. E., Nash, K. B. and Williams, M. 1953. An insecticide-resistant strain of the German cockroach from Corpus Christi, Texas. *J. Econ. Entomol.*, 46: 385–386.

Hemingway, J., Small, G. J. and Monro, A. G. 1993. Possible mechanisms of organophosphorus and carbamate insecticide resistance in German cockroaches (Dictyoptera: Blattellidae) from different geographical areas. *J. Econ. Entomol.*, 86: 1623–1630.

Lee, C. Y. 1997. Insecticide resistance and its underlying mechanisms in the German cockroach, *Blattella germanica* (L.) (Dictyoptera: Blattellidae). *J. Biosci.*, 8: 156–172.

Lee, C. Y. 1998. Control of insecticide-resistant German cockroaches, *Blattella germanica* (L.) (Dictyoptera: Blattellidae) in food-outlets with hydramethylnon-based bait stations. *Trop. Biomed.*, 15: 45–51.

Lee, C. Y., Hemingway, J., Yap, H. H. and Chong, N. L. 2000. Biochemical characterization of insecticide resistance in the German cockroach, *Blattella germanica*, from Malaysia. *Med. Vet. Entomol.*, 14: 11–18.

Lee, C. Y., Lee, L. C., Ang, B. H. and Chong, N. L. 1999b. Insecticide resistance in the German cockroach from hotels and restaurants in Malaysia. *In*: Proceeding of the 3rd International Conference on Urban Pests Robinson (ed. Robinson, W. H., Rettich, F. and Rambo, G. W.), pp. 171–182, Graficke zavody Hronov, Czech Republic.

Lee, C. Y., Lee, L. C., Liew, C. Y. and Chong, N. L. 1999c. Residual performance of an alpha-cypermethrin/flufenoxuron mixture against German cockroaches, *Blattella germanica* (L.) (Dictyoptera: Blattellidae). *In*: Proceeding of the 3rd International Conference on Urban Pests Robinson (ed. Robinson, W. H., Rettich, F. and Rambo, G. W.), pp. 618, Graficke zavody Hronov, Czech Republic.

Lee, C. Y. and Robinson, W. H. 2001. Handbook of Malaysian Household and Structural Pests. 96 pp. Pest Control Association of Malaysia, Kuala Lumpur.

Lee, C. Y., Yap, H. H. and Chong, N. L. 1997. Elevated esterase detection in insecticide resistant German cockroaches (Dictyoptera: Blattellidae) using modified Pasteur-Georghiou's filter-paper method. *Trop. Biomed.*, 14: 81–86.

Lee, C. Y., Yap, H. H. and Chong, N. L. 1998. Sublethal effects of deltamethrin and propoxur on longevity and reproduction of German cockroaches, *Blattella germanica*. *Entomol. Exp. Appl.*, 89: 137–145.

Lee, C. Y., Yap, H. H., Chong, N. L. and Jaal, Z. 1999a. Urban Pest Control-A Malaysian Perspective. 134 pp. Universiti Sains Malaysia, Penang.

Lee, C. Y., Yap, H. H., Chong, N. L. and Lee, R. S. T. 1996. Insecticide resistance and synergism in field collected German cockroaches (Dictyoptera: Blattellidae) in Peninsular Malaysia. *Bull. Entomol. Res.*, 86: 675–682.

Lee, K. M. and Lee, C. Y. 2002. Prevalence of insecticide resistance in field-collected populations of the German cockroach, *Blattella germanica* (Linnaeus) (Dictyoptera: Blattellidae) in Peninsular Malaysia. *Med. Entomol. Zool.*, 53: 219–225.

Lee, L. C. and Lee, C. Y. 1998. Characterization of pyrethroid and carbamate resistance in a Malaysian field collected strain of the German cockroach, *Blattella germanica* (L.) (Dictyoptera: Blattellidae). *Trop. Biomed.*, 15: 1–9.

LeOra Software 1997. POLO-PC: Probit and Logit Analysis. LeOra Software, California.

McDonald, I. C. and Cochran, D. G. 1968. Carbamate resistance in a carbaryl-resistant strain of the German cockroach. *J. Econ. Entomol.*, 61: 670–673.

Robertson, J. L. and Preistler, H. K. 1992. Pesticide Bioassays with Arthropods. CRC, Boca Raton.

Scharf, M. E., Lee, C. Y., Neal, J. J. and Bennett, G. W. 1999. Cytochrome P450 MA expression in insecticide resistant German cockroaches (Dictyoptera: Blattellidae). *J. Econ. Entomol.*, 92: 788–793.

Scott, J. G., Ramaswamy, S. B., Matsumura, F. and Tanaka, K. 1986. Effect of method of application on resistance to pyrethroid insecticides in *Blattella germanica* (Orthoptera: Blattellidae). *J. Econ. Entomol.*, 79: 571–575.

Siegel, S. and Castellan, N. J. 1988. Nonparametric Statistics for the Behavioral Sciences. McGraw-Hill Book Company, New York.

Siegfried, B. D., Scott, J. G., Roush, R. T. and Zeichner, B. C. 1990. Biochemistry and genetics of chlorpyrifos resistance in the German cockroach, *Blattella germanica* (L.). *Pestic. Biochem. Physiol.*, 38: 110–121.

Umeda, K., Yano, T. and Hirano, M. 1988. Pyrethroid-resistance mechanism in German cockroach, *Blattella germanica* (Orthoptera: Blattellidae). *Appl. Entomol. Zool.*, 23: 373–380.

Webb, J. E. 1961. Resistance of some species of cockroaches to organic insecticides in Germany and France, 1956–59. *J. Econ. Entomol.*, 54: 805–806.

Yu, S. J. 1991. Insecticide resistance in the fall armyworm, *Spodoptera frugiperda* (J. E. Smith). *Pestic. Biochem. Physiol.*, 39: 84–91.

Zhai, J. and Robinson, W. H. 1991a. Pyrethroid resistance in a field population of German cockroach, *Blattella germanica* (L.). *Jpn. J. Sanit. Zool.*, 42: 241–244.

Zhai, J. and Robinson, W. H. 1991b. Measuring cypermethrin resistance in the German cockroach (Orthoptera: Blattellidae). *J. Econ. Entomol.*, 85: 348–351.