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Dominance of Insecticide Resistance Presents a Plastic Response

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ABSTRACT

Dominance level of insecticide resistance provided by one major gene (an insensitive acetylcholinesterase) in the mosquito *Culex pipiens* was studied in two distinct environments. Dominance level was found to be very different between environments, varying from almost complete dominance to almost recessive when either propoxur (a carbamate insecticide) or chlorpyrifos (an organophosphorus insecticide) was used. To better understand this plastic response, three environmental parameters were manipulated and their interactions studied. For chlorpyrifos, each parameter had a small effect, but when all parameters were changed, the dominance level was greatly affected. For propoxur, one environmental parameter had a large effect by itself. It was further studied to understand the causal relationship of this plasticity. Recessivity of resistance was associated with more demanding environments. These results are discussed in the context of the various theories of the evolution of dominance. It appears that dominance of insecticide resistance cannot be directly predicted by Wright's physiological theory.

THE evolution of dominance has been the object of extensive controversy. FISHER (1928, 1931, 1958) proposed that the modification of dominance by other loci (modifier genes) was the basis of the dominance of wild-type alleles. WRIGHT severely criticized this theory, showing that the selection pressure on dominance modification would only be of the order of the mutation rate. He proposed an alternative hypothesis known as WRIGHT's physiological theory (1929, 1934, 1977). WRIGHT assumes that most loci code enzymes and that most mutations are deleterious, causing a reduction in enzymatic activity. If the wild type is more active than necessary, then the rate of reaction is likely to be substrate limiting rather than enzyme limiting. Thus a deleterious allele that only slightly reduces enzyme activity should appear recessive or nearly recessive.

Growing evidence against FISHER's theory (CHARLESWORTH 1979; ORR 1991) makes the physiological theory the most appropriate. HALDANE (1930), MULLER (1932) and PLUNKETT (1933) have proposed alternative models but all are related to WRIGHT's theory, and KACSER and BURNS (1981) and KEIGHTLEY and KACSER (1987) have given a detailed enzyme kinetic analysis of dominance. However, the physiological theory of dominance has remained mostly theoretical due to the absence of clear empirical evidence (but see ORR 1991).

Insecticide-resistance genes have occurred recently in numerous insect species and have been intensively studied. Dominance levels of insecticide resistance pro-

vided by these genes have been studied and some general patterns emerge (*e.g.*, Table 1). Resistance to DDT and pyrethroids through target (sodium channel) insensitivity tends to be recessive. Resistance to cyclodiene through target (GABA receptor) insensitivity is generally described as codominant. When the resistance gene corresponds to a detoxification enzyme, resistance is codominant to dominant. Resistance to organophosphorus (OP) or carbamate (CB) insecticides through insensitive acetylcholinesterase (AChE) is codominant to dominant. This general pattern suggests that some cellular or physiological factors, not taken into account by WRIGHT's theory, are important to influence the dominance level.

The dominance of an insecticide-resistance gene is best described by the relative position (D) of the mortality lines of heterozygotes compared to both susceptible and resistant homozygotes (STONE 1968). This measure is closely related to h , the dominance of the fitness value associated with the resistance gene, when the insecticide concentration varies (RAYMOND *et al.* 1989). For pest management purposes, some authors have defined the concept of "effective dominance" by considering the survival of heterozygotes and both homozygotes at a given insecticide concentration (*e.g.*, CURTIS *et al.* 1978; ROUSH and MCKENZIE 1987; for review see ROUSH and DALY 1990). For example, an insecticide concentration that kills heterozygotes and susceptible homozygotes makes the resistance "effectively" recessive. Inversely, a lower concentration that kills only susceptible homozygotes makes resistance "effectively" dominant. This type of variation (*i.e.*, according to the insecticide concentration) will not be considered further in this paper.

As far as we know, a variation of dominance level (D or h) for a given mortality level has never been de-

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TABLE 1

Examples of dominance levels of insecticide resistance provided by several insecticide resistance genes

Resistance mechanisms	Insecticide resistance	Dominance levels	Species	References
Insensitive sodium channel	DDT and pyrethroids	Recessive	<i>Musca domestica</i>	FARNHAM <i>et al.</i> (1984)
			<i>Culex pipiens</i> complex	HALLIDAY and GEORGHIOU (1985a,b)
			<i>Leptinotarsa decemlineata</i>	ARGENTINE <i>et al.</i> (1989)
Insensitive GABA receptor	Cyclodienes	Codominant to dominant	<i>Boophilus microplus</i>	STONE (1962)
			<i>Musca domestica</i>	GEORGHIOU (1969)
			<i>Anopheles sp.</i>	GEORGHIOU (1969)
			<i>Culex sp.</i>	GEORGHIOU (1969)
			<i>Tribolium castaneum</i>	BEEMAN and STUART (1990)
			<i>Boophilus microplus</i>	STONE <i>et al.</i> (1976)
Insensitive AChE	Carbamates and OPs ^a	Codominant to dominant	<i>Musca domestica</i>	PLAPP and TRIPATHI (1978)
			<i>Nephotettix cincticeps</i>	HAMA and IWATA (1978)
			<i>Leptinotarsa decemlineata</i>	IOANNIDIS <i>et al.</i> (1992)
			<i>Culex tritaeniorhynchus</i>	TAKAHASHI and YASUTOMI (1987)
			<i>Culex pipiens</i> complex	This study
			<i>Musca domestica</i>	TATE <i>et al.</i> (1974)
			<i>Blatella germanica</i>	COCHRAN (1994)
Multifunction oxidase	Carbamates	Codominant to dominant	<i>Culex pipiens</i> complex	PASTEUR and SINEGRE (1978)
			<i>Culex pipiens</i> complex	PASTEUR <i>et al.</i> (1984)
Esterases	OPs	Codominant to dominant	<i>Culex pipiens</i> complex	PASTEUR and SINEGRE (1978)
			<i>Culex pipiens</i> complex	PASTEUR <i>et al.</i> (1984)

^a OPs, organophosphates.

scribed in the literature. In this paper, we investigate the dominance level of insecticide resistance and its variation conferred by an insensitive allele of the *Ace* locus that encodes for AChE. This variation was discovered fortuitously when the same bioassays were performed in two different laboratories. The environmental parameters responsible for this variation were subsequently identified and manipulated to better understand this plastic response.

MATERIALS AND METHODS

Insects: Two strains of mosquitoes were used as follows: (1) S-LAB, a susceptible homozygous reference strain isolated by GEORGHIOU *et al.* (1966) and (2) MSE, a strain resistant to OP and carbamate insecticides, homozygous for an insensitive AChE (RAYMOND *et al.* 1986; BOURGUET *et al.* 1996). Both MSE and S-LAB strains were transferred in two laboratories, one located in Riverside, California, the other in Montpellier, France. They will be referred here respectively as A and B. F₁ individuals (MSE males × S-LAB females) were obtained in each location.

Insecticide bioassays: Resistance characteristics of the two strains and the F₁ progeny were analyzed by bioassays performed on fourth instars. Two insecticides of technical grade were used in alcohol solution: chlorpyrifos (Interchim, Montluçon, France) and propoxur (Bayer, Leverkusen, Germany). In all bioassays, larvae were exposed to the insecticide for 24 hr, and the final concentration of alcohol was systematically adjusted to 1%. Each bioassay cup held 20 larvae in 100 ml of water solution, unless otherwise indicated, and five replicates were done for each insecticide concentration tested. A control, where larvae experienced the same environmental conditions except for the presence of the insecticide, was run in each experiment. Dominance levels were measured as $D = (R_{F1} - 1) / (R_R - 1)$, where R_R and R_{F1} are the resistance ratio at a given mortality level. R_R and R_{F1} are respectively defined by the ratios LC_R/LC_S and LC_{F1}/LC_S , where LC_S , LC_R and LC_{F1}

are the insecticide concentrations needed to obtain a given mortality level for susceptible, resistant and F₁ mosquitoes, respectively. When mortality curves were not linear, LCs were estimated directly from the curves at different mortality levels. D varies linearly between 0 (complete recessivity) to 1 (complete dominance).

Dominance of chlorpyrifos resistance: Bioassays were performed in A and B laboratories on the two strains and their F₁ progeny to estimate the dominance of chlorpyrifos resistance. Among the various environmental parameters differing between A and B, three were manipulated: the food used to feed the larvae, the water, and the type of cups used for bioassays. Larval food was yeast extract in A and dried dog food in B, which will be referred to as Fa and Fb, respectively. Bioassays were done in tap water in A and in distilled water in B, and they will be referred to as Wa and Wb, respectively. Cups used for bioassays were in plastic in A and in wax in B; their shapes were different (see Figure 1), and they will be referred to as Ca and Cb, respectively. Dominance levels were estimated in environment A (using Fa, Wa, Ca) and in environment B (using Fb, Wb, Cb). To test the influence of each parameter, the dominance of chlorpyrifos resistance was estimated in environment A when only one environmental parameter was changed (*i.e.*, with Fb, Wa, Ca or Fa, Wb, Ca or Fa, Wa, Cb). Dominance was also measured when two parameters were changed (*i.e.*, with Fb, Wb, Ca or Fb, Wa, Cb or Fa, Wb, Cb). Finally, dominance was estimated when all three parameters were changed (*i.e.*, with Fb, Wb, Cb).

Dominance of propoxur resistance: Bioassays were performed in A (with Fa, Wa and Ca) and B (with Fb, Wb and Cb) on the two strains and the F₁ to estimate the dominance of propoxur resistance in these two environments. Then, several parameters were manipulated, and their effects were examined by doing bioassays on F₁ larvae using a propoxur concentration of 5 or 20 ppm. In the A environment (with Fa, Wa and Ca), the water/air interface accessible for larvae in Ca (65 cm²) was reduced by 94% (4 cm²) or 98% (1 cm²). These experimental cups will be referred as Ca94 and Ca98 (see Figure 1). In the B environment (with Fc, Wc and Cc; the food Fc was a mixture of prawn powder and mice food; Wc

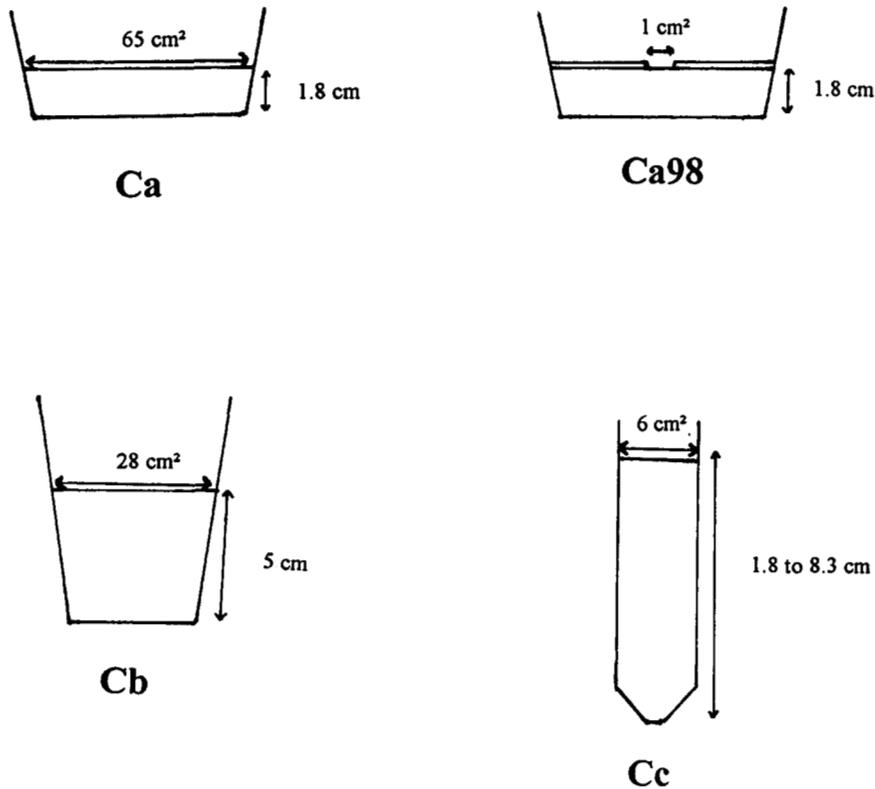


FIGURE 1.—Different types of cups used for bioassays in cross section. The surface of the water interface and the depth of water are indicated. (A) Waxed cups with (Ca98) and without (Ca) a 98% reduction of the water/air interface. (B) Plastic cups (Cb). (C) Falcon tubes (Cc) used with a variable water volume. See text for explanations.

was tap water available in B), the same reduction of water/air interface in Ca was performed. Four replicates were run in both environments with a concentration of 20 ppm. The effect of light was also investigated by performing the experiment with Ca and Ca98 in environment B at the same time in total darkness (three replicates were performed with a concentration of 20 ppm).

The possible modification of propoxur concentration when the water/air interface was reduced was investigated in B environment by running simultaneously a bioassay in Ca and Ca98. The water solution (with 20 ppm) in the two cups was linked together and was constantly homogenized by a pump system. The larvae were not allowed to change cups (three replicates were performed).

The influence of larval density and of the depth of the water solution in the cup was investigated using cups of type C (50 ml Falcon tube referred to as Cc, see Figure 1). Three densities (1, 10 or 20 larvae per cup) were assayed with 5 ppm of propoxur at five depths (1.8, 2.9, 4.7, 6.5 and 8.3 cm, corresponding respectively to 5, 10, 20, 30 or 40 ml). Respectively 30, eight and nine replicates were performed for densities 1, 10 and 20.

Statistical analysis: Mortality data were analyzed using the Log-Probit program of RAYMOND (1993), based on FINNEY (1971). Mortality lines were considered identical when their parallelism was not rejected at the 0.05 probability level, and the 95% confidence limits of the resistance ratio included the value 1. Effects of light, of reduction of water/air interface and of interaction of the cup with the insecticide on mortality were tested using a Fisher's exact test on 2×2 contingency tables. The effects of larval density and water volume were investigated using a generalized linear logit model (McCULLAGH and NELDER 1989) as implemented by the GLIM program (BAKER and NELDER 1985). A model incorporating the density and volume effects plus their interactions was constructed on a logit scale and was reduced according to CRAWLEY (1993). Effect of the density (respectively water volume) was estimated by

removing the variable density (respectively water volume) from the model, and the resulting changes in deviance and in degree of freedom were used for approximate chi-square tests.

RESULTS

In all bioassays, mortality curves obtained on both parental strains (MSE and S-LAB) with both insecticides were linear ($P > 0.1$) (Figures 2 and 4), which is consistent with the homogeneity of susceptibility or resistance factors, as previously found (RAYMOND *et al.* 1986; BOURGUET *et al.* 1996).

Dominance of chlorpyrifos resistance: Chlorpyrifos mortality lines for S-LAB, MSE and F_1 in A and B environments are presented in Figure 2. Both S-LAB and MSE larvae displayed distinct mortality curves in each environment (parallelism not rejected: for MSE, $\chi^2 = 1.27$, d.f. = 5, $P > 0.9$ and for S-LAB, $\chi^2 = 3.9$, d.f. = 4, $P > 0.4$; the ratio of the LC_{50} s being different from 1 for both strains, $P < 0.05$), resistance being higher in A than in B. The same phenomenon was observed for the F_1 , but the mortality lines were not parallel ($\chi^2 = 13$, d.f. = 7, $P < 0.0001$). In the B environment, increase of resistance was much larger in F_1 than in the two parental strains, so that the resulting effect was a change in dominance level according to the mortality level (Figure 3A). Thus, the dominance level, which was about 0.7 and constant in the A environment, was a monotonic function of mortality in the B environment (between 0.15 for 2% mortality to 0.55 at 98% mortality) (Figure 3A).

To possibly identify environmental factors responsi-

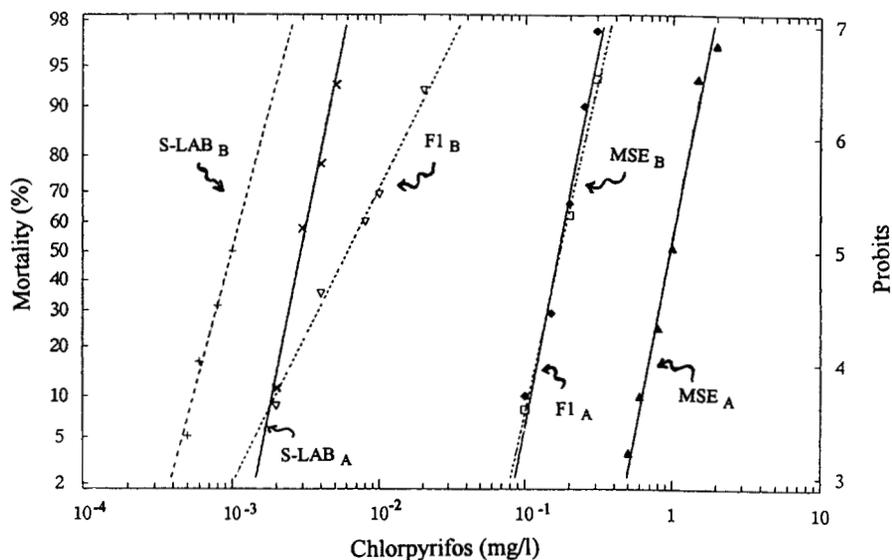


FIGURE 2.—Chlorpyrifos mortality lines obtained in bioassays with the susceptible strain (S-LAB), the resistant strain (MSE) and the F_1 . The three mortality lines were obtained in both the A (Fa, Wa and Ca, —) and B environments (Fb, Wb and Cb, ---).

ble for this change in dominance level, three parameters were manipulated in the A environment to “mimic” the B environment: the food used to raise the larvae, the type of water, and the type of cups used to perform the bioassays. When only one of these factors was changed, the dominance level changed only slightly (Figure 3B). When two of these factors were changed simultaneously, the dominance level changed toward the values of the B environment and became a monotonic or nonmonotonic function of the mortality, depending of the nature of the two factors being manipulated (Figure 3C). When all three factors were simultaneously changed, the resulting dominance level was close to the one of the B environment (Figure 3C), and the slight residual difference indicated that some minor unknown environmental parameters influenced the dominance level. Because of the complex relationship of dominance with the mortality in the various environmental conditions, no simple statistical tests could be used to test the significance of each factor and their interactions. In addition, examination of Figure 3C indicates that interaction terms should be taken into account, as an additive effect alone would probably not explain the variation in dominance level.

Dominance of propoxur resistance: Propoxur mortality lines of S-LAB, MSE and F_1 in A and B environments are presented in Figure 4A. As previously found for chlorpyrifos resistance, both S-LAB and MSE larvae displayed distinct mortality curves in both environments (parallelism is rejected for S-LAB, $\chi^2 = 21.7$, d.f. = 5, $P < 0.001$; but not for MSE, $\chi^2 = 5.27$, d.f. = 5, $P > 0.3$; the ratio of the LC_{50} s being different from 1 for both strains, $P < 0.05$), resistance being higher in A than in B. For the F_1 , the mortality line was a linear function of the dose (in Log-probit coordinates) in the A environment ($P > 0.1$) but not in B ($P < 0.05$). In this latter case, this was not due to the heterogeneity of parental strains (D. BOURGUET, D. FOURNIER and M. RAYMOND,

unpublished results). As a result, the dominance level was almost constant in environment A (from 0.93 for 2% mortality to 0.97 at 98% mortality) and was dependent on the mortality level in environment B (from 0.2 for 2% mortality to 1 at 80% mortality, Figure 4B).

The effect of the three parameters (food, water and cup) were investigated in the A environment. All had an effect on the dominance level, and the effect of the cup alone was large (data not shown). The effect of the cup was also investigated in the B environment (Fc, Wc, Ca vs. Fc, Wc, Cb). As previously found in the A environment, the effect of the cup alone was important (Figure 5). Therefore, further studies were undertaken to understand how the cup induced a change of dominance level: various parameters related to the cup were manipulated, and their influence in F_1 mortality was recorded.

For a fixed volume of water solution, the surface of the water/air interface is different according to the shape of the cup. This interface was artificially reduced to evaluate how F_1 mortality was affected. In both environments, surface reductions increased mortality significantly ($P < 0.001$), although there was no differences between 94 and 98% surface reduction (Table 2).

A possible modification of the propoxur concentration induced by the cup was investigated in the B environment. Two bioassays on F_1 larvae were simultaneously carried out with Ca and Ca98. The water solution of the two cups (containing 20 ppm propoxur) was constantly homogenized by a pump system. Thus larvae were subjected to exactly the same toxic conditions in the two cups. Mortalities in each cup were not affected by the pump system (Table 3), indicating that the homogenization of the water solution between cups has no effect (Fisher exact test, $P > 0.3$).

As the shape of cups Ca and Cb are different (Figure 1), the different amount of light received in each cup could affect (for example) the physiological status of larvae. This effect was tested by performing bioassays

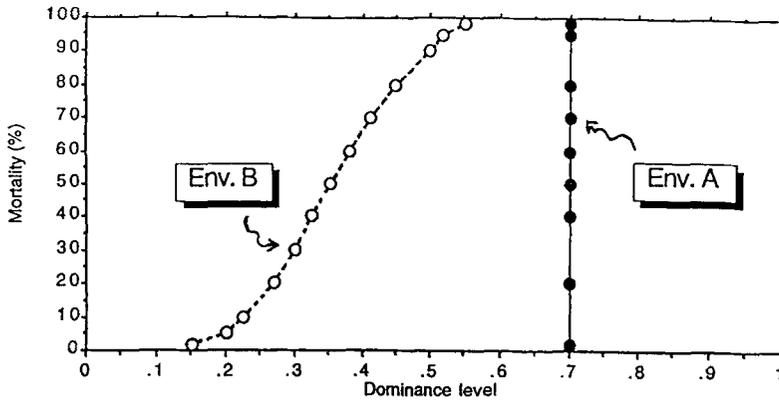
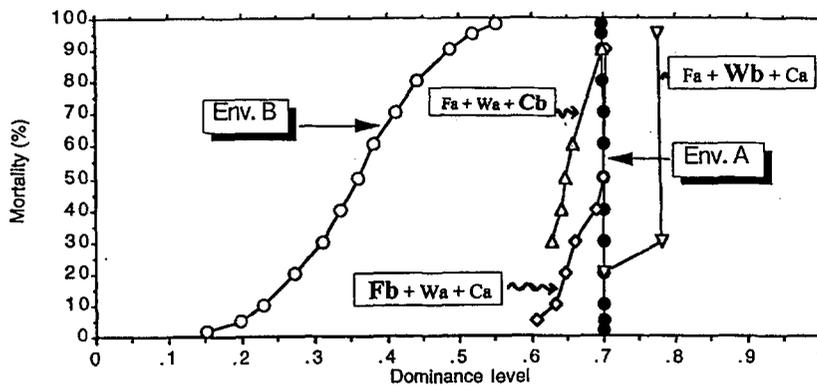
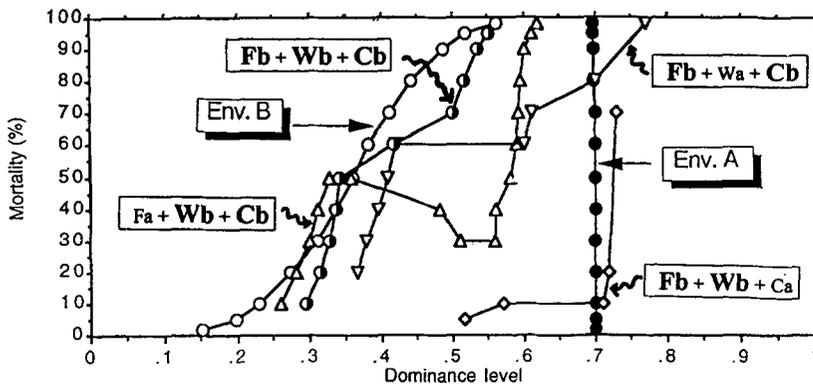
A**B****C**

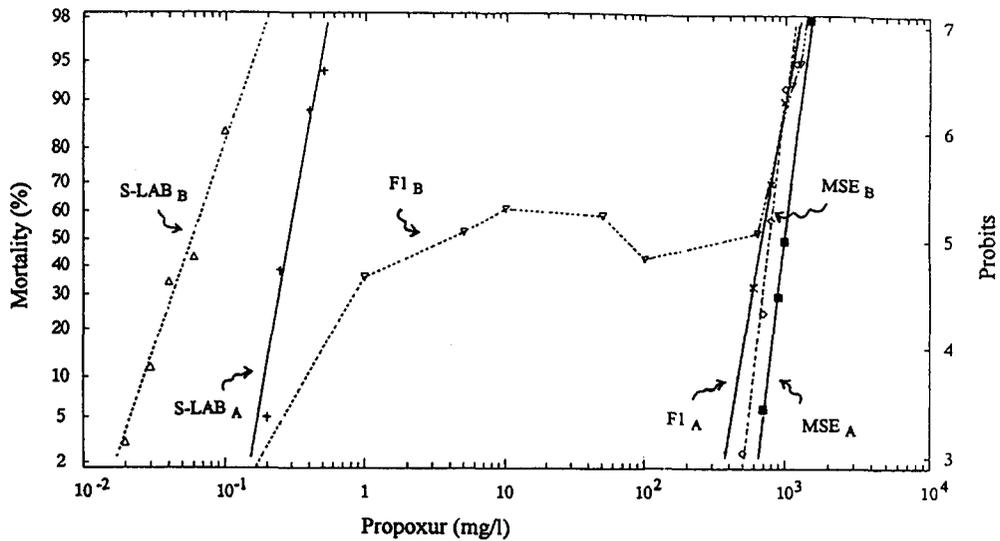
FIGURE 3.—Variation in the dominance level of chlorpyrifos resistance. (A) Difference between the A and the B environments computed from Figure 2. (B) Effect of changing only one parameter in the A environment toward the B one. (C) Effect of changing two or three parameters simultaneously in the A environment toward the B one. See text for explanations.

simultaneously in “normal” light (in the laboratory) and in total darkness. This was done in the B environment (Fc, Wc) using Ca and Ca98 at 20 ppm propoxur. No significant effect was found (Table 4, Fisher exact test, $P > 0.15$), indicating that light had an undetectable influence on propoxur mortality.

The difference in shape between the cups might influence the outcome of a bioassay. Larvae, during a bioassay, experience a greater water depth and a higher larval density at the water/air interface in Cb than in Ca. These two factors are important as larvae breathe

at the surface and regularly dive to the bottom to escape disturbances or to search for food. To manipulate the depth with a constant water/air surface, cylindrical tubes were used (Cc, see Figure 1). Both density (one to 20 larvae per tube) and depth (from 1.8 to 8.3 cm) were simultaneously manipulated, with a constant propoxur concentration of 5 ppm. The experiment was performed in the B environment (with Fc and Wc). Both density and depth had a significant effect ($P < 0.001$), the interaction between both being nonsignificant ($P > 0.3$; Table 5). When only one larva was pres-

A



B

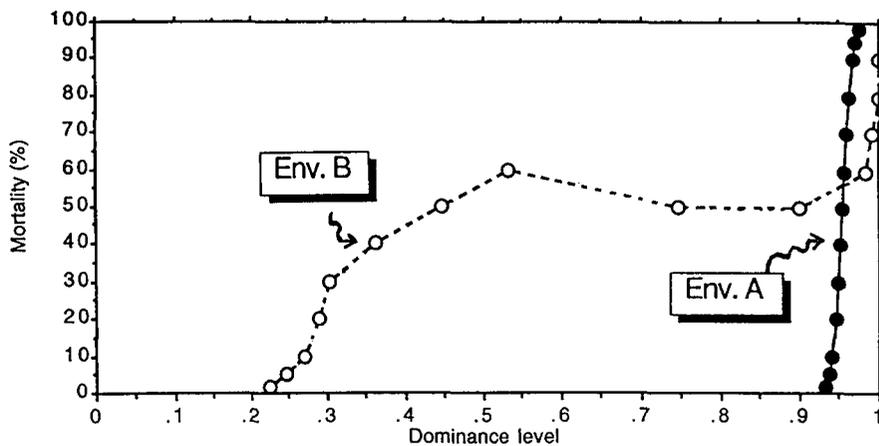


FIGURE 4.—Propoxur mortality lines obtained in bioassays with the susceptible strain (S-LAB), the resistant strain (MSE) and the F_1 . (A) The three mortality lines were obtained in both A (Fa, Wa and Ca, —) and B environments (Fb, Wb and Cb, ---). (B) Variation of the dominance level in both environments computed from the mortality lines.

ent in Cc, an increase of water depth had no effect on mortality (Figure 6). At higher densities, mortality increase with increased water depth.

DISCUSSION

Our results show that the dominance level of insecticide resistance in a *Culex pipiens* strain is influenced by environmental conditions. This situation is an opportunity to better understand the physiological basis for dominance level and to evaluate the potential for its possible evolution.

How do environmental factors influence dominance?

In environment A, dominance had a constant value for both insecticides and did not vary with mortality level. In environment B, dominance was not constant and varied according to the mortality level (Figure 4B). For propoxur a marked decrease in mortality was apparent when doses increased (~100 ppm) (Figure 4A). This unusual situation was not an artifact (D. BOURGUET, D. FOURNIER and M. RAYMOND, unpublished results). Overall, variations from near recessivity to near dominance could be observed by manipulating only three

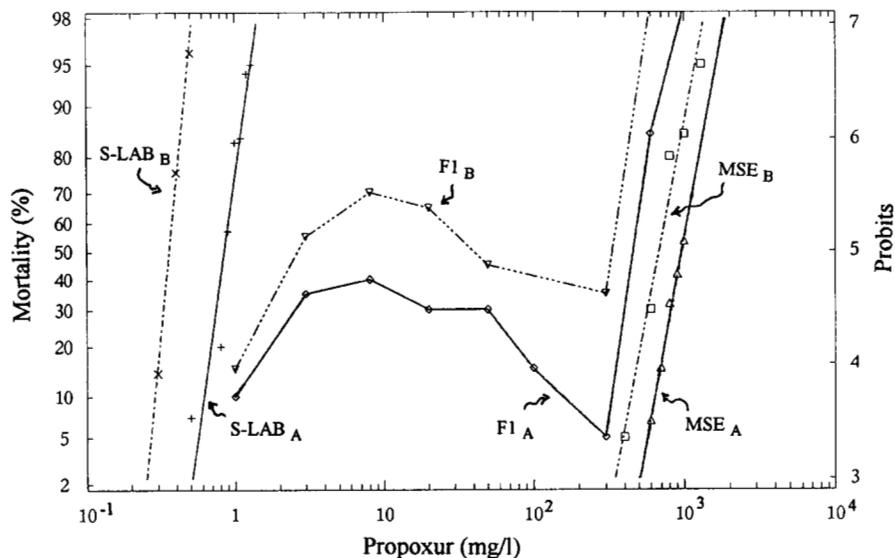


FIGURE 5.—Effect of the type of cup (Ca vs. Cb) in bioassays of the susceptible strain (S-LAB), the resistant strain (MSE) and the F₁ with propoxur in the B environment (with Fc and Wc). ---, cup Cb; —, cup Ca. See text for explanations.

parameters: the type of food used to feed the larvae, the type of water and the type of cup used to perform the bioassay (Figure 3C). The first two parameters were not studied further, as they act mainly in synergy with other factors and have limited effects by themselves. The third one (the type of cup) displayed a large effect alone in bioassays with propoxur and was analyzed in detail. The variation in dominance level observed in distinct cups could not be attributed to factors potentially influencing the insecticide concentration, such as the cup material, the volume/surface ratio, or the amount of incident light (Tables 3 and 4). Only the depth of the cup or a certain amount of air surface seems to influence the dominance level (Tables 2 and 5; Figure 6). Both a greater water depth and a reduced air surface have the same effect of increasing mortality of heterozygous larvae, thus changing the dominance level. The effect on mortality of these two factors can be explained by the same phenomenon, *i.e.*, a longer swimming time for larvae. Larvae breathe at the surface

and regularly dive to the bottom to escape disturbances or to search for food. When a larva wants to reach the water surface after a dive, it generally needs several attempts, going down and up several times if the surface has been artificially reduced by floating material. Thus, increasing water depth or reducing the water surface both have the consequence of increasing swimming activity in larvae. This hypothesis is compatible with the higher mortality found for higher larval density (Table 5, Figure 6), because each larva dives more often in higher density due to the disturbance caused by the other larvae.

Although the causal relationship between the swimming activity in heterozygote larvae and the dominance level is still unknown (but under current investigation), it is worthy of note that recessivity of resistance is associated with more demanding environments, which is compatible with a pleiotropic cost associated with resistance.

Implications: It is generally believed that the dominance level for a given gene is a fixed parameter. Evolution of dominance through the selection of modifiers has been proposed by FISHER (1928, 1931, 1958), but this process is probably of negligible importance in nat-

TABLE 2
Water/air interface influence on F₁ mortality
in A and B environments

Cup ratio	A environment		B environment	
	R	P ^a	R	P
Ca/Ca94 ^b	0.026	***	0.29	***
Ca/Ca98 ^c	0.026	***	0.27	***
Ca94/Ca98	1.010	NS	0.92	NS

All experiments were done using 20 ppm propoxur. In each environment, the variation in mortality due to a reduction of the water/air interface is measured by the ratio (R) of mortalities in each condition, and a Fisher exact test is performed to evaluate the significance of this change.

^a P value: *** P < 0.0001; NS, P > 0.05.

^b Ca with a 94% reduced water/air surface.

^c Ca with a 98% reduced water/air surface.

TABLE 3
Influence of water solution homogenization
on the F₁ mortality

Cup	Nonhomogenized	Homogenized	P
	M ^a (N) ^b	M (N)	
Ca	5 (60)	3 (60)	1.00 (NS)
Ca98 ^d	63 (60)	73 (60)	0.33 (NS)

All experiments were done using 20 ppm propoxur.

^a Percentage of mortality.

^b Number of larvae tested.

^c P value of Fisher's exact test; NS, nonsignificant.

^d Ca with a 98% reduced water/air surface.

TABLE 4
Influence of light on the F₁ mortality

Cup	Normal light M ^a (N) ^b	Darkness M (N)	P ^c
Ca	3.6 (56)	5.4 (56)	1.00 (NS)
Ca98 ^d	48.3 (58)	61.1 (54)	0.19 (NS)

All experiments were done using 20 ppm propoxur.

^a Percentage of mortality.

^b Number of larvae tested.

^c P value of Fisher's exact test; NS, nonsignificant.

^d Ca with a 98% reduced water/air surface.

ural populations, as stated by theoretical works (*e.g.*, EWENS 1965, 1967) and empirical studies (CHARLESWORTH 1979; ORR 1991).

The dominance displayed by wild-type alleles is now classically explained by a biochemical process, where the substrate is considered limiting so that the exact gene dosage in homozygote *vs.* heterozygote has relatively little influence on the output of the enzymatic reaction (WRIGHT 1929, 1934, 1977). This idea has been extended to the study of flux through enzymatic pathways, where the "phenotype" studied is related to the quantity of the end product: again, the dominance of the wild-type allele at one locus within the pathway arises when the substrate is limiting (KACSER and BURNS 1981; KEIGHTLEY and KACSER 1987).

Several authors have claimed that WRIGHT's theory of dominance explains why resistance to insecticides through insensitive AChE is codominant to dominant (ROUSH and DALY 1990; FOURNIER and MUTERO 1994). The main basis of this statement is that the amount of AChE activity necessary for life in laboratory conditions is generally <30% [*e.g.*, 25% for *Drosophila* (HOFFMANN *et al.* 1992) and 2.3% for *Tetranychus urticae* (SMIS-SAERT *et al.* 1975)]. Thus, in heterozygotes the inhibition of 50% of the AChE corresponding to the entire

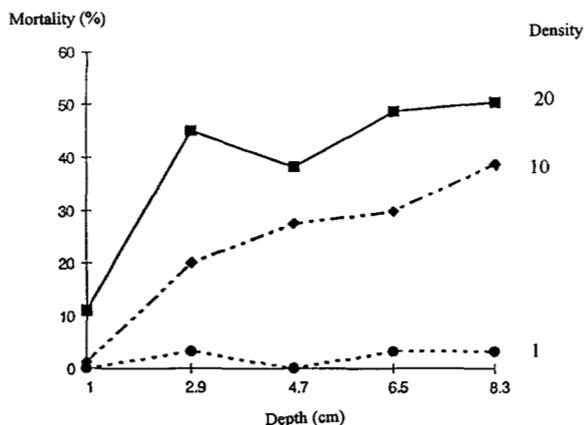


FIGURE 6.—Influence of larval density and water depth on mortality of F₁ mosquitoes at 5 ppm of propoxur. Densities are indicated in larvae per cup, which were of type Cc. See text for explanations.

TABLE 5
Influences of density, volume (*i.e.*, depth) and their interaction on F₁ mortality

GLIM model	Scaled deviance	Deviance differences ^a	d.f.	P ^b
<i>Density + Volume</i>	8.8	—	8	NS
– <i>Density</i>	137.9	129.1	2	***
– <i>Volume</i>	139.9	131.1	4	***

The influence of each parameter was estimated using a GLIM analysis. See text for explanations.

^a Differences in deviance from the basic model *density + volume*.

^b NS, nonsignificant; *** *P* < 0.0001.

susceptible counterpart would not affect the viability, and the resistance would appear as dominant.

This explanation cannot explain all the different dominance levels found in our experiments. The reason is that the biochemical theory (or WRIGHT's theory) of dominance states that the phenotype studied must be monotonically related to the quantity of the enzymatic product. For the *Ace* gene, this statement clearly does not fit. When the phenotype studied is insecticide mortality, mortality of heterozygotes has no simple monotonic relationship with insecticide concentration, as exemplified by the concentration range where mortality decreases as dose increases (unilateral Fisher exact test, *P* = 0.025; Figure 4A): dominance of insecticide resistance is not directly related to the expression level of the resistance gene.

Physiological processes other than a simple enzymatic reaction or a linear enzymatic pathway should be considered to understand how dominance of insecticide resistance is determined. As an illustration, recessivity of target-site insensitivity in several species resistant to pyrethrinoids or DDT (see Table 1) has a simple physiological explanation. The target is the voltage dependent sodium channel (Na⁺Vdp), and in intoxicated susceptible insects, the inhibited target is left permanently open (LUND and NARAHASHI 1983). The permanent opening of only a few percent of Na⁺Vdps is sufficient to cause death (LUND 1984). Thus, heterozygous insects that possess 50% susceptible channels are phenotypically similar to susceptible insects in the presence of insecticide. One may predict that if the insecticide inhibited the Na⁺Vdp by closing it instead of opening it, dominance level would be codominant or dominant. This is verified by considering another insecticide target-site, *e.g.*, the GABA-gated chloride channels. These chloride channels are differently affected by insecticides: avermectins leave the channels permanently open, whereas cyclodiene leave them in a closed position (CLARK *et al.* 1994). As expected, resistance to avermectins is recessive [*e.g.*, *Musca domestica* (KONNO and SCOTT 1991), *Leptinotarsa decemlineata* (ARGENTINE and CLARK 1990)], whereas resistance to cyclodienes is codominant to

dominant [*e.g.*, *M. domestica* (GEORGHIOU 1969), *Tribolium castaneum* (BEEMAN and STUART 1990)]. Thus, when the insecticide target is a channel, the dominance level of resistance is the result of a molecular process clearly distinct from WRIGHT's explanation.

In conclusion, the dominance of insecticide resistance cannot be directly inferred from the expression of the *Ace* gene using the WRIGHT's physiological theory. In addition, dominance level of insecticide resistance in the situation described here has no fixed value but depends on environmental parameters. This phenomenon gives new insight on dominance studies and resistance management. Some predictive models have investigated the influence of different dominance levels on the evolution of insecticide resistance (*e.g.*, GEORGHIOU and TAYLOR 1977; CURTIS *et al.* 1978), but none have considered dominance as a variable parameter. How conclusions of these models will be affected by this phenomenon remains to be determined. But it will first be necessary to determine all the factors interacting with a resistant gene to give the complex dominance levels of insecticide resistance. Finally, it will be useful to understand how dominance varies in treated populations.

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