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RESEARCH ARTICLE

Influence of UV-A radiation on oxidative stress and antioxidant enzymes in *Mythimna separata* (Lepidoptera: Noctuidae)

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Abstract Abiotic stress factors, including ultraviolet (UV) radiation, significantly affect insect life. UV-A radiation (320–400 nm) has been widely used for insect control since it increases the production of ROS and causes oxidative cell damage. In the present study, we evaluated the effects of UV-A irradiation on an important pest in China, the ear-cutting caterpillar, *Mythimna separata* (Lepidoptera: Noctuidae). We exposed 3-day-old *M. separata* adults to UV-A radiation for different periods of time (0, 30, 60, 90, and 120 min) and evaluated the resulting total antioxidant capacity and the activity of the antioxidant enzymes superoxide dismutase, catalase, peroxidase, and glutathione-S-transferase. The total antioxidant capacity significantly increased after exposure to UV-A radiation for 60 min but decreased after 90 and 120 min of exposure, compared with the control. The antioxidant activity of glutathione-S-transferase, superoxide dismutase, catalase, and peroxidase increased after 60-min exposure, and it was decreased at the longest exposure period 120 min. The longest exposure time period relatively activates the xenobiotic detoxifying enzymes like glutathione-S-transferase, superoxide dismutase, catalase, and peroxidase enzymes. The longest duration of UV-A radiation may cooperate with pesticide detoxification mechanism in insects, making them more susceptible to insecticides. Our results demonstrated that UV irradiation causes oxidative stress, affects the activity of antioxidant enzymes, and disturbs the physiology of *M. separata* adults.

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Introduction

Abiotic stress factors, including ultraviolet (UV) radiation, significantly affect insect life because they increase the production and accumulation of reactive oxygen species (ROS). These free radicals of oxygen increase cell antioxidant capacity and oxidant production. At very low levels, they are not deleterious and play vital roles in cell signaling and defense (Kamata and Hirata 1999; Wang et al. 2001; Lijun et al. 2005). However, at higher levels, they are harmful to DNA and proteins. Other free radicals, superoxide (O_2^-) and hydrogen peroxide (H_2O_2), are byproducts of cell metabolism that react indiscriminately with any molecule with which they come in contact, including proteins, membrane lipids, carbohydrates, nucleic acids, and other cellular components. These reactions lead to various cytotoxic effects and complications in chronic diseases (Cao et al. 2007; Graves et al. 2009; Zhao et al. 2013). Like other eukaryotes, insects have evolved a complex enzymatic and non-enzymatic defense system to combat oxidative stress. Antioxidant enzymes mitigate damage to DNA and proteins and also regulate the lipid peroxidation level (Felton and Summers 1995). The main antioxidant enzymes in insects are superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX) (Felton and Summers 1995; Wang et al. 2001). SOD catalyzes the dismutation of superoxide radical into oxygen and H_2O_2, whereas both CAT and POX catalyze the dismutation of H_2O_2 into oxygen and water. Another important enzyme, glutathione-S-transferase (GST), eliminates lipid peroxidation products or hydroperoxides from the cells (Ahmad et al. 1991; Dubovskiy et al. 2008). UV-A (320–400 nm) has been used broadly in integrated pest

management to monitor and control Lepidoptera (Antignus 2000; Kojima et al. 2005). UV radiation directly affects insect behavior, biochemistry, and developmental physiology (Gunn 1998; Mackerness et al. 1999; Mazza et al. 2002) as it significantly increases oxidative stress. The effects of UV-A radiation on cell biochemistry, adult longevity, and reproduction have been studied in various insect species, including cotton bollworm (*Helicoverpa armigera* [Hubner 1805]), red flour beetle (*Tribolium castaneum* [Herbst 1797]) (Meng et al. 2009, 2010; Zhang et al. 2011 Sang et al. 2012), cricket (*Gryllus bimaculatus*) (Meyer-Rochow et al. 2002), and the butterfly species *Papilio xuthus* (L.) and *Pieris napi* (L.). Currently, it was found that UV-A radiation has effected on the biology of *M. separata* (Ali et al. 2016).

The ear-cutting caterpillar *Mythimna separata* (Walk.) (Lepidoptera: Noctuidae) is an important pest in China and neighboring countries. It severely damages more than 104 different plant species, including millet, wheat, rice, and corn (Zou 1956; Kuang-po et al. 1964; Ruilo and Ziangshi 1987; Chen et al. 1995; Chen and Hu 2000; Wang et al. 2006). Therefore, its control and management are of great socioeconomic importance. So, on the bases of previous finding "UV-A effect on lifespan, reproduction and the developmental stages *of M. separate*." In the present study, we attempted to investigate what sort of physiological responses to UV-A particularly the evaluation of total antioxidant capacity (T-AOC) and antioxidant activity of four antioxidant enzymes (CAT, SOD, POX, and GST) in *M. separata* adults was done.

Materials and methods

Insects

Insects were collected for the experiment from insect Resources Utilization and Sustainable Pest Management Key Laboratory, Huazhong Agricultural University, Wuhan, China. *M. separata* were reared at room temperature 26 ± 2 °C, with 60 ± 10% RH and 14:10 h L:D. Larvae were fed an artificial diet as described (Chun 1981). Three-day old adults were selected and placed in 100-ml plastic containers with 10% honey solution.

UV irradiation

Adults were divided into five equal groups, each group contained 15 adults and placed in the dark for 2 h. From each treatment, five adults were selected and exposed to UV-A radiation (peak emission 365 nm; irradiance of 350 μW cm^{-2}; Spectronics, Westbury, NY, USA) for 0 (control), 30, 60, 90, and 120 min. Each treatment was repeated in triplicate. After exposure, the individuals were immediately frozen in liquid nitrogen and stored at −80 °C until analysis.

Enzyme extraction

A commercially available assay kits from (Nanjing Jiancheng Bioengineering Institute, China) was used for enzyme extraction. All procedures were followed as the kit manufacturer gave the instructions. Samples were homogenized in 0.9% saline solution with a ratio of 1:9 (W_{flies}:$V_{normal\ saline}$). The homogenate was centrifuged at 10,000*g* for 15 min at 4 °C. After centrifugation, the supernatant was used for further analysis. The method was used to calculate the protein (enzyme) concentration (Bradford 1976).

Measurement of total antioxidant capacity

According to manufacturer's instructions T-AOC, A015 was measured by using an available assay kit (Nanjing Jiancheng Bioengineering Institute). It is based on the ability to reduce ferric iron in a pool of antioxidant substances present in the supernatant. The antioxidant reacts as a reductant redox-linked colorimetric reaction in this assay. A relatively stable complex formed between Fe^{2+} and porphyrin at 520 nm. The amount of protein to lift the absorbance by 0.01 nm min^{-1} mg^{-1} protein was characterized as one unit of T-AOC.

The antioxidant enzyme activities determination

The spectrophotometer was used to determine the activities of enzymes (SOD: A001-3, CAT: A007-1, POX: A084-1, and GST: A005) by using available assay kits (Nanjing Jiancheng Bioengineering Institute), in accord with the instructions of the manufacturer protocols.

The SOD activity was resolved spectrophotometrically at 450 nm by utilization of xanthine and xanthine oxidase frameworks (Marklund and Marklund 1974). One unit of SOD action was characterized as the measure of enzyme required to bring about half hindrance of the xanthine and xanthine oxidase system reaction in 1 mg ml^{-1} protein extraction. SOD activity was communicated as unit per milligram protein.

The CAT activity was directed by measuring the abatement in absorbance at 240 nm because of decomposition of H_2O_2 (Luck 1971). One unit of CAT development was described as the whole that breaks down H_2O_2 every second per gram protein. CAT activity was imparted as unit per gram protein.

The POX activity was measured spectrophotometrically at 420 nm by the activation of oxidation in the H_2O_2 presence (Reddy et al. 1985). One unit of POX activity was characterized as the sum that catalyzes 1 μg substrate per minute per milligram of protein. POX activity was expressed as unit per milligram protein.

The GST activity was resolved to utilize 1-chloro-2, 4-dinitrobenzene (CDNB) as a substrate. (Habig et al. 1974). The development of GSH–CDNB conjugate was observed by the adjustment in absorbance at 412 nm was used as a

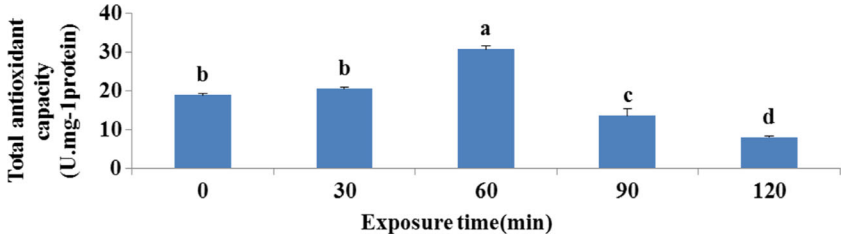

Fig. 1 Changes in the total antioxidant capacity of *Mythimna separata* adults after 0, 30, 60, 90, and 120 min of exposure to ultraviolet (UV-A) radiation. Data are presented as means (±SE) of the replicate experiments. *Letter above bars* indicate significant differences ($P < 0.05$) determined by ANOVA with Tukey's post test

substrate to determine the activity of GST. One unit of GST activity was defined as the amount that catalyzes the conjugation of 1 μmol l^{-1} GSH with CDNB per minute per milligram of protein. GST activity was expressed as unit per milligram protein.

Statistical analysis

Data analyses were performed by SPSS 16.0 (SPSS Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) is conjunction with Tukey's post test was used to determine significant difference at $p < 0.05$.

Results

Total antioxidant capacity

No significant changes were observed in the T-AOC of *M. separata* adults after exposure to UV-A radiation for 30 min, but a significant increase ($p < 0.05$) was noted after 60 min of exposure, whereas a significant decrease occurred after 90 and 120 min of exposure compared with the control (Fig. 1).

Activity of antioxidant enzymes

No significant changes were found in the activity of SOD in *M. separata* adults after exposure to UV-A radiation for 30 and 90 min. A significant increase ($p < 0.05$) was observed in SOD activity after 60 min while a significant decrease was seen at 120 min as compare to the control group as shown in (Fig. 2).

The activity of CAT in *M. separata* adults did not change after 30-min exposure to UV-A radiation. However, a significant increase ($p < 0.05$) was seen in the activity of CAT after 60 min of exposure. A significant decrease was observed in the activity of CAT after 90 and 120 min of exposure as compare to the control group (Fig. 3).

The activity of POX in *M. separata* did not show any difference among the controls, 30 and 90 min of exposure. A marked ($p < 0.05$) elevation was observed at 60-min exposure. However, a significant decrease was observed in enzyme activity after 120 min as compare to the control group (Fig. 4).

No changes were found in the activity of GST between control and 30 min of UV-A radiation exposure. A significant increase ($p < 0.05$) was observed in the activity of GST after 60 and 90 min of exposure, and a significant decrease was observed in the activity of GST after 120 min of exposure, compared with the control (Fig. 5).

Discussion

Solar UV radiation has three main components, UV-A, UV-B, and UV-C. Usually, UV-C is fully obstructed by the ozone layer, whereas both UV-A and UV-B have the capacity to reach the Earth's surface (Karentz 1994; Cockell 2001; Franco et al. 2009; Dahms and Lee 2010). UV radiation is usually considered a resilient ecological stress factor for living organisms (Urbach 1989; Schauen et al. 2007). It can cause

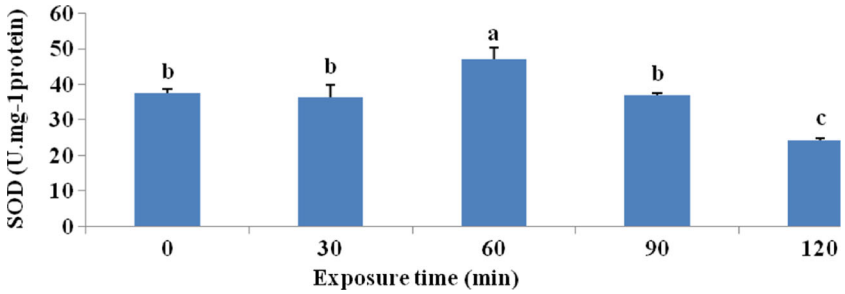

Fig. 2 Changes in the activity of superoxide dismutase (SOD) in *Mythimna separata* adults after 0, 30, 60, 90, and 120 min of exposure to ultraviolet (UV-A) radiation. Data are presented as means (±SE) of the replicate experiments. *Letter above bars* indicate significant differences ($P < 0.05$) determined by ANOVA with Tukey's post test

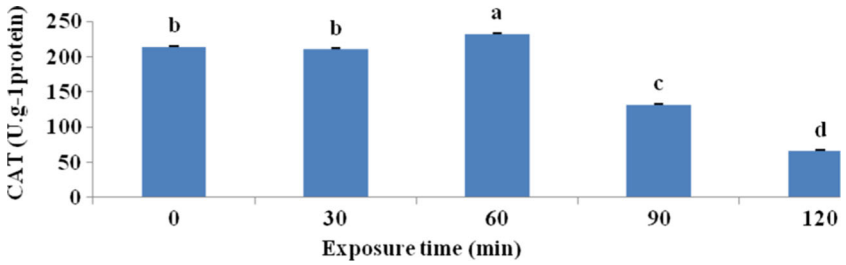

Fig. 3 Changes in the activity of catalase (CAT) in *Mythimna separata* adults after 0, 30, 60, 90, and 120 min of exposure to ultraviolet (UV-A) radiation. Data are presented as means (±SE) of the replicate experiments. *Letter above bars* indicate significant differences ($P < 0.05$) determined by ANOVA with Tukey's post test

damage to nucleic acids, membrane fatty acids, and amino acids (Jurkiewicz and Buettner 1994; Vile and Tyrrell 1995), leading to cell toxicity, genetic changes, and modifications in cell signaling pathways (McMillan et al. 2008). The absorption of weak UV radiation below 320 nm by nucleic acid bases can generate ROS due to photo-oxidation reactions produced by endogenous photosensitizers (Ravanat et al. 2001; Cadet et al. 2005).

T-AOC has been widely used as a tool to assess redox status in various organisms (Ghiselli et al. 2000; Meng et al. 2009; Sashidhara et al. 2011). Our results showed that the exposure of *M. separata* adults to UV-A radiation for 60 min significantly increased T-AOC compared with the control, revealing that the insects could effectively manage the oxidative stress and free radicals associated with this exposure. However, longer exposure periods of 90 or 120 min decreased their ability to defend against ROS (Meng et al. 2009). The antioxidant system of organisms may be unable to remove significant amounts of ROS produced under harsh environmental conditions (Foyer et al. 1994).

A significant increase in the activity of antioxidant enzymes, such as SOD, CAT, POX, and GST is a sign of oxidative stress since these four defensive enzymes function cooperatively to handle the relatively by high amounts of ROS inside the cell (Foyer et al. 1994). The main role of SOD is the reduction of superoxide radicals in the cells produced by the stimulation of extracellular factors such as UV radiation. In the present study, the activity of SOD increased in *M. separata* adults after 60 min of exposure to UV-A radiation, revealing increased production of superoxide radicals. However, a longer exposure (120 min) significantly reduced the activity of SOD compared with the control, probably because the elevated amount of UV radiation inhibits the defensive antioxidant system of the cells, including the effective reduction of accumulated superoxide radicals by SOD (Heck et al. 2003; Polte and Tyrrell 2004). These results were in agreement with previous studies that also reported variations in SOD activity in response to the increased production of ROS (John et al. 2001; Krishnan and Kodrík 2006; Karthi et al. 2014).

CAT is a crucial element in the insect antioxidant system, and also, it is a light-sensitive antioxidant enzyme that is responsible for the catalysis of H_2O_2 to water and oxygen and is directly controlled by the amount of H_2O_2 in the cell (Fridovich 1978; Boldt and Scandalios 1995; Lesser 2006). The cooperative action of SOD and CAT for the stepwise reduction of oxygen has been studied (Munday and Winterbourn 1989; Sies 1991). Our results showed that the activity of CAT increased in *M. separata* adults after 60 min of exposure to UV-A light, revealing the increased activity of SOD. Longer exposures (90 or 120 min) to UV-A radiation caused a significant decrease in the activity of CAT. This finding agreed with results reported for the Oriental leafworm moth *Spodoptera litura* (Karthi et al. 2014). Previous studies reported a strong correlation between CAT gene expression and longevity in *Drosophila melanogaster* (Orr and Sohal 1994); decreased CAT activity or interruption of the CAT gene expression led to death after eclosion (Griswold et al.

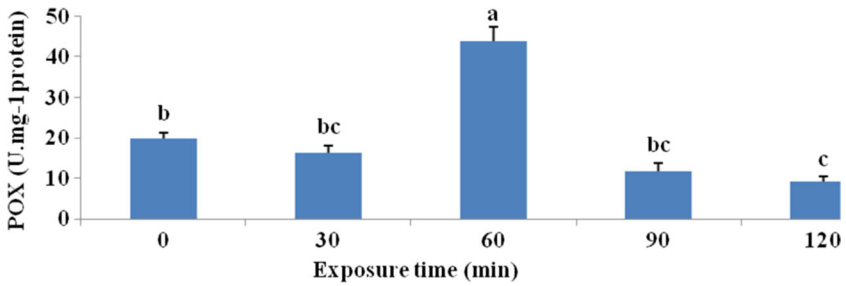

Fig. 4 Changes in the activity of peroxidase (POX) in *Mythimna separata* adults after 0, 30, 60, 90, and 120 min of exposure to ultraviolet (UV-A) radiation. Data are presented as means (±SE) of the replicate experiments. *Letter above bars* indicate significant differences ($P < 0.05$) determined by ANOVA with Tukey's post test

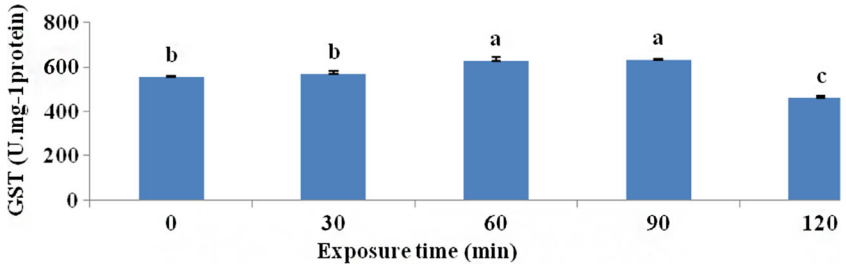

Fig. 5 Changes in the activity of glutathione-S-transferase (GST) in *Mythimna separata* adults after 0, 30, 60, 90, and 120 min of exposure to ultraviolet (UV-A) radiation. Data are presented as means (±SE) of the replicate experiments. *Letter above bars* indicate significant differences ($P < 0.05$) determined by ANOVA with Tukey's post test

1993; Orr and Sohal 1994). Therefore, the level of CAT may indicate oxidative stress in insects.

POX is also responsible for increasing stress tolerance in organisms (Clavaron-Mathews et al. 1997). The activity of POX in *M. separata* adults significantly increased after 60 min of exposure to UV-A radiation but decreased after 120 min of exposure, results that were in agreement with those reported in *H. armigera* (Meng et al. 2009). It is already known that negative feedback from an excess of substratum due to oxidative change can reduce the enzyme activity (Tabatabaie and Floyd 1994). We observed that the level of POX activity was lower than SOD, indicating that CAT may have a more important role in scavenging H_2O_2 than POX (Meng et al. 2009).

The GST plays a crucial role in the detoxification of broad spectrum of a toxic chemical that may provoke to mutagenic events and cytotoxicity (Coles et al. 1990; Hayes and Pulford 1995). Aside from the detoxification of the foreign compounds (pesticides and chemicals), there are various harmful endogenous compounds formed as a by-product of normal metabolism that is GST substrate. The aerobic respiration process can provoke the production of ROS (the superoxide anion O_2^-, hydrogen peroxide H_2O_2, and the hydroxal radical OH) (Finkel and Holbrook 2000). The production of the Reactive Oxygen Species (ROS) damages the membrane lipids which trigger the formation of lipid peroxidation products which can propagate a chain reaction in lipid peroxidation in an aerobic environment, which will ultimately end in membrane destruction (Slater 1984). So, GST is another important antioxidant enzyme in insects that effectively metabolizes lipid peroxides (Ahmad et al. 1991; Konno and Shishido 1992). In the present study, the activity of antioxidant enzymes (SOD, CAT, and POX) increased significantly only at 60 min. While the activity of GST increased significantly at both 60 and 90 min of UV-A radiation exposure, indicating that GST possibly has a greater role in the management of oxidative stress. It might be possible the ROS in *M. separata* due to UV-A radiation cause severe damage to membrane lipids that enhance the production of lipid peroxidation products, so GST effectively removed toxic lipid peroxidation for a longer duration (60 and 90) and protected the cells from potential oxidative damage. These results were in agreement with those reported in *H. armigera* (Meng et al. 2009). However, a longer exposure (120 min) decreased the activity of GST in *M. separata* adults, as in *S. litura* (Karthi et al. 2014).

Conclusion

The present study demonstrated that UV-A irradiation could cause oxidative stress in *M. separata* adults and disrupt the functional activity of antioxidant enzymes. A relatively short period of exposure (60 min) to UV-A radiation increased the activity of SOD, CAT, POX, and GST, which defend against oxidative damage due to the overproduction and accumulation of ROS. However, a longer exposure (90 and 120 min) reduced the T-AOC and antioxidant enzyme activity, leading to high levels of oxidative stress. UV-A radiation can cause irreversible oxidative damage to *M. separata* adults.

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