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An oppositely charged insect exclusion screen with gap-free multiple electric fields

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An electric field screen was constructed to examine insect attraction mechanisms in multiple electric fields generated inside the screen. The screen consisted of two parallel insulated conductor wires (ICWs) charged with equal but opposite voltages and two separate grounded nets connected to each other and placed on each side of the ICW layer. Insects released inside the fields were charged either positively or negatively as a result of electricity flow from or to the insect, respectively. The force generated between the charged insects and opposite ICW charges was sufficient to capture all insects. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4767635]

The single-charged dipolar screens have been used to exclude pathogens and pests from plant cultivation,[1] storage, and processing areas,[2] thus reducing the use of agrochemicals such as fungicides and insecticides. The screens have three components: insulated conductor iron wires (ICWs) in parallel arrays, two grounded stainless steel nets on both sides of the ICW layer, and an electrostatic direct current (DC) voltage generator that supplies a charge to the ICWs. The ICWs are connected to each other and a voltage generator, and are negatively charged to dielectrically positively polarize a cover insulator on the surface of the iron wire side and negatively on the outer surface of the insulator sleeve. The negative surface charges of the ICWs polarize the grounded nets, creating a positive charge on the surface of the ICW-side of the nets. The opposite charges act as dipoles that form an electric field between the ICW layer and grounded nets. Insects entering the electric field are attracted to the ICW. A negative charge released from the insects to the grounded net is detected immediately after they enter the electric field. We postulated that the strong attraction between the insects and ICW was a result of this release.

Successful insect capture depends on the formation of an electrostatic barrier with no spaces through which the insects can pass. However, parallel ICWs with negative charges create a static electric field with no electricity transfers between the ICWs or insects, which is ineffective at attracting insects to enter the field. In a survey of screens installed on greenhouse windows, we observed that insects rarely entered this static electric field. Therefore, we constructed an electric field screen with oppositely charged ICWs of equal voltages using two voltage generators. This paper describes the successful formation of gap-free electric fields with no spaces for insect escape.

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Figure 1(a) shows a simplified version of the oppositely charged electric field screen examined for insect capture in all of the electric fields. An iron wire (30 cm length, 2 mm diameter) was passed through a vinyl chloride sleeve (1 mm thick; resistance $1.5 \times 10^9\ \Omega$) to make an ICW. The upper and lower ICWs were parallel and linked to negative and positive voltage generators (Max-electronics, Japan), respectively. Two grounded stainless steel nets (1.5 mm mesh, $3.0 \times 30\ \text{cm}^2$) were placed 3 mm from each side of the ICW layer. The ICWs were electrified with equal negative and positive voltages, represented as ICW(–) and ICW(+), respectively. Figure 1(b) is a cross-section view of the screen that shows the electric fields, with A1 and A2 between ICW(–) and the grounded nets, B1 and B2 between ICW(+) and the nets, and C between ICW(–) and ICW(+).

Adult common fruit flies, *Drosophila melanogaster* (Drosophilidae), were used as test insects. The fruit flies were reared following the method described by Matsude *et al.*[1] and newly emerging adults, 15–24 h after eclosion, were used as active flies for the experiments. To collect insects, we constructed an insect aspirator consisting of a polypropylene tube (10 mm diameter) with a pointed tip (1 mm tip diameter). The opposite open end of the tube was linked to an aspirator (aspiration pressure 1.2 kg/cm^2). The insect was attracted to the pointed tip and released near the net in fields A and B and near ICW(–) or ICW(+) in field C by stopping aspiration. Experiments were conducted at 25.0–25.3 °C and 45%–50% relative humidity.

In the first experiment, we determined the range of voltages that captured all insects that were transferred inside the screen (Table I). Voltages from 1.0–8.0 kV were tested. Insect attraction was detected at >2.0 kV. In fields A and B, the insects were attracted to ICW(–) and ICW(+), respectively, regardless of the release position (arrows a and b in Fig. 2(a)). From 2.0–5.2 kV, the force of the ICWs was insufficient to

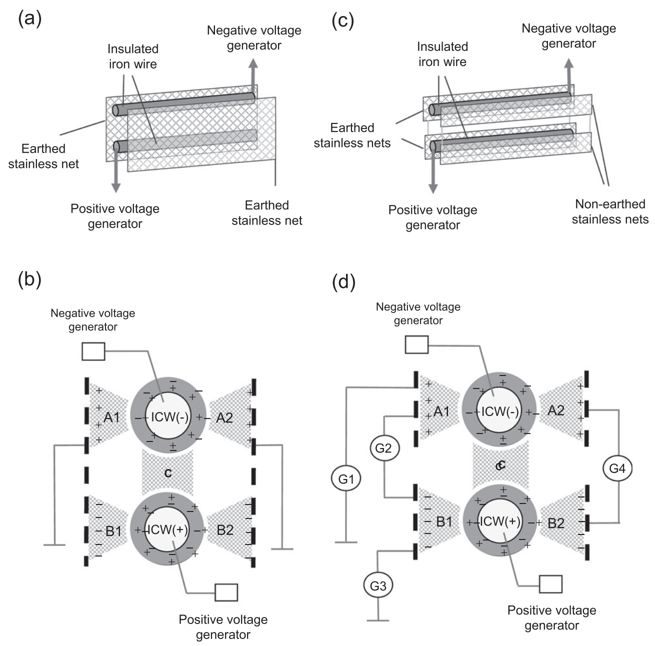

FIG. 1. Diagrams and cross-section views of an oppositely charged electric field screen ((a) and (b)) and the modified version ((c) and (d)). The electric fields (A1, A2, B1, B2, and C) formed are shown in (b) and (d). ICW(–) and ICW(+) represent the insulated conductor iron wire charged with equal negative or positive voltages, respectively. G1–G4 represent galvanometers.

restrain the attracted insects, thus allowing escape. At >5.3 kV, all insects were strongly attracted to ICW(–) or ICW(+) and could not move from the ICWs (supplementary videos 1 and 2). The mode of attraction differed in field C. At lower voltages of 2.0–5.2 kV, the insects released near ICW(–) were attracted to ICW(–) (arrow c in Fig. 2(a)), while the insects near ICW(+) were attracted to ICW(+) (arrow d in Fig. 2(a)). The attraction force of either ICW was insufficient to restrain the attracted insects. At >5.3 kV, the insects released near ICW(–) were attracted to ICW(–) (supplementary video 3), whereas the insects near ICW(+) were first attracted to ICW(+) and then to ICW(–) (arrow e in Fig. 2(a)). The length of time they stayed on ICW(–) decreased as the voltage increased, and was 3-8 s at 5.8 kV (supplementary video 4) and <1 s at 8 kV (supplementary video 5). In this voltage range, the attraction was sufficient to prevent the insects from escaping ICW(–). There were no significant differences among the ratios of insects attracted to ICWs and insects removed from ICWs (after being attracted) in the different electric fields (A, B, and C) at the various applied voltages. The experiment demonstrated that an oppositely charged electric field screen successfully created a gap-free electrostatic barrier that trapped insects.

Next, the mechanism of insect attraction to the screen was clarified. Based on the results, we hypothesized that the attraction was the consequence of three successive events in the insects: (1) polarization in the electric field, (2) positive or negative charging, and (3) attraction toward the ICW. The first issue was identifying a polarization site in the insects. Studies have reported that the cuticle, which is the outer protective layer that covers the body of many invertebrates, is efficiently charged because of its high conductivity.[3–7] We postulated that the cuticle structure was a potential site for polarization in the adult fruit flies studied. Therefore, we focused on a mechanism that would provide a positive or negative charge to the insects.

For these tests, we used a modified electric field screen (Fig. 1(c)). In this screen, the nets on each side were separated and linked to each other by a wire. The nets on one side were linked separately to a grounded line. Figure 1(d) shows the galvanometer (detection limit, 0.1 μA; PC520M, Sanwa Electric Instrument, Japan) arrangement to determine the direction and magnitude of the electric current. Four galvanometers were integrated in two lines between the nets on both sides and two grounded lines on one side. The experiment was conducted at 5.3 kV. First, we confirmed that insect attraction occurred similarly in all fields. The results suggested that the insects were charged positively in field A and negatively in field B and drawn to the oppositely charged pole. The electricity transfer to or from the insect likely caused electrification in the insects. Moreover, we

TABLE I. Attraction of *D. melanogaster* adults released into the electric field of a doubly charged dipolar screen.

Fields of insect entrance	Points of insect release	Attraction to ICWs	% insects[a]													
			1		2		4		5		5.3		5.8		8[b]	
			Attracted	Removed	Attracted	Removed	Attracted	Removed	Attracted	Removed	Attracted	Removed	Attracted	Removed	Attracted	Removed[c]
A1	not defined	ICW(-)	0	-[d]	79.0 ± 7.4 v	100	97.0 ± 4.5 w	11.5 ± 6.4 y	100	1.0 ± 2.2 z	100	0	100	0	100	0
A2	not defined	ICW(-)	0	-	80.0 ± 10.0 v	100	98.0 ± 2.7 w	9.2 ± 2.4 y	100	1.0 ± 2.2 z	100	0	100	0	100	0
B1	not defined	ICW(+)	0	-	80.0 ± 10.0 v	100	97.0 ± 4.5 w	10.5 ± 7.0 y	100	1.0 ± 2.2 z	100	0	100	0	100	0
B2	not defined	ICW(+)	0	-	81.0 ± 8.9 v	100	96.0 ± 6.5 w	11.9 ± 7.9 y	100	2.0 ± 2.7 z	100	0	100	0	100	0
C	near ICW(-)	ICW(-)	0	-	83.0 ± 5.7 v	100	99.0 ± 2.2 w	9.1 ± 4.2 y	100	2.0 ± 2.7 z	100	0	100	0	100	0
	near ICW(+)	ICW(+)	0	-	78.0 ± 5.7 v	100	99.0 ± 2.2 w	11.1 ± 4.1 y	100	2.0 ± 2.7 z	0	-	0	-	0	-
		ICW(+) → (-)[e]	0	-	0	-	0	-	0	-	100	0	100	0	100	0

[a] Twenty adults were used for each field and applied voltage, and means and standard deviations were calculated from the data provided by five replications. The different letters on the mean values indicate significant differences ($p<0.05$) according to Tukey's method.

[b] Voltages applied to ICW(-) and ICW(+).

[c] Percentages of insects removed from ICWs after attraction.

[d] No occurence.

[e] Arrow means subsequent attraction of ICW(+)-attracted insects to ICW(-).

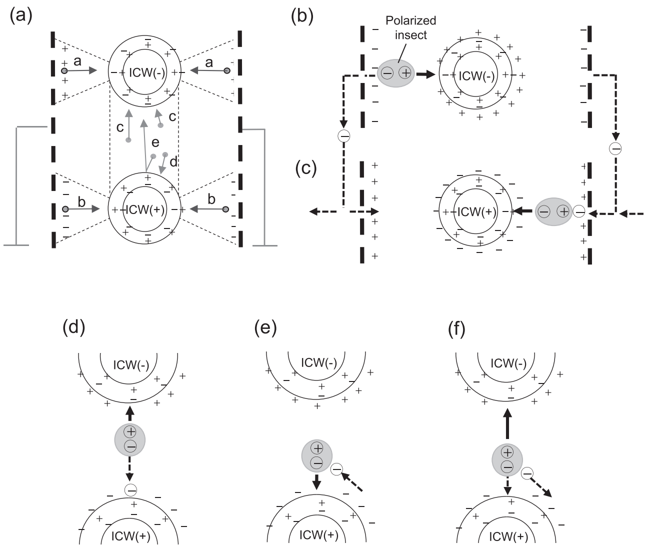

FIG. 2. A schematic diagram of insect attraction in the electric fields formed in the oppositely charged electric field screen. (a) The points of insect release (dots) and directions of insect attraction (solid arrows) in the fields. (b-f) Positive ions and free electron localization around the ICWs and along the nets. Solid and dotted arrows represent insect attraction and electricity transfer directions, respectively. (b and d) Electricity removal from an insect polarized in field A or C, causing the positively charged insect to be drawn to ICW(–). (c and e) Free electron addition to an insect polarized in field B or C, causing the negatively charged insect to be drawn to ICW(+). (f) Deprival of intrinsic and added electricity from the insect to charge it positively, by which the insects initially attracted to ICW(+) were drawn to ICW(–) (enhanced online). [URL: http://dx.doi.org/10.1063/1.4767635.1] [URL: http://dx.doi.org/10.1063/1.4767635.2] [URL: http://dx.doi.org/10.1063/1.4767635.3] [URL: http://dx.doi.org/10.1063/1.4767635.4] [URL: http://dx.doi.org/10.1063/1.4767635.5]

successfully monitored the electricity transfer from and to the insect in fields A and B, respectively.

When an insect was released in A1, the current was recorded in galvanometer G1, indicating that the insect electricity flowed toward the ground through the grounded line. In A2, the insect electricity was transferred to B2 through the line connecting the nets. The short current occurred immediately after insect release, but before attraction. The recorded currents in both cases were very close: $0.14 \pm 0.041\,\mu$A (average $\pm$ SD of insects in all fields, n = 10 per field) in A1 and $0.12 \pm 0.042\,\mu$A in A2. Moreover, the magnitude increased additively when multiple insects were released simultaneously in a field: $0.21 \pm 0.052\,\mu$A when two insects were released simultaneously and $0.32 \pm 0.067\,\mu$A for three. These results supported our hypothesis of insect attraction based on their positive charge (Fig. 2(b)). The negative charge of the cuticle shifted towards the grounded-net-side of the insect because the ICW-side surface of the grounded net was oppositely charged.[2] The insects polarized positively on the ICW side and negatively on the net side of the cuticle. Subsequently, the negative charge on the grounded-side of the cuticle transferred to the grounded net and then to the ground or field B and the adults became net positively charged. Attraction was then generated between the positive insect and negative ICW.

Releasing an insect in field B caused electricity to transfer from field A to the insect. When the insect was released in B1, the electricity moved to B1 from A1, but not from the ground. However, electricity came from the ground when the connecting line between the nets was removed. The recorded current magnitudes were the same ($0.14 \pm 0.032\,\mu$A) as those of when the insects were released in field A. The insects in field B were likely polarized and electrified with electricity from field A or the ground (Fig. 2(c)). The insects became net negative. Similarly, attraction was generated between the negative insect and positive ICW.

The results suggested that removed or added electricity was essential to attract insects to fields A and B of the electric field screen. Finally, the origin of the electricity transferred to the insect in field B was studied. Charged dipoles cause atmospheric ionization to create a distinct distribution of positive ions around the negative pole and free electrons around the positive pole.[8] In the screen, we hypothesized that positive ions gathered around ICW(–) and free electrons from the nets in field A, while free electrons accumulated near ICW(+) and positive ions along the net in field B (Figs. 2(b) and 2(c)). The free electrons by the net could potentially charge the insects negatively.

Furthermore, this hypothesis explained the movements of insects released in field C. The insects were deprived of a negative charge and became net positive, leading to direct attraction to ICW(–) (Fig. 2(d)). By contrast, the insects released near ICW(+) were charged with free electrons localized around ICW(+), becoming net negative and drawn toward ICW(+) (Fig. 2(e)). The higher voltages were sufficient to push electricity out of the insect that had been attracted to ICW(+). These insects became net positive, and were drawn to ICW(–) (Fig. 2(f)).

An oppositely charged electric field screen, which is an electrostatic device that could exclude pest insects from facilities such as greenhouses, crop warehouses, and fruit and vegetable processing factories, was constructed to examine the mechanisms of attraction of insects that invaded the screen. The screen consisted of two parallel insulated conductor wires (ICWs) charged oppositely with equal voltages and two separate grounded nets linked to each other and placed on each side of the ICW layer. Electric fields formed between the following: (1) ICW(–) and the grounded nets, (2) ICW(+) and the nets, and (3) ICW(–) and ICW(+). Insects released inside the fields were charged as a result of removing or adding electricity from or to the insect, respectively. Attraction was generated between the charged insects and opposite charges of the ICWs. A charge greater than 5.3 kV was sufficient to capture all insects. Therefore, the screen generated multiple electric fields to trap insects without spaces through which they could pass.

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