In vitro experiments of Pediculus humanus capitis (Phthiraptera: Pediculidae) resistance to permethrin and 6-paradol in East Jakarta: Detoxification enzyme activity and electron microscopic changes in lice

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Abstract

Background and Aim: Pediculus humanus capitis, the human head louse, remains a global health problem. This study evaluated the resistance of head lice to permethrin and 6-paradol mediated by in vitro detoxification enzyme activity experiments and to describe physical changes in the lice using scanning electron microscopy (SEM).

Materials and Methods: The adult stages of P. h. capitis were collected from patients exposed to 1% permethrin and three different concentrations of 6-paradol (0.00005%, 0.0001%, and 0.00015%) using a filter paper diffusion bioassay. Healthy P. h. capitis adults were served as the control. The in vitro bioassays were conducted after 10, 20, 30, and 60 min of exposure. The activities of acetylcholinesterase (AChE), glutathione S-transferase (GST), and oxidase were analyzed. Physical changes in the lice were analyzed using SEM.

Results: Permethrin and 6-paradol exhibited low toxicity against the lice. At 60 min, 1% permethrin had killed 36.7% of the lice present, while 6-paradol had killed 66.7-86.7%. Permethrin induced significantly elevated AChE, GST, and oxidase activity; 6-paradol also caused significantly elevated AChE, GST, and oxidase activity. Permethrin did not cause any ultrastructural morphological changes on the lice, while 6-paradol severely damaged the head, thorax, respiratory spiracles, and abdomen of the dead lice.

Conclusion: This in vitro experimental of P. h. capitis is the first study to report P. h. capitis in East Jakarta shows complete resistance to permethrin and 6-paradol, and to describe the associated increase in AChE, GST, and oxidase activity. It was observed that 6-paradol severely damaged the head, thorax, respiratory spiracles, and abdomen of the dead lice.

Keywords: 6-paradol, detoxifying enzyme, electron microscopy, Pediculus humanus capitis, permethrin, resistance.

Introduction

Pediculus is the infestation of the head with hematophagous lice Pediculus humanus capitis De Geer (Phthiraptera: Pediculidae), an obligate ectoparasite [1-3]. Pediculus remains a global health problem and commonly affects children between 6 and 12 years of age [4,5]. The previous study has reported that the prevalence rates of pediculosis ranged from 13.3 to 49% in children aged 6-13 years in rural areas [1]. In Turkey, the prevalence range in children aged 6-11 years was 3.96-27.2%, and the infestation rate among girls was 3.4 times higher than that among boys [6]. The prevalence rates have been shown to be 67.3% in primary school girls in a low-income area in the southeast of Iran [7], 49% in children between the ages of ten and 12 in Malaysia [8], and 83% in rural populations in Mali [9]. Many negative effects of pediculosis have been reported, including social embarrassment, isolation, parental anxiety, peer criticism, and difficulty for school authorities [2,5]. Therefore, pediculosis has drawn the attention of researchers. Some have studied the biological aspects of lice concerning resistance to commonly used pediculicides [2,10].

The primary treatment for head lice involves the use of topical chemical drugs, which include a wide variety of neurotoxic synthetic insecticides, such as dichloro diphenyl trichloroethane (DDT), lindane, malathion, carbaryl, permethrin (1%), and d-phenothrin [10,11]. However, these pediculicial agents’ frequent and
intensive use has caused lice to develop resistance to the drugs. In addition, multiple treatments for pediculosis, including overdoses, raise serious human health concerns [4]. A previous study [10] reported that pediculicide-resistant human lice corresponded to voltage-gated sodium channel (VGSC) α-subunit gene known as knockdown resistance (kdr), allowing pediculicides to kill the lice more slowly. These kdr mutations induce insensitivity of the nervous systems of insects to pediculicides, such as DDT, organophosphates, and pyrethroids. Three kdr-type point mutations, MB15I, T917I, and L920F, have been found in permethrin- and DDT-resistant human lice [1,10].

Hodgdon et al. [12] reported that kdr-type point mutations are found worldwide. Uruguay, the UK, and Australia exhibited kdr allele frequencies of 100%, while the USA, Argentina, Brazil, Denmark, the Czech Republic, Egypt, and Israel exhibited kdr allele frequencies between 11% and 97%. Regarding primary school children in Thailand, kdr T9171 and L920F point mutations were discovered in permethrin-resistant head lice [13]. In Honduras [14], Chile [15], and Madagascar [16], the T9171 kdr allele was found in head lice resistant to pyrethroid insecticides. However, in Senegal, it has been reported that the presence of a point mutation of GhCl is associated with ivermectin-resistant head lice [17]. In Iran, six novel point mutations, namely, H813P (located in IIS1-2 extracellular loop), I927F, L928A, R929V, L930M, and L932M (located in IIS5) in the VGSC α-subunit gene were found in head lice resistant to pyrethroid insecticides [18]. In Mexico, a new point mutation, T929I, was found in head lice resistant to insecticides, especially pyrethroids [19]. These kdr-type point mutations are induced by frequent and inadequate doses of pediculicidal agents, rendering alternative topical drugs necessary to treat these resistant human lice [1].

The resistant human lice mechanisms are associated with kdr-type mutations and with metabolic detoxifying enzyme systems, such as monoxygenases, esterases, and glutathione S-transferases (GST) [20]. Hemingway et al. [21] demonstrated increased GST and monoxygenase activity in head lice from Israeli associated with resistance to DDT and permethrin. Brogdon [22] showed that individually resistant insects were associated with elevated detoxifying enzyme activity. These detoxifying enzyme systems are involved in permethrin-resistant lice mechanism, so that the lice survive under the pressures of pediculicidal agents.

So far, no studies have analyzed the resistance of human lice to permethrin in Jakarta, Indonesia’s capital city. Therefore, this study examined human lice from crowded urban areas in East Jakarta. The study focused on detecting the resistance of human lice to permethrin (1%) using in vitro experiments to select effective management strategies [10,12]. The mechanism of permethrin-resistant lice was examined concerning the detoxifying enzymes acetylcholinesterase (AChE), GST, and oxidase. Furthermore, scanning electron microscopy (SEM) was used to examine physical changes in the lice after in vitro treatment with permethrin compared with 6-paradol. For permethrin-resistant lice, this study used 6-paradol [(4-hydroxy-methoxyphenyl)-3decen-one], a bioactive plant compound, to investigate the similar mechanisms of 6-paradol associated with detoxifying enzyme systems to kill lice in an in vitro setting. This study used 6-paradol because human lice develop resistance to chemical pediculicides, such as DDT, malathion, carbaryl, and lindane [1,10]. To the best of our knowledge, this is the first in vitro study to evaluate the resistance of human head lice from East Jakarta to permethrin and 6-paradol mediated by metabolic enzyme systems and to describe any changes in the lice as seen by SEM.

The compound 6-paradol is derived from 6-shogaol [(4-hydroxy-methoxyphenyl)-4decen-one] through a biotransformation process [23,24]. The 6-shogaol comes from Zingiber officinale Roscoe (ginger), Zingiberaceae family. Pharmacologically, 6-shogaol and 6-paradol exhibit neuroprotective effects in a mouse model of multiple sclerosis; they exerted anti-neuroinflammatory and anti-oxidative activity in the central nervous system [25].

In addition, 6-paradol of *Z. officinale* origin has many target sites of detoxifying enzyme systems; therefore, this study aimed to evaluate the resistance of head lice to permethrin and 6-paradol mediated by in vitro detoxification enzyme activity experiments and to describe physical changes in the lice using SEM.

**Materials and Methods**

**Ethical approval**

The study has passed the ethical approval of the Research Module Management Team of The Medical Faculty, University of Indonesia, Indonesia (KET-019/UN2.F1.DI.2/PDP.01/Riset-2/2021).

**Study period and location**

The study was conducted from January 2020 to February 2021. The study site was Jln. Kayu Manis VII RT 08 RW 07, Kayu Manis Subdistrict, Matraman District, East Jakarta (Figure-1). The samples were processed at Laboartory of Department of Parasitology, Faculty of Medicine, University of Indonesia.

**6-paradol**

The 6-paradol (catalog number S5551) was purchased from the manufacturer, P.T.Beatrix Indonesia, Jakarta, Indonesia. All of the larval bioassays used a 0.0025% stock solution of 6-paradol. Dimethyl sulfoxide was used as a solvent to dissolve 6-paradol. A series of concentrations of 6-paradol was used (0.0005%, 0.0001%, and 0.00015%) in triplicate.

**1% permethrin**

PediTox lotion containing 1% permethrin (PT Comiphar, No. Reg. DTL. 13041329411, Jakarta,
Indonesia) was purchased in a local market in Central Jakarta, Indonesia.

**Collection of head lice**
This study used the common method to collect head lice as previously described [26,27]. Briefly, the adult head lice were obtained from a population of children between the ages of 10 and 12 in East Jakarta, Indonesia, with the approval of their guardians. Lice were collected using a clean plastic louse comb, and the lice were carefully removed from the plastic comb teeth. After combing, the lice were placed into plastic boxes [26]. The subjects had not been treated with any pediculicide solution for at least the preceding month. As per the methods reported by Jadhav et al. [28], the head lice used in this study were protected from sunlight and heat, and the *in vitro* test was initiated within 1 h after collection.

**Filter paper diffusion bioassay**
The filter paper diffusion method was used in this bioassay as previously described and modified [26,28]. One milliliter of the test sample (permethrin or 6-paradol) was distributed evenly over a filter paper (4.5-cm diameter) held in the lower half of the glass Petri dish (5-cm diameter). After 10 min, ten head lice were placed carefully on the filter paper with the test sample with the help of a “0” fine hairbrush. The study used three replications. The number of head lice used for the treatment with permethrin was 30, 6-paradol was 90 (30 head lice for a concentration of 0.00005%, 30 head lice for a concentration of 0.0001%, and 30 head lice for a concentration of 0.00015%), and control was 30. Hence, the total head lice were 150. The petri dish was covered with a lid during the test. Observations of dead-head lice (% mortality) were recorded at 10, 20, 30, and 60 min post introduction of lice on filter paper impregnated with the test sample. The study used permethrin (1%), 6-paradol (0.00005%, 0.0001%, and 0.00015%), and control (distilled water) were tested for pediculicidal activity.

After the bioassay was completed, 27 head lice treated with permethrin were used to analyze AChE, GST, and oxidase activity, and the remaining three head lice were used for SEM examination. To check the action of the enzyme, the same sample of head lice was used. The same was done in the treatment involving 6-paradol and control. In the 6-paradol group, 87 head lice were used to examine AChE, GST, and oxidase activity, and the remaining three head lice were used for SEM examination. In the control group, 30 head lice were used to examine the action of the enzyme.

**AChE, GST, and oxidase activity**
This study analyzed the activity of AChE, GST, and oxidase using the same sample, namely, 30 head lice from the control group, 27 lice from the permethrin group, and 87 from the 6-paradol group. Eighty-seven head lice from the 6-paradol group consisted of 30 lice at a concentration of 0.00005%, 30 lice at a concentration of 0.0001%, and 27 lice at a concentration of 0.00015%. In this study, AChE, GST, and oxidase activities were conducted using the Centers for Disease Control and Prevention method [22]. The unit of enzyme activity is absorbance (Abs) per minute (min) or Abs/min [29].

In the AChE activity, the lice were homogenized with 1000-µL 0.25-M KPO₄ (pH 7.2). At room temperature, 100-µL aliquots of test sample homogenate were loaded into enzyme-linked immunosorbent assay (ELISA) microplate wells in triplicate. Similarly, 100-µL positive and negative controls were added to microplate wells. Acetylcholine iodide and dithiobis (2-nitrobenzoic acid) were each added at a volume of 100-µL into the wells containing the test sample, positive and negative controls, respectively. The plates were read immediately (T₀) with an ELISA reader at 414-nm and read again at 10 min (T₁). The unit of AChE activity was Abs 414-nm/min [22,29]. ELISA reader (ThermoFisher Scientific, Multiskan™ FC Microplate Photometer, Catalog number 51119000, type 300, Finland).

In the GST activity, the lice were homogenized with 1000-µL 0.25-M KPO₄ (pH 7.2). At room temperature, 100-µL aliquots of test sample homogenate were loaded into ELISA microplate wells in triplicate. Similarly, 100-µL positive and negative controls were added to microplate wells. Next, 100-µL reduced glutathione solution (Sigma G4251, China) and 100-µL 1-chloro-2,4'-dinitrobenzene were added to each well containing a test sample. The plates were read immediately (T₀) with an ELISA reader at 340-nm and read again at 5 min (T₅). The unit of GST activity was Abs 340-nm/min [22,26].

The lice were homogenized with 1000-µL 0.25 M KPO₄ (pH 7.2) in the oxidase activity. The study used positive controls (i) 1:55 (22-µL cytochrome stock, 1.2-mL KPO₄ buffer) and (ii) 1:110 (11-µL cytochrome stock, 1.2-mL KPO₄ buffer). At room temperature, 100-µL aliquots of the test sample homogenate were loaded into ELISA microplate wells in triplicate. Next, 100-µL KPO₄ was added to the negative and positive sample wells. Afterward, 100-µL cytochrome-C-positive control (cytochrome-C bovine heart) and 200-µL 3,3’5,5’-Tetramethyl-Benzidine Dihydrochloride solution were added to each well. One drop of 3% hydrogen peroxide (H₂O₂) was added to each well and incubated for 5 min. The plates were read immediately (T₀) with an ELISA reader at 620-nm. The unit of oxidase activity was Abs 414-nm/min [22,29]

**SEM study**
This study evaluated the electron microscopic changes in the lice exposed to permethrin and 6-paradol according to the protocol described by Nunes et al. [30]. Briefly, the phases of the process are as follows: The lice were pre-fixed in 2.5% glutaraldehyde.
at 4℃ for 6 h and then fixed in 1% osmium tetroxide for 2 h and rinsed in 0.1-M phosphate buffer (pH 7.2). Then, the samples were dehydrated in an acetone series in ascending order (30%, 50%, 70%, 80%, 90%, and 100% v/v) for 15 min each and in absolute acetone twice for 20 min, then embedded in epoxy resin (Beijing Daji Keyi Technology Co., Ltd., Beijing, China). Specimens were mounted on stubs with double-sided carbon contact tape and observed using a JEOL JSM-6390LA analytical scanning electron microscope. A low-vacuum chamber pressure of 150 Pa was used. Images of the specimens were taken at 3024×2304 pixels and scanned at a speed of 12 min 54 s.

**Statistical analysis**
All statistical analyses, including the lice mortality rate, probit analysis, and detoxifying enzyme activity, were conducted using Statistical Package for the Social Sciences version 20.0. The louse mortality rate (%) was calculated using the following formula:

\[
\text{% mortality} = \frac{\text{Number of dead head lice}}{\text{Total number of head lice}} \times 100
\]

Lethal concentration of 50% (LC₅₀) and lethal time of 50% (LT₅₀) values were calculated by probit analysis. AChE, GST, and oxidase activities were calculated according to the formula below [22,29];

\[
\text{Abs value at 5 min or 10 min} - \text{Abs value at 0 min} \quad \text{Enzyme activity} = \frac{\text{Abs}}{5 \text{ min or 10 min}}
\]

The permethrin-resistant lice were distinguished by the poor efficacy of permethrin in the in vitro experiments and increases in all detoxifying enzyme activities [22,31]. The 6-paradol-resistant lice were similarly identified. Twenty-seven head lice from the permethrin group and 87 head lice from the 6-paradol group (30 head lice from a concentration of 0.00005%, 30 head lice from a concentration of 0.0001%, and 27 head lice from a concentration of 0.00015%) were used to test for paired samples. Paired samples t-test tests two paired samples, whether they have significantly different means or not. The two paired samples are the absorbance values of AChE, GST, and oxidase at 0 min to 5 or 10 min. All samples were normally distributed. Differences were considered statistically significant at p<0.05 [32]

**Results**

**Movement of the head lice**
At 0 min, all lice in the control, permethrin, and 6-paradol groups moved actively. In the control group, all lice moved actively at all-time points (100%, 10/10). In the permethrin group, at ten and 20 min, as much as 80% (24/30) of the lice were still actively moving or alive. In contrast, at 30 and 60 min, only 63.3% (19/30) of the lice were still alive. In the 6-paradol group, live lice differed according to the concentrations of 6-paradol. At 60 min, the live lice comprised 33.3% (10/30), 26.7% (8/30), and 13.3% (4/30) in 0.00005%, 0.0001%, and 0.00015% 6-paradol, respectively. Figure-2 indicates the numbers of live lice after in vitro exposure to permethrin and 6-paradol at all-time points.

**Efficacy of permethrin and 6-paradol**
Table-1 indicates the head lice mortality rate after in vitro treatment with 1% permethrin and 6-paradol. At all-time points, the healthy control samples showed no dead lice (0.0%). For the permethrin group, at 60 min, the mortality rate was 36.7% (11/30). In contrast, at 60 min, 6-paradol killed 66.7%, 73.3%, and 86.7% of the lice at 0.00005%, 0.0001%, and 0.00015%, respectively. Overall, permethrin and 6-paradol exhibited low efficacy (Figure-3). The LT₅₀ values for permethrin and 6-paradol are indicated in Table-2. For permethrin, the values were recorded at 37.666 and 354.670 min, respectively. In contrast, for 6-paradol, the values varied according to the concentration. The highest concentration of 6-paradol (0.00015%) exhibited LT₅₀ and LT₉₀ values of 9.926 and 76.160 min, respectively. The lower concentrations of 6-paradol, 0.00005%, and 0.0001% had higher LT₅₀ and LT₉₀ values than the high concentration. Overall, in vitro treatment with permethrin killed lice more slowly than that of 6-paradol.

**Detoxifying enzyme activity**
This study used 30 head lice from the control group, 27 from the permethrin group, and 87 from the 6-paradol group to examine AChE, GST, and oxidase activity. All head lice (100%, 30/30) had increased AChE, GST, and oxidase activity in the control group. The mean Abs value for AChE at 0 min was 0.398±0.016 and increased for 10 min then to 0.541±0.020 (Figures-4 and 5). In GST, the mean abs at 0 min were 0.511±0.007 and increased to 1438±0.005 in 5 min later (Figures-4 and 5). In oxidase, the mean Abs value at 0 min was 1.661±0.001 and increased to 1.733±0.001 (Figures-4 and 5) 5 min later. The percentage increase in Abs values from AChE (0-10 min) was 36.1±6.74%, GST (0-5 min) was 181.3±3.70%, and oxidase (0-5 min) was 4.4±0.04%. In addition, the average increase in AChE, GST, and oxidase activity (Abs/min) was 0.014±0.002, 0.093±0.001, and 0.007±0.0 Abs/min, respectively.

**Table-1: Mortality rates of head lice after exposure to permethrin and 6-paradol.**

| Treatment   | 10 min | 20 min | 30 min | 60 min |
|-------------|--------|--------|--------|--------|
|             | Dead % | Dead % | Dead % | Dead % |
| Control     | 30     | 0      | 0      | 0      |
| Permethrin  | 30     | 6      | 20     | 11     | 36.7   | 11     | 36.7   |
| (1%)        |        |        |        |        |
| 6-paradol   | 0.00005%| 30    | 5      | 16.7   | 10     | 33.3   | 14     | 46.7   | 20     | 66.7   |
|             | 0.0001%| 30    | 2      | 6.7    | 16     | 53.3   | 18     | 60     | 22     | 73.3   |
|             | 0.00015%| 30  | 15     | 50     | 20     | 66.7   | 23     | 76.7   | 26     | 86.7   |

N=Number of the lice
In the 6-paradol group, all head lice (100%, 87/87) indicated increased values of Abs AChE (0-10 min), GST (0-5 min), and oxidase (0-5 min) (Figure-5). In the 6-paradol treatment with a concentration of 0.00005%, there was an increase in the mean Abs value of AChE by 70.6±29.49%, GST by 97.9±9.4%, and oxidase by 2.8±3.06%. At 0.0001%, the mean increase in Abs values from AChE was 31.9±2.28%, GST was 104.0±9.65%, and oxidase was 7.4±8.4%. At 0.00015%, the mean increase in Abs values of AChE, GST, and oxidase increased by 71.2±3.98%, 106.3±10.1%, and 7.5±8.5%, respectively.

Table-2: The LT of permethrin and 6-paradol.

| Treatment | Z     | SE    | p-value | 95% CI | A²  | p-value | LT₅₀ (min) | LT₉₀ (min) |
|-----------|-------|-------|---------|--------|-----|---------|-----------|-----------|
| Permefrin | 1%    | 6-paradol | 0.00005% | 4.391  | 0.892 | 0.000    | 2.168     | 5.662     |
|           |       |       |         | 0.00001% | 4.597 | 1.147 | 0.000    | 3.024     | 7.519     |
|           |       |       |         | 0.00015% | 3.177 | 0.456 | 0.001    | 0.555     | 2.341     |

SE=Standard error, Sig=Significant, CI=Confidence interval, LT=Lethal time

In the permethrin group, all head lice (100%, 27/27) exhibited an increase in the Abs values of AChE, GST, and oxidase from 0 to 5 min or 10 min (Figure-4). There was an increase in the mean value of Abs AChE (0-10 min) by 30.6±3.83%, GST (0-5 min) by 61.7±7.14%, and oxidase (0-5 min) by 14.5±1.2%. In addition, this study found a fluctuating increase in AChE, GST, and oxidase (Abs/min) activity in each head lice (Figure-6a). The average increase in AChE, GST, and oxidase activity (Abs/min) increased by 0.006±0.001, 0.019±0.002, and 0.013±0.001 Abs/min, respectively. The paired sample t-test results discovered that the activity of AChE, GST, and oxidase increased significantly (p<0.05) (Table-3).

Figure-1: Study site of head lice in East Jakarta. Jakarta city map (A), and head lice sampling location map (B). [Image sources: (a) https://commons.wikimedia.org/wiki/File:Jakarta_Wikivoyage_Map.svg; (b) https://www.google.com/maps].

Figure-2: Numbers of live lice after in vitro exposure to permethrin and 6-paradol at 0, 10, 20, 30, and 60 min.

Figure-3: The efficacy of permethrin and 6-paradol against lice in vitro.

In the 5-paradol group, all head lice (100%, 87/87) indicated increased values of Abs AChE (0-10 min), GST (0-5 min), and oxidase (0-5 min) (Figure-5). In the 6-paradol treatment with a concentration of 0.00005%, there was an increase in the mean Abs value of AChE by 70.6±29.49%, GST by 97.9±9.4%, and oxidase by 2.8±3.06%. At 0.0001%, the mean increase in Abs values from AChE was 31.9±2.28%, GST was 104.0±9.65%, and oxidase was 7.4±8.4%. At 0.00015%, the mean increase in Abs values of AChE, GST, and oxidase increased by...
Table-3: AChE, GST, and oxidase activity in head lice after in vitro treatment of 1% permethrin and 6-paradol.

| Treatment   | n  | Enzyme | Mean±SD | Paired-samples t-test |
|-------------|----|--------|---------|-----------------------|
|             |    |        | T0      | T5 or T10             | t-value | sig. (two-tailed) |
| Permethrin 1%| 27 | AChE   | 0.201±0.004 | 0.262±0.006 | 19.673  | 0.000             |
|             |    | GST    | 0.310±0.007 | 0.501±0.024 | 19.686  | 0.000             |
|             |    | Oxidase| 0.928±0.007 | 1.062±0.007 | 8.496   | 0.000             |
| 6-paradol   |    |        | T0=0 min, T5=5 min, T10=10 min. AChE (0 min and 10 min), GST (0 min and 5 min). Oxidase (0 min and 5 min), sig (significant). AChE=Acetylcholinesterase, GST=Glutathione S-transferase |
| 0.00005%    | 30 | AChE   | 0.225±0.058 | 0.401±0.023 | 14.075  | 0.000             |
|             |    | GST    | 0.391±0.053 | 0.201±0.004 | 21.678  | 0.000             |
|             |    | Oxidase| 0.966±0.345 | 1.003±0.345 | 6.566   | 0.000             |
| 0.0001%     | 30 | AChE   | 0.245±0.018 | 0.323±0.026 | 20.245  | 0.000             |
|             |    | GST    | 0.415±0.037 | 0.850±0.111 | 22.662  | 0.000             |
|             |    | Oxidase| 1.308±0.235 | 1.385±0.163 | 6.566   | 0.000             |
| 0.00015%    | 27 | AChE   | 0.286±0.068 | 0.390±0.099 | 18.591  | 0.000             |
|             |    | GST    | 0.449±0.087 | 0.907±0.187 | 21.095  | 0.000             |
|             |    | Oxidase| 2.446±0.498 | 2.492±0.517 | 16.253  | 0.000             |

Figure-4: In the permethrin group, AChE, GST, and oxidase activity increased from 0 min to 5 min or 10 min. ACHE (absorbance 414 nm), GST (absorbance 340 nm), oxidase (absorbance 620 nm). Control group is black, permethrin group is blue (AChE), red (GST), and green (oxidase). AChE=Acetylcholinesterase, GST=Glutathione S-transferase.

Figure-5: In the 6-paradol group, all concentrations of 6-paradol caused an increase in AChE, GST, and oxidase activity from 0 min to 5 min or 10 min. AChE (a) (absorbance 414 nm), (b) GST (absorbance 340 nm), (c) oxidase (absorbance 620 nm). AChE=Acetylcholinesterase, GST=Glutathione S-transferase.

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activity were found in each individual head lice (Figure-6). For example, in the 6-paradol treatment with a concentration of 0.00005%, the average increase in AChE enzyme activity (Abs/min) was 0.017±0.004 Abs/min, GST was 0.039±0.009 Abs/min, and oxidase was 0.008±0.001 Abs/min. At 0.0001%, the average increase in the activity of AChE, GST, and oxidase enzymes increased by 0.008±0.001, 0.044±0.07, and 0.008±0.007 Abs/min, respectively. In addition, at 0.0015%, the average increase in the activity of AChE, GST, and oxidase enzymes increased by 0.010±0.003 Abs/min, 0.046±0.010 Abs/min, and 0.005±.001 Abs/min, respectively (Table-3).

The paired sample t-test results showed that the 6-paradol group at concentrations of 0.00005%, 0.0001%, and 0.00015% showed that all AChE, GST, and oxidase activities increased significantly (p<0.05) (Table-3).

Electron microscopic changes in lice

Figure-7 shows SEM images of the lice treated with permethrin. After in vitro treatment with permethrin, smooth outer architecture, head (antennae and eyes), thorax (legs with hook-like claws), and abdomen (respiratory spiracles) did not exhibit any ultrastructural morphological changes. Permethrin caused the loss of some sensory hairs of the dead lice.

Figure-8 shows SEM images of the lice treated with 0.00015% 6-paradol. This study used the dead lice exposed to 0.00015% of 6-paradol in 60 min to represent SEM changes for the entire experiment. After in vitro treatment with 6-paradol (0.00015%), smooth outer architecture, the head, thorax, and abdomen exhibited no ultrastructural morphological changes in the lice. These findings showed that 6-paradol damaged the chitin layers of the head and thorax, causing an irregularly or abnormally shaped head and thorax. Furthermore, the respiratory spiracles and chitin layers of the abdomen were damaged, while some sensory hairs fell out.

Discussion

This study demonstrated the low efficacy of permethrin (1%) against head lice using in vitro experiments (36.7% mortality, 11/30). During a 60-min period, permethrin killed lice slowly, with LT<sub>50</sub> and LT<sub>90</sub> values of 37.666 and 354.670 min, respectively. The low efficacy of permethrin indicated that lice from East Jakarta were resistant to this specific pediculicide. This was demonstrated by 63.3% (19/30) of the lice treated with permethrin survived 60 min of exposure. This study’s determination of permethrin-resistant head lice was based on the parasitological approach, an in vitro bioassay method. Although 6-paradol killed lice quicker than permethrin, its efficacy was low. To the best of our knowledge, this study is the first to report that lice from East Jakarta show resistance to permethrin and 6-paradol.

Similarly, Kristensen et al. [33] in Denmark used an in vitro bioassay approach to determine the resistance of head lice to permethrin; 17 of 24 samples (Danish

Figure-6: (a and b) AChE, GST, and oxidase activity of each individual head louse exposed to permethrin (1%) and 6-paradol (0.00005%). AChE (blue), GST (red), oxidase (green). The number of lice consisted of 27 head lice from permethrin group and 30 head lice from 6-paradol (0.00005%) group. (c and d) AChE, GST, and oxidase activity of each individual head louse exposed to 6-paradol (0.0001%) and 6-paradol (0.00015%). AChE (blue), GST (red), oxidase (green). The number of lice consisted of 30 head lice from 6-paradol (0.0001%) group and 27 head lice from 6-paradol (0.00015%) group. AChE=Acetylcholinesterase, GST=Glutathione S-transferase.
head lice population) were examined for permethrin resistance, and all of the lice survived different doses for 4 h. Six samples had between 3% and 25% mortality rates, and one sample showed 60% mortality. Many parasitological surveys to determine the resistance of lice to permethrin have been reported in Europe, precisely the Czech Republic [34], the UK [35], and Denmark [33] and Israel [36], the USA [37], Argentina [38], Japan [39], and Australia [40]. Results from the study are in agreement with those from a study by Kristensen et al. [33], who found that head lice were permethrin-resistant using an in vitro bioassay method.

Clinical trials of permethrin have not been conducted among residents in Jakarta to determine its efficacy. No studies have examined kdr-type gene mutations related to the failure of permethrin to treat head lice. One previous study reported that the efficacy of permethrin was poor to fair [1]. Recently, Kalari et al. [41] reported that the efficacy of permethrin for treating lice in Iran ranged from 60% to 80%. Heukelbach et al. [42] indicated that the efficacy of dimethicone for treating lice was 98%. kdr-type gene mutations cause the poor efficacy of permethrin. Three kdr-type point mutations (M815I, T917I, and L920F) in the VGSC α-subunit gene are associated with permethrin-resistant phenotypes responsible for kdr-type resistance [13-15]. These kdr mutant alleles have been found worldwide [10], and they are most prevalent in countries with easy access to pediculicidal agents [12]. In Germany, Bialek et al. [43] reported that kdr mutant alleles were not associated with clinical treatment failure of pyrethroids. In Senegal, it was

![Figure-7](image-url): Ultrastructural changes of head lice after in vitro treatment with permethrin. There are obvious changes in the abdomen, especially sensory hair loss (white arrows) in b and c. Head (a), thorax (b), and abdomen (c).

![Figure-8](image-url): Ultrastructural changes of head lice after in vitro treatment with 6-paradol. The whole body of head lice (a). Obvious ultrastructural changes in head lice (white arrows) were found on the head (b), spiracle (c), thorax (d), and abdomen (e).
reported that the presence of a point mutation of GluCl is associated with ivermectin-resistant head lice [17]. In addition, several novel kdr point mutations of the VGSC α-subunit gene have been discovered. For example, in Iran, six-point mutations, H813P (located in IIS1-2 extracellular loop), I927F, L928A, R929V, L930M, and L932M (located in IIS5), were found in head lice resistant to pyrethroid insecticides [18] and in Mexico, a new point mutation, T929I, was found in head lice resistant to insecticides, especially pyrethroids [19].

Our study showed that the resistance of lice to permethrin is mediated by detoxifying enzyme activity. In the permethrin group, AChE, GST, and oxidase activities increased by 30.6%, 61.7%, and 14.5%, respectively. Statistically, the activity of these enzymes increased significantly. Ab's values of these enzymes were also increased in the 6-paradol group. These results agree with those from González Audino et al. [31], who reported that increased monoxygenase, esterase, and GST activity were associated with resistance of lice to permethrin. Furthermore, Brogdon [22] reported that elevated detoxifying enzyme activity levels (such as AChE, GST, esterase, and oxidase) were associated with insecticide-resistant species of Anopheles. Thus, it can be deduced that the mechanism of permethrin-resistant lice is likely associated with increased detoxifying enzyme activity.

Our study used 6-paradol, a bioactive plant compound, to compare permethrin's efficacy (1%) because synthetic pediculicides, such as carboxyl, DDT, lindane, and malathion, have also been reported to cause resistance [10]. The compound 6-paradol is a non-pungent metabolite of shogaoil [25]. A previous study indicated that 6-paradol exhibits neuroprotective effects to decrease neuroinflammation-associated central nervous system disorders [25,44]. Kim et al. [45] reported that 6-paradol inhibited cytochrome P450 enzyme activity in human liver microsomes. These findings showed that 6-paradol was associated with increased AChE, GST, and oxidase activity. This study also showed significantly elevated oxidase activity in the 6-paradol group (Table-3).

Plant products can be used as safe alternatives to pediculicidal agents due to low toxicity to mammals and easy biodegradability [46]. Citronellaa java (essential oils) from Cymbopogon nardus (0.25-mg/cm²) exhibited adulticidal activity against female P. h. capitis [47]. Spearmint, clove, thyme, eucalyptus, and anise essential oils, as potential pediculicides, showed different levels of effectiveness against head lice [48]. Akkad et al. [49] reported that after 1 h of exposure in vitro, 1% ivermectin and lemon juice caused 100% mortality in lice; tea tree oil caused 96.7% mortality, and virgin olive oil caused 23.3% mortality. Candy et al. [50] reported that clove oil diluted in coconut oil or sunflower oil showed adulticidal activity (>90% lice mortality after 2 h). In our study, 6-paradol exhibited 86.7% mortality after 1 h. Moreover, the effectiveness of 6-paradol was lower than that of ivermectin, lemon juice, and tea tree oils as previously reported by Akkad et al. [49].

Electron microscopic findings indicated that permethrin did not cause damage to the head, thorax, or abdomen of the lice (Figure-7), while 6-paradol seriously damaged the head, thorax, respiratory spiracles, and abdomens of the dead lice. The 6-Paradol caused damage to the chitin layer of the head, thorax, and abdomen so that the shape of the head, thorax, and abdomen was abnormal (Figure-8). Akkad et al. [49] reported that olive oil, tea tree oil, lemon juice, and ivermectin caused electron microscopic alterations in dead-head lice; they damaged sensory hairs, respiratory spiracles, and/or clinching claws. Electron microscopic alterations are caused by antioxidant stress induced by pediculicidal agents, ivermectin, and essential oils. Thus, the mechanism by which pediculicides from chemical and natural products kill human head lice can be visualized using electron microscopic changes.

Conclusion

Our findings showed that human head lice, P. h. capitis, from East Jakarta, were permethrin-resistant and 6-paradol treatment with these pediculicides yielded increases in AChE, GST, and oxidase activity. The electron microscopic findings indicated that permethrin did not induce damage to the head, thorax, and abdomen of the lice. In contrast, 6-paradol severely damaged the dead lice’s head, thorax, respiratory spiracles, and abdomen. Alternative pediculicidal agents are urgently required to create optimal management strategies.

Authors’ Contributions

RS, LS: Designed the study. RS, RA, APA, and NSL: Collected the samples from the fields and conducted bioassay. RS, RA, APA, and YY: Conducted the biochemical assay. RS and RA: Examined head lice with scanning electron microscope. RS, LS, RW, IPS, and YY: Carried out data analysis. RS, LS, RA, APA, YY, RW, NSL, and IPS: Drafted the manuscript. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

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