Original Article

Genetic Analysis of Hexythiazox Resistance in the Citrus Red Mite, *Panonychus citri* (McGREGOR)*

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The inheritance mode of hexythiazox resistance was analyzed in the citrus red mite, *Panonychus citri* (McGREGOR), which was selected for resistance in the laboratory after collection from a citrus orchard at Haibara-machi in Shizuoka Prefecture, Japan. The reciprocal and back cross experiments were conducted using the susceptible Haibara-S and the resistant Haibara-R strains, in which the values of LC_{50} were 0.462 ppm and over 8000 ppm, respectively. The inheritance mode of hexythiazox resistance in the eggs of Haibara-R strain was suggested to be incompletely recessive controlled by a single major gene. The estimated values of degree of dominance (D) were -0.40 and -0.59 for the heterogeneous female eggs, SR and RS, respectively.

INTRODUCTION

Hexythiazox, *trans*-5-(4-chlorophenyl)-*N*-cyclohexyl-4-methyl-2-oxo-3-thiazolidine-carboxamide, is a selective miticide which is active against various phytophagous mites of agricultural importance, and has no or little effects on their natural enemies.¹⁾ The miticide interferes with mite growth and reproduction, and does not show cross-resistance to conventional miticides. Thus, hexythiazox has been used on various crops under the integrated pest management programs. The development of hexythiazox resistance, however, was recently reported in several species of mites.²⁻⁵⁾

Development of insecticide/miticide resistance is influenced by genetic, biological/ecological and operational factors.⁶⁻⁸⁾ Keiding discussed the genetics of resistance as one

of the important issues of resistance risk assessment.⁹⁾ The genetic studies have been reported in resistances to several miticides.¹⁰⁻³⁰⁾ And the dominance of resistance seems to be one of the critical factors affecting the rate of resistance development and its reversion. The understanding of dominance would be also effective for prediction and management of resistance.

In this study, as a part of the risk assessments of hexythiazox resistance in the citrus red mite, *Panonychus citri* (McGREGOR), we investigated the inheritance mode of hexythiazox resistance.

MATERIALS AND METHODS

1. Citrus Red Mite and Bioassay

The original strain of citrus red mite, *Panonychus citri* (McGREGOR), was collected from a citrus orchard at Haibara Agricultural Research Station (Nippon Soda Co., Ltd.) in Shizuoka Prefecture, Japan. As reported previously,⁸¹⁾ the strain was selected for resistance and for susceptibility with hexy-

* Studies on Hexythiazox Resistance in Phytophagous Mites (Part 3). For Part 2, see pp. 493–501.

thiazox to obtain resistant (Haibara-R) and susceptible (Haibara-S) ones, respectively. And they have been maintained in the laboratory at 25°C and 70% relative humidity under 16L-8D photoperiod during experiment. A detached citrus leaf method was adopted for rearing and bioassay. To prevent the detached leaf from drying, it was put with wet cotton in a glass Petri dish.

Ovicidal tests were conducted for all bioassays with dipping method. About 10 adult females were placed to oviposit on an individual detached leaf for two days and then they were removed. About 80 eggs laid on the detached leaf were dipped for 10 sec in various concentrations of hexythiazox (10% WP) solutions with 0.033% spreader, Rabiden SS®. The procedures were repeated twice at each concentration. The number of unhatched eggs was counted 7 days after treatment and the percent mortality was calculated. Data were analysed by probit regressions³²⁾ after Abbott's correction for natural mortality.³³⁾

2. Parental Strain

As parental strains for the genetic analysis of hexythiazox resistance, the resistant Haibara-R and the susceptible Haibara-S strains were used.

In the arrhenotokous reproduction system in mites,³⁴⁾ females from fertilized eggs are diploid, while males from unfertilized eggs are haploid. Mated female adults oviposit both fertilized and unfertilized eggs, whereas virgin ones lay only unfertilized eggs.

To assay the susceptibility of male and female eggs separately, only male eggs were obtained as follows: teleiochrysalid females isolated from adult males were maintained on the detached leaf, and these virgin adult females laid only unfertilized male eggs.

3. Reciprocal Crosses

For a better understanding, the gene symbols, SS, RR, SR, RS, S and R, were used for each genotype of egg and adult on the assumption of a single major gene. Reciprocal crosses between the Haibara-R and Haibara-S strains were made in order to produce F1 female eggs, which were SR (from

SS♀ × R♂) and RS (from RR♀ × S♂), for genetic analysis.

Ten teleiochrysalid females from the Haibara-R and the Haibara-S were separately inoculated to the different detached leaves. Twelve adult males of the Haibara-S and the Haibara-R were added to the teleiochrysalids of the Haibara-R and the Haibara-S, respectively. They were allowed to mate for 5 days to be cross-fertilized. The procedures were repeated to get *ca.* 400 mated females for each reciprocal cross.

The susceptibility to hexythiazox in the eggs laid by the reciprocally crossed females was investigated. F1 eggs from each cross, SS♀ × R♂ or RR♀ × S♂, consisted of diploid female eggs and haploid male eggs, SR+S or RS+R, respectively. Since the only female eggs (SR or RS) could not be separately laid from male eggs, the susceptibility of female eggs could be expected by the correction using the susceptibility of parental male eggs (S or R) and the sex ratio of citrus red mite (♀:♂ = 2:1) according to the following formula reported by Inoue¹⁹⁾:

$$X = 3(B - A)/2$$

where X is susceptibility of F1 female eggs (SR or RS) at each concentration of hexythiazox solution, A is that of male eggs (S or R) and B is that of female and male eggs (SR+S or RS+R).

The degree of dominance (D) was estimated for the heterogeneous F1 female eggs with the following formula³⁵⁾:

$$D = (2X_b - X_a - X_c)/(X_a - X_c)$$

where X_a is $\log_{10} LC_{50}$ of the homogeneous resistant eggs (RR), X_b is $\log_{10} LC_{50}$ of the heterogeneous eggs (SR or RS) and X_c is $\log_{10} LC_{50}$ of the homogeneous susceptible eggs (SS). This formula would result in -1 if the resistance is fully recessive, 0 if there is no dominance and $+1$ if the resistance is completely dominant.

4. Haploid F2 Eggs

About 400 teleiochrysalid F1 females (SR or RS), which had developed from eggs laid by reciprocally crossed females, were inoculated to the detached leaves for 5 days. They were

developed into virgin adult females ovipositing haploid F2 eggs (S+R or R+S). The susceptibilities of F2 male eggs to hexythiazox were tested, and compared with those of the parental males (S or R).

5. Back Crosses

Back crosses between the 2 types of *ca.* 400 heterogeneous F1 females, SR♀ or RS♀, and the parental resistant male (R♂) were made to generate B1 eggs, SR+RR+S+R or RS+RR+R+S, respectively. The crossing procedures were similar to that of the reciprocal crosses described before. The susceptibilities of the obtained B1 eggs to hexythiazox were assayed.

RESULTS

1. Parental Strain

Table 1 summarizes the results of susceptibility test to hexythiazox for each genotype of eggs. In the Haibara-S, the susceptible parental strain, LC₅₀ and LC₉₅ values of eggs of female with male (SS+S) were 0.462 and 3.40 ppm, respectively, and those of only male eggs (S) were 0.491 and 2.03 ppm, respectively. It was suggested that there was no difference in susceptibility to hexythiazox between male (S) and female (SS) eggs. In the Haibara-R, the hexythiazox resistant parental strain, both LC₅₀ and LC₉₅ values of eggs of female with male (RR+R) were over 8000 ppm, and the same results were obtained in the only male eggs (R) (Figs. 1 and 3). From these results the susceptibility of female eggs (RR) was likely to be similar to that of male eggs (R) in the strain Haibara-R as well as in Haibara-S. It was also demonstrated that the resistance level was high in the Haibara-R, and the resistance ratios were over 17,000 and over 2400 for LC₅₀ and LC₉₅ values, respectively.

2. Reciprocal Crosses

The concentration-mortality lines of the reciprocal F1 eggs derived from the different crosses, SS♀ × R♂ and RR♀ × S♂, are shown in Figs. 1 and 2, respectively.

In the cross between the Haibara-S females and the Haibara-R males (SS♀ × R♂), the F1 eggs line (SR+S) was drawn closer to the line of the Haibara-S than that of the Haibara-

R. LC₅₀ and LC₉₅ values of the F1 eggs (SR+S) were 3.60 and 53.0 ppm, respectively, and those of the heterogeneous F1 eggs (SR) were expected to be 8.67 and 51.3 ppm, respectively (Table 1).

In the cross between the Haibara-R females and the Haibara-S males (RR♀ × S♂), the F1 eggs line (RS+R) was drawn intermediately

Fig. 1 Hexythiazox concentration-mortality relationships for susceptible (Haibara-S, SS+S; □) and resistant (Haibara-R, RR+R; ■) parents, F1 (SR+S; ●) from reciprocal cross (SS♀ × R♂), and B1 (SR+RR+S+R; ▲) from back cross (SR♀ × R♂) in the eggs of citrus red mite. The dotted line represents the response expected for B1 if hexythiazox resistance is controlled by a single major gene.

Fig. 2 Hexythiazox concentration-mortality relationships for susceptible (Haibara-S, SS+S; □) and resistant (Haibara-R, RR+R; ■) parents, F1 (RS+R; ●) from reciprocal cross (RR♀ × S♂), and B1 (RS+RR+S+R; ▲) from back cross (RS♀ × R♂) in the eggs of citrus red mite. The dotted line represents the response expected for B1 if hexythiazox resistance is controlled by a single major gene.

Table 1 Susceptibilities to hexythiazox in susceptible (Haibara-S) and resistant (Haibara-R) strains and their F1 progenies and the degree of dominance.

Strain or cross	Genotype of eggs	Susceptibility ^{a)}			Resistance ratio ^{c)}		Degree of dominance
		Slope ^{b)}	LC ₅₀ (95% CL), ppm	LC ₉₅ (95% CL), ppm	LC ₅₀	LC ₉₅	
〈Parental strain〉							
Susceptible (Haibara-S)	SS♀ + S♂	1.90	0.462 (0.175-0.963)	3.40 (1.41-90.2)	1.0	1.0	—
	S♂	2.67	0.491 (0.437-0.552)	2.03 (1.61-2.45)	1.1	0.60	—
Resistant (Haibara-R)	RR♀ + R♂	—	>8000	>8000	>17,000	>2400	—
	R♂	—	>8000	>8000	>17,000	>2400	—
〈Reciprocal cross〉							
SS♀ × R♂	SR♀ + S♂	1.41	3.60 (3.06-4.22)	53.0 (39.9-74.3)	7.8	16	—
	SR♀ (estimated)	2.22	8.67 (3.86-17.0)	51.3 (23.6-569)	19	15	-0.40
RR♀ × S♂	RS♀ + R♂	0.577	35.7 (19.7-73.6)	>8000	77	>2400	—
	RS♀ (estimated)	1.00	3.48 (2.28-5.13)	153 (78.8-388)	7.5	45	-0.59

^{a)} 0-2 day-old eggs.^{b)} Slope of regression equation.^{c)} LC of the each genotype/LC of the susceptible parent (SS♀ + S♂).

Fig. 3 Hexythiazox concentration-mortality relationships for susceptible (Haibara-S, S; $\square$) and resistant (Haibara-R, R; $\blacksquare$) parents and F2 (S+R; $\circ$, or R+S; $\bullet$) from reciprocal F1 virgin females (SR $\varnothing$ or RS $\varnothing$, respectively) in the eggs of citrus red mite.

The dotted line represents the response expected for F2 if hexythiazox resistance is controlled by a single major gene.

between the lines of the Haibara-S and the Haibara-R. LC_{50} and LC_{95} values of the F1 eggs (RS+R) were 35.7 and over 8000 ppm, respectively (Table 1). All survivors of the ovicidal tests at the concentrations over 125 ppm successfully developed into adult males, which were certainly resistant to hexythiazox. And LC_{50} and LC_{95} values of the heterogeneous F1 eggs (RS) were expected to be 3.48 and 153 ppm, respectively, which were closer to those of the Haibara-S than the Haibara-R.

The values of degree of dominance (D) for the heterogeneous F1 female eggs of SR and RS genotype were calculated to be -0.40 and -0.59 , respectively (Table 1). However, these values were over-estimated because the LC_{50} of parental resistant Haibara-R were assumed to be 8000 ppm for calculation, but actually over 8000 ppm. Thus, the values of D were practically considered to be smaller than those calculated here.

3. Haploid F2 Progeny

The concentration-mortality lines of the 2 types of F2 male eggs are shown in Fig. 3. The F2 eggs, S+R or R+S, were derived from the heterogeneous F1 virgin female adults, SR and RS, respectively. In addition to the similarity

in susceptibility between each type of F2 eggs, the plateau at 50% mortality was observed.

4. Back Crosses

The concentration-mortality lines of the B1 eggs from back crosses between the heterogeneous F1 adult females and the parental resistant Haibara-R adult males, SR $\varnothing$ $\times$ R σ and RS $\varnothing$ $\times$ R σ , are shown in Figs. 1 and 2, respectively. The B1 eggs consisted of SR+RR+S+R or RS+RR+R+S. There was no difference in susceptibility between each type of B1 eggs, and the plateau at 50% mortality was also observed.

DISCUSSION

From the experiments of reciprocal crosses between the Haibara-R and the Haibara-S strains of citrus red mite, *Panonychus citri* (MCGREGOR), the values of degrees of dominance (D) were estimated to be -0.40 and -0.59 for the heterogeneous female eggs, SR and RS, respectively (Table 1). Because the values were located between -1 and 0 , the inheritance of hexythiazox resistance seemed to be incompletely recessive.

If we assume that hexythiazox resistance is controlled by a single major gene according to the theory by Tsukamoto,³⁶⁾ the F2 eggs would be S and R at the ratio of 1:1, and the B1 eggs would be SR (or RS), RR, S and R at the ratio of 2:2:1:1 (in case of sex ratio, $\varnothing$: σ = 2:1¹⁹⁾). Therefore, the susceptibility of F2 male eggs and B1 eggs may be theoretically calculated as the average of the susceptibility of each genotype at the given ratio.

The susceptibilities of F2 eggs (Fig. 3) and B1 eggs (Figs. 1 and 2) were observed almost as expected by the above mentioned theory. In addition, because of the plateau at 50% mortality, in each type of F2 eggs (Fig. 3), susceptible and resistant eggs, S+R or R+S, appeared to be segregated at the ratio of 1:1. Also in each type of B1 eggs (Figs. 1 and 2), the eggs of heterogeneous female, resistant female, susceptible male and resistant male, SR+RR+S+R or RS+RR+R+S, appeared to exist at the expected ratio. The cytoplasm in the cell of one type of F2 eggs (S+R), which were laid by F1 female adults (SR) from the reciprocal cross SS $\varnothing$ $\times$ R σ , were considered to

be inherited from the Haibara-S (Fig. 3). On the contrary, the cytoplasm of another F2 eggs (R+S) seemed to be derived from the Haibara-R in the same manner. It was observed that there was a similarity in the susceptibility to hexythiazox between the different 2 types of F2 eggs, in spite of the different origin of cytoplasm. In the 2 types of B1 eggs (Figs. 1 and 2) including female eggs, which were SR and RR from the Haibara-S and RS and RR from the Haibara-R, similar results to the F2 male eggs were obtained. From this data, the resistance to hexythiazox in the both female and male eggs of the Haibara-R of citrus red mite was not likely to be controlled by the factors of cytoplasm, but nucleus, in the cell. From these results, the inheritance mode of hexythiazox resistance in the eggs of the Haibara-R of citrus red mite was suggested to be incompletely recessive determined by a single major gene.

Recently, the genetic analysis of hexythiazox resistance was reported in the two-spotted spider mite, *T. urticae* (Koch), from roses in Australia.¹⁵⁾ The inheritance mode of hexythiazox resistance in this species seemed to be incompletely dominant controlled by a single major gene. The result in the two-spotted spider mite did not agree with our result in the citrus red mite. It was considered that mechanisms involved in hexythiazox resistance would be possibly different between these species.

Determination of genetics of resistance is necessary for resistance risk assessments.⁹⁾ Therefore, the dominance of resistance has been studied in other miticides,¹⁰⁻³⁰⁾ and it varied with miticides, mite species and mite strains. For example, dominant and/or incompletely dominant inheritance mode of resistance was reported in the following miticides: amitraz (*P. citri*),¹⁹⁾ benzoxyamate (*P. citri*),²²⁾ binapacryl (*P. ulmi*),¹²⁾ chlordimeform (*T. kanzawai*),²¹⁾ dimeton (*T. urticae*),²⁴⁾ formethanate (*T. urticae*),¹³⁾ hexythiazox (*T. urticae*),¹⁵⁾ malathion (*T. urticae*),²⁹⁾ parathion (*T. pacificus*, *P. ulmi* and *T. urticae*),^{10,11,14)} phenthoate (*T. kanzawai*),²¹⁾ tetradifon (*P. ulmi* and *T. urticae*),^{13,24)} and vamidothion (*P. ulmi*).¹²⁾ In addition to hexythiazox resistance in *P. citri*, recessive and/or incompletely

recessive inheritance mode of resistance was reported in cyhexatin (*T. urticae* and *T. pacificus*),^{18,17)} DDT (*T. urticae*),²⁷⁾ dicofol (*P. citri*, *T. kanzawai*, *T. urticae*, *P. ulmi* and *T. telarius*),^{18,21,25,26,30)} dimeton (*T. urticae*),³⁰⁾ parathion (*T. urticae*)³⁰⁾ and propargite (*T. pacificus*).^{16,20)}

As previously reported,⁵⁾ in the field selection experiment with hexythiazox using Haibara strain of citrus red mite, the rate of resistance development was slow. The resistance developed after as many as 18 selections during 6 years. This slow development of resistance might be attributed to the following factors. There might be susceptible immigrants from untreated orchards and susceptible remains which escaped from selection treatments in the treated orchard. In the early stage of resistance, resistant individuals (RR, R) might mate mostly with susceptible ones (SS, S), resulting in emergence of heterogeneously resistant ones (SR, RS). The heterogeneous individuals are nearly as susceptible as susceptible ones to hexythiazox because of incompletely recessive resistance. Thus they could be killed as well as susceptible individuals by the selection treatments. In this manner, the few resistant gene would be effectively swamped out by susceptible immigrants and remains, therefore retarding resistance development. Tabashnik & Croft³⁷⁾ studied the influence of biological and operational factors on the rate of resistance development to pesticides using computer simulation. And they concluded that high immigration of susceptible individuals and functionally recessive resistance could retard resistance development.

In addition, reversion of hexythiazox resistance in the citrus red mite was observed under hexythiazox-free field conditions (Yamamoto *et al.*, unpublished data). The incompletely recessive mode of hexythiazox resistance might be considered as one of the causes of this reversion. Croft & Baan⁹⁾ also concluded that recessive resistance tends to be less stable in the field.

The genetic as well as biological and operational factors influencing resistance development may vary regionally and locally even in a same species and/or miticide.⁹⁾ Although

the possible geographical difference must be considered, the risk assessments of hexythiazox resistance on the inheritance mode of resistance before wide-scale field use would be a great help to managing hexythiazox resistance in the citrus red mite.

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要 約

ミカンハダニにおけるヘキシチアゾクス抵抗性の遺伝解析*

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静岡県榛原郡榛原町の柑橘園から採集し, ヘキシチアゾクスで室内淘汰を繰り返したミカンハダニ (*Panonychus citri* MCGREGOR) における, ヘキシチアゾクス抵抗性の遺伝様式を分析した。LC₅₀ 値がそれぞれ 0.462 ppm と 8000 ppm 以上の感受性系統 (Haibara-S) と抵抗性系統 (Haibara-R) との正逆交配および戻し交配の結果から, 卵におけるヘキシチアゾクス抵抗性は, 不完全劣性の単一主働遺伝子に支配されていると推定された。ヘテロ接合体をもつ卵の優性度 (*D*) は, -0.40 (SR) および -0.59 (RS) と計算された。

* 植食性ハダニ類のヘキシチアゾクス抵抗性に関する研究 (第3報)