Research Article

5-Aminolevulinic Acid-Based Photodynamic Therapy Pretreatment Mitigates Ultraviolet A-Induced Oxidative Photodamage

Hui Hua,1 Jiawei Cheng,1 Wenbo Bu,2 Juan Liu,1 Weiwei Ma,1 Chencen Si,1 Jie Wang,1 Bingrong Zhou,1 and Dan Luo1

1Department of Dermatology, The First Affiliated Hospital of Nanjing Medical University, Nanjing 210029, China
2Institute of Dermatology, Chinese Academy of Medical Sciences (CAMS) & Peking Union Medical College (PUMC), Nanjing, Jiangsu, China

Correspondence should be addressed to Bingrong Zhou; bingrong.2002@163.com and Dan Luo; danluo2005@163.com

Received 25 June 2018; Revised 30 August 2018; Accepted 16 September 2018; Published 7 November 2018

Aim. To determine whether 5-aminolevulinic acid-based photodynamic therapy (ALA-PDT) is effective in combating ultraviolet A- (UVA-) induced oxidative photodamage of hairless mice skin in vivo and human epidermal keratinocytes in vitro.

Methods. In in vitro experiments, the human keratinocyte cell line (HaCaT cells) was divided into two groups: the experimental group was treated with ALA-PDT and the control group was left untreated. Then, the experimental group and the control group of cells were exposed to 10 J/m² of UVA radiation. ROS, O₂⁻ species, and MMP were determined by fluorescence microscopy; p53, OGG1, and XPC were determined by Western blot analysis; apoptosis was determined by flow cytometry; and 8-oxo-dG was determined by immunofluorescence. Moreover, HaCaT cells were also treated with ALA-PDT. Then, SOD1 and SOD2 were examined by Western blot analysis. In in vivo experiments, the dorsal skin of hairless mice was treated with ALA-PDT or saline-PDT, and then, they were exposed to 20 J/m² UVA light. The compound 8-oxo-dG was detected by immunofluorescence.

Conclusion. In human epidermal keratinocytes and hairless mice skin, UVA-induced oxidative damage can be prevented effectively with ALA-PDT pretreatment.

1. Introduction

Skin photodamage has become a major public health issue given the tremendous increase in the number of patients suffering from it. Skin photodamage is caused by excessive exposure to ultraviolet (UV) radiation of the sun [1–4]. Ultraviolet radiation can cause acute reactions, such as erythema and edema; moreover, constant exposure to UV radiation can also lead to chronic skin reactions, such as photoaging and carcinoma [5, 6].

The major source of UV radiation is sunlight. There are two types of UV radiation that can reach the earth’s atmosphere: UV radiation A (UVA) and UV radiation B (UVB), of which UVA constitutes 95%. Compared to UVB, the wavelength of UVA is longer; therefore, UVA penetrates deeper into the skin than UVB. Recent studies have reported that UVA is probably more mutagenic than UVB [7]. The UVA-induced skin damage may be indirect; it can trigger excessive production of ROS, which causes oxidative damage to proteins, lipids, and DNA. This leads to the generation of several types of oxidative products, such as 7,8-dihydro-8-oxo-guanosine (8-oxoG) and 8-oxo-7,8-dihydro-2′-deoxyguanosine (8-oxo-dG) [8, 9]. If the human body fails to remove UV mutagenic photoproducts within a definite period of time, the DNA cannot be repaired completely. These adverse products finally lead to the development of skin cancer.

Skin photodamage can be prevented by adopting effective measures of UV protection. Currently, sunscreen lotions and protective clothing are the most effective photoprotective measures [10, 11]; however, many people find it difficult to use them on a regular basis. Previous studies have shown...
that these strategies have only caused a modest reduction in actinic keratoses (AKs) and squamous cell carcinomas (SCCs) of the skin; however, there has been no reduction in basal cell carcinomas (BCCs) of the skin [12, 13]. Some ingredients in sunscreens, such as benzophenone-3 (BP-3), can cause skin irritation and phototoxicity in susceptible populations; BP-3 is extensively used in organic sunscreens [14]. Currently, there is no worldwide consensus on the testing and labeling of sunscreens that offer UVA protection [15]. In fact, sunscreen alone may not be able to provide adequate protection from ultraviolet A. Therefore, it is very important to develop targeted chemoprevention strategies.

5-Aminolevulinic acid-based photodynamic therapy (ALA-PDT) is a noninvasive therapy; photosensitizer, oxygen, and light are the key components of ALA-PDT. Moreover, ALA is a precursor of protoporphyrin IX (PpIX). A topical formulation of ALA is used to target skin tissues; light of appropriate wavelength is used to activate the photosensitizer, which produces reactive oxygen species (ROS). Ultimately, this leads to cell necrosis and apoptosis [16, 17]. Previous studies have shown that ALA-PDT has a therapeutic effect on a variety of photodamage diseases, such as skin tumors and photoaging [18, 19]; moreover, it also prevents the onset of photodamage diseases, such as nonmelanoma skin cancers (NMSCs) and actinic keratoses (AKs). Goldberg et al. conducted a study on patients with a history of NMSCs and multiple AKs; they found that the onset of NMSCs can be prevented and delayed in these patients [20]. Togsvard-Bo et al. conducted a study on high-risk renal transplant recipients; they found that the onset of AK was significantly delayed when patients’ normal skin was treated with repeated PDT for a long period of time [21]. The results indicate that ALA-PDT can prevent the occurrence of photodamage diseases, but we still do not know the exact mechanism through which ALA-PDT exerts inhibitory effect on UV-induced damages. In this study, hairless mice skin and HaCaT cells were pretreated with ALA-PDT. Then, they were exposed to UVA radiation to determine whether UVA-induced photodamage can be prevented with ALA-PDT pretreatment. We also determined the potential mechanisms through which ALA-PDT inhibits UVA-induced photodamage. The results indicate that UVA-induced DNA damage can be significantly reduced by ALA-PDT pretreatment, which upregulates p53-dependent DNA repair and activates the antioxidant enzymes. This indicates that UVA-induced oxidative damage can be inhibited with ALA-PDT pretreatment.

2. Material and Methods

2.1. Cell Culture, ALA-PDT Treatment, and UVA Irradiation.

The immortalized human keratinocyte cell line (HaCaT) was grown at 37°C in a humidified atmosphere of 5% CO₂; the cell culture medium was Dulbecco’s modified Eagle’s medium (DMEM), which was supplemented with 10% fetal bovine serum (FBS) and 1% penicillin-streptomycin. Thereafter, HaCaT cells were subcultured by trypsinization, and they were used in subsequent passages. Under standard conditions, HaCaT cells were grown to >70% confluency. Then, subsequent experiments were performed. The cells were divided into three groups, namely, control group, UVA group, and ALA-PDT + UVA group. No treatment was provided to cells in the control group. In the UVA group, cells were irradiated with 10 J/cm² of UVA light. In the ALA-PDT + UVA group, cells were incubated with 0.5 mmol/L of ALA for 4 h. Then, the cells were exposed to red laser light of 3 J/cm² intensity (50 mW/cm² for 60 s). Finally, these cells were irradiated with 10 J/cm² of UVA light (3.7 mW/cm² for 45 min). The UVA radiation was delivered using a UVA fluorescent lamp (340–400 nm wavelength, a peak at 305 nm, Sigma SS-04P, Shanghai, China). The intensity of UVA radiation was measured with a UV radiometer (Philips, Amsterdam, Netherlands). Before irradiating the cells with UVA light, the medium was removed and the cells were covered with a thin layer of phosphate-buffered saline (PBS).

2.2. Cell Viability Measurement. Cell viability was measured using a CCK-8 Kit (Beyotime Biotechnology, Shanghai, China). In brief, HaCaT cells (2000/100 μL) were seeded into 96-well plates. Then, they were treated with ALA-PDT and UVA alone or in combinations. Thereafter, cells of each well were incubated with 10 μL of CCK-8 solution for 2 h. To determine cell density, we measured the absorbance of cell culture at 450 nm with a Thermo Scientific Microplate Reader.

2.3. Measurement of Intracellular ROS and O₂⁻. A fluorescent probe was used to measure the intracellular ROS and O₂⁻ species produced by HaCaT cells. Cells were plated in 6-well plates or 96-well plates. Then, they were incubated in the dark with 10 μmol/L DCFH-DA or 5 μmol/L Dihydroethidium for 20 min at 37°C (Beyotime Biotechnology, Shanghai, China). The fluorescence intensity was measured with a SpectraMax 190 microplate reader (Molecular Devices, Sunnyvale, USA). Cells were observed under a fluorescence microscope, and they were also photographed randomly by a Nikon camera with constant time, exposure, and gain (Nikon, Tokyo, Japan).

2.4. Flow Cytometry Analysis of Apoptosis. HaCaT cells had been treated with ALA-PDT by the abovementioned process. Then, these cells were harvested and washed with PBS. Finally, these cells were double-stained with an Annexin-V-FITC apoptosis detection kit (Beyotime Biotechnology, Shanghai, China). The cells were incubated with PI (10 μL) and Annexin-V-FITC (5 μL) at room temperature for 15 min in the dark. Then, they were quantitatively analyzed with a FACScan flow cytometer (BD, Franklin Lakes, NJ, USA). Cells stained with Annexin-V(+) /PI(−) were apoptotic in nature.

2.5. Evaluation of Mitochondrial Membrane Potential (MMP).

The fluorescent probe JC-1 (Beyotime Biotechnology, Shanghai, China) was used to determine the mitochondrial membrane potential (MMP) of HaCaT cells. Cells were cultured in 96-well plates and 6-well plates; these cells were incubated with JC-1 staining solution (5 μg/mL) for 20 min at 37°C and rinsed twice with JC-1 staining buffer. A
fluorescence microscope (Nikon, Tokyo, Japan) was used to determine the relative amounts of dual emissions from mitochondrial JC-1 monomers (490 nm excitation and 530 nm emission) or aggregates (525 nm excitation and 590 nm emission). The fluorescence intensity of mitochondrial JC-1 monomers and aggregates was determined with a SpectraMax 190 microplate reader (Molecular Devices, Sunnyvale, USA). An increase in the green/red fluorescence intensity ratio indicates mitochondrial depolarization.

2.6. Immunofluorescence Analysis for Detection of 8-Oxo-dG. HaCaT cells were cultured on coverslips and fixed in 4% paraformaldehyde for 15 min. Then, they were permeabilized with 0.5% Triton X-100 for 10 min. This blocked the nonspecific binding with PBS, which contained 1% bovine serum albumin (BSA) for 30 min. Then, they were incubated overnight with anti-8-oxo-dG monoclonal antibody at 4°C (1:800; Trevigen, Gaithersburg, USA). Subsequently, cells were washed again and incubated with Cy3-conjugated secondary antibody (1:1000, Beyotime Biotechnology, Shanghai, China) for 2 h. After washing stained cells with PBS, photomicrographs were taken with a fluorescence microscope (Nikon, Tokyo, Japan). The 8-oxo-dG-positive nuclei appeared red in color.

2.7. Western Blotting for Detection of SOD1, SOD2, p53, XPC, and OGG1. After treating HaCaT cells with ALA-PDT mentioned above, Western blot analysis was performed on these cells. Cells were lysed in a RIPA buffer (Beyotime Biotechnology, Shanghai, China). Protein concentrations were quantified with a bicinchoninic acid protein assay kit (BCA, Beyotime Biotechnology, Shanghai, China). Then, equal amounts of 20 μg protein/sample were separated with sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE). After transferring the samples into PVDF membranes, the samples were allowed to react with specific primary antibodies: SOD1 (1:1000; CST, Boston, MA, USA), SOD2 (1:500; CST), p53 (1:1000; Sigma, St. Louis, MO, USA), XPC (1:1000; CST), and OGG1 (1:500; Sigma). Subsequently, the cells were incubated with HRP-conjugated anti-mouse or anti-rabbit IgG for 2 h. Protein expression levels were determined with an enhanced chemiluminescence (ECL) detection system. β-Actin was used as an internal control.

2.8. Animal. All animal experiments were performed after receiving approval from the Animal Use Committee of Nanjing Medical University in China. We included 28 female BALB/c athymic nude mice, 4–6 weeks old, and the weight of each mouse was between 19 and 22 g. We purchased these mice from Model Animal Research Center of Nanjing University in China. After acclimatizing the mice to experimental conditions, they were randomly divided to three groups (10 animals in each group): the control group (no treatment), the ALA-PDT + UVA group (10% ALA + 12 J/cm² PDT + 20 J/cm² UVA), and the UVA group (saline + 20 J/cm² UVA).

2.9. ALA-PDT Treatment and UVA Irradiation. A piece of medical cotton was soaked with a specific concentration of ALA solution (10%; Fudan-Zhangjiang Bio-Pharmaceutical Co., Shanghai, China). Then, the cotton soaked with ALA solution was applied on approximately 4.0 cm² of dorsal skin. In the UVA group, physiological saline was used as a negative control. The treated areas were covered with layers of plastic wrap and black plastic sheeting, and they were secured with a medical tape. We removed these dressings after 2 h. The treated tissues were irradiated for 10 min with a PDT laser (XD-635AB; Fudan-Zhangjiang Bio-Pharmaceutical Co., Shanghai, China) of wavelength 635 nm; the energy density of the PDT laser was 12 J/cm² (50 mW/cm² for 4 min). The mice were treated with ALA-PDT or physiological saline for two days. After these mice were anesthetized with 0.4% chloral hydrate (0.1 mL/10 g), they were irradiated with 20 J/cm² of UVA light (3.7 mW/cm² for 90 min).

2.10. Immunofluorescence Analysis of 8-Oxo-dG. After fixing the specimens in 4% paraformaldehyde, they were embedded in a paraffin bath. After blocking endogenous proteins, sections were incubated overnight at 4°C with anti-8-oxo-dG monoclonal antibody (1:1000; Trevigen, Gaithersburg, USA). After washing the sections with PBS, photomicrographs were taken with a fluorescence microscope. The ALA-PDT solution (10%; Fudan-Zhangjiang Bio-Pharmaceutical Co., Shanghai, China) of wavelength 635 nm; the energy density of the PDT laser was 12 J/cm² (50 mW/cm² for 4 min). The mice were treated with ALA-PDT or physiological saline for two days. After these mice were anesthetized with 0.4% chloral hydrate (0.1 mL/10 g), they were irradiated with 20 J/cm² of UVA light (3.7 mW/cm² for 90 min).

2.11. Statistical Analysis. Statistical analysis was performed using the SPSS software for Windows, version 16.0 (SPSS, Chicago, IL, USA). Statistical analysis was carried out by one-way analysis of variance (ANOVA) and Student-Newman-Keuls (SNK-q) test. Data are expressed as the mean ± SD for each group. The values of *p < 0.05 were considered to be statistically significant, and they are indicated in the figures.

3. Results

3.1. Sublethal Dose of ALA-PDT Induced Intracellular ROS. We determined whether sublethal doses of ALA-PDT affected intracellular ROS levels. We incubated HaCaT cells with 0.5 mmol/L of ALA for 4 h. Cells were exposed to 3 J/cm² intensity of red laser light. The results of the CCK-8 assay indicated that there was no significant difference between the cell viability of the ALA-PDT group and the control group (p > 0.05) (Figure 1(a)). The ROS levels were determined by the fluorescent probe DCFH-DA. The HaCaT cells were treated with sublethal doses of ALA-PDT. Compared to the control group, these cells showed stronger green fluorescence and increased fluorescence intensity (p < 0.05; Figure 1(c)).

3.2. Sublethal Dose of ALA-PDT Increased the Levels of SOD1 and SOD2 Proteins. The expression of SOD1 and SOD2 proteins was tested by Western blot analysis to evaluate the level of antioxidant enzymes in HaCaT cells treated with a sublethal dose of ALA-PDT. Compared to the control group, the levels of SOD1 protein increased by 117.56%, 151.15%, and 123.66% in HaCaT cells treated with ALA-PDT at 24 h, 36 h, and 48 h, respectively. The levels of SOD2 protein in the ALA-PDT group increased by 64.94%, 86.36%, and
58.44% at 24 h, 36 h, and 48 h, respectively, compared to those of the control group \((p < 0.05; \text{Figure } 1(b))\).

### 3.3. ALA-PDT Pretreatment Reduces UVA-Induced Oxidative Damage

After irradiating HaCaT cells with UVA light, we assessed the extent of oxidative damage by measuring the amount of ROS and \(O_2^-\) species generated in this process. The number of ROS and \(O_2^-\) species increased tremendously in HaCaT cells when they were irradiated with UVA light. However, the UVA-induced oxidative damage was reduced significantly when HaCaT cells were subjected to ALA-PDT pretreatment: the number of ROS and \(O_2^-\) species declined tremendously in HaCaT cells subjected to ALA-PDT pretreatment, and the fluorescence intensities were reduced by 34.54% and 35.44%, respectively \((p < 0.05 \text{ and } p < 0.05, \text{respectively}; \text{Figure } 2)\).

### 3.4. ALA-PDT Pretreatment Inhibits UVA-Irradiated Cytotoxicity

The cytotoxic effects of UVA and ALA-PDT were determined by performing the CCK-8 assay. The results indicated that cell viability decreased by 36.14% at 24 h after the samples were irradiated with UVA light. However, ALA-PDT pretreatment reduced by 15.07% UVA-induced cytotoxicity in those UVA-irradiated HaCaT cells \((p < 0.05; \text{Figure } 3(a))\).

### 3.5. ALA-PDT Pretreatment Suppressed UVA-Induced Apoptosis

In this study, HaCaT cells were doubly stained with Annexin-V/PI. Then, the apoptosis rate of these cells was determined by flow cytometry. Annexin-V(−)/PI(−) cells are live cells and Annexin-V(+)/PI(−) cells are early-stage apoptotic cells. Annexin-V(+)/PI(+) cells are late-stage apoptotic or necrotic cells. The apoptosis rate was expressed as a percentage of apoptotic cells in total cells. As shown in Figure 3(b), the early and late-stage apoptosis was significantly increased with UVA light. Compared to the UVA group, apoptosis significantly decreased by 31.60% in HaCaT cells subjected to ALA-PDT pretreatment \((p < 0.05)\).

### 3.6. ALA-PDT Pretreatment Alleviates the UVA-Induced Mitochondrial Dysfunction

In order to determine the effect of ALA-PDT and UVA on mitochondria, we performed an assay to determine the changes in MMP by performing flow cytometry with the lipophilic fluorochrome JC-1. The accumulation of JC-1 in mitochondria led to the formation of JC-1 aggregates detected in the red channel. When the MMP was depolarized, JC-1 remained in the cytoplasm as monomers; these monomers were detected in the green channel. As shown in Figure 3(c), control cells exhibited bright red fluorescence. This indicated that control cells had a strong MMP. After being exposed to UVA, cells...
typically lost their MMP. Mitochondrial fluorescence intensity was undetected in these cells. The UVA-induced reduction of MMP can be significantly prevented by subjecting HaCaT cells to ALA-PDT pretreatment.

3.7. ALA-PDT Pretreatment Inhibited the Level of 8-Oxo-dG. Immunoﬂuorescence detected 8-oxo-dG, which is the characteristic product of UVA-induced oxidative damage on DNA. When HaCaT cells were exposed to UVA, there was a significant increase in 8-oxo-dG generation. However, ALA-PDT pretreatment could significantly reduce the elevated levels of 8-oxo-dG in HaCaT cells subjected to UVA light (p < 0.05; Figure 4(a)). In vivo, we also observed that UVA light induced the production of 8-oxo-dG in the skin of hairless mice; however, ALA-PDT can inhibit the excessive generation of 8-oxo-dG in the skin of hairless mice, which was exposed to UVA radiation (p < 0.05; Figure 4(b)).

3.8. ALA-PDT Pretreatment Increased the Levels of p53, XPC, and OGG1 Proteins. To determine whether ALA-PDT pretreatment can increase the expression level of proteins involved in DNA damage repair, we determined the expression of p53, XPC, and OGG1 proteins in HaCaT cells by Western blot analysis. The results indicated that compared to the unirradiated group, the expression of p53, XPC, and OGG1 proteins signiﬁcantly increased by 36.48%, 48.97%, and 136.45% in the UVA-irradiated group (p < 0.05). In the ALA-PDT pretreatment group, the levels of p53, XPC, and OGG1 signiﬁcantly increased by 25.38%, 33.80%, and 29.64%, respectively, than those in the UVA group (p < 0.05; Figure 5).

4. Discussion

When human epidermal keratinocytes and the skin of hairless mice were pretreated with ALA-PDT, the UVA-induced oxidative damage was reduced signiﬁcantly. ROS plays a signiﬁcant role in the mechanism of ALA-PDT [22]. High-level ROS can disrupt cellular processes, while low-level ROS can mediate cellular signaling [23]. Moreover, ROS can elicit oxidative damage and apoptosis in photoaged fibroblasts, which may be the basis for the rejuvenating effects on photoaged skin [24]. The mechanism of acne treatment is as follows: ROS suppresses the expression of IL-1α on keratinocyte hyperkeratosis via the FGFR2b pathway [25]. In our previous study, low concentration of ALA (0.5 mmol/L) and low intensity of red light (3 J/cm²) did not have a signiﬁcant eﬀect on cell viability; however, the p53-dependent pathway was activated suﬃciently with excessive production of ROS. Therefore, a sublethal dose of ALA-PDT was used in subsequent cell experiments.

When HaCaT cells were exposed to UVA radiation, the production of reactive oxygen species (ROS) increased tremendously; the UVA radiation interacted with endogenous chromophores to produce ROS, such as superoxide radical (O$_2^-$) and singlet oxygen (O$_2$). The reactive oxygen species

![Figure 2: UVA-induced oxidative damage was reduced with ALA-PDT pretreatment.](image-url)
can cause damage to cellular proteins, lipids, and DNA, which leads to the formation of oxidative DNA lesions [26]. Moreover, 8-oxo-dG is a characteristic biomarker of DNA oxidation because guanine bases are most susceptible to oxidation [27]. Hu et al. pretreated keratinocytes with oxyresveratrol or kuwanon O; the two phenolic compounds were extracted from the roots of *Morus australis*. They reported both of them were able to inhibit the generation of ROS in keratinocytes, which were irradiated with UVA, and enhanced the cell viability and antioxidative defense capability of keratinocytes [28]. In our study, when HaCaT cells were exposed to UVA light, it increased the generation of ROS, O$_2^-$, and 8-oxo-dG species. Moreover, ALA-PDT pretreatment protected HaCaT cells from UVA-induced damage by suppressing the generation of cellular ROS, O$_2^-$, and 8-oxo-dG.

UVA-mediated apoptosis was partially induced indirectly by generating ROS. It has been well established that after being exposed to UVA light, keratinocytes undergo apoptosis [29–31]. When HaCaT cells were exposed to UVA, apoptosis was induced in these cells; the signs of apoptosis were as follows: cell viability decreased, the fragmentation of DNA increased, and cell morphology is alerted. A previous study reported that ellagic acid pretreatment can successfully suppress UVA-induced apoptosis [32]. In our study, we proved that ALA-PDT pretreatment could successfully suppress UVA-induced apoptosis in HaCaT cells.

**Figure 3:** ALA-PDT pretreatment inhibits cytotoxicity and apoptosis of cells irradiated with UVA. Cells were treated with a sublethal dose of ALA-PDT, then these cells were irradiated with 10 J/cm$^2$ of UVA light. (a) The cell viability was detected by CCK-8 assay at 450 nm. (b) The apoptosis of HaCaT cells was measured by using Annexin-V and PI in conjunction with flow cytometry; Annexin-V(+)/PI(-) cells were early-stage apoptotic cells. (c) Early apoptosis was indicated by a decrease in mitochondrial membrane potential. When the fluorescence probe JC-1 underwent a transition from red light to green light, it indicated a decrease in cell membrane potential. This was an indicator of early apoptosis. The fluorescence intensity of the green/red ratio was determined by a fluorescence microplate reader. Data were expressed as mean ± SD, $n = 3$ for each group, *$p < 0.05$, #$p > 0.05$. 
Complex pathways are involved in the initiation and progression of UV-mediated apoptosis of keratinocytes. Mitochondrial-, death receptor-, ER stress-, and ROS-mediated apoptosis have been reported in these studies [33, 34]. Petruk et al. reported that Opuntia raw extract, which is a phenolic antioxidant, was able to protect cells against UVA-induced apoptosis by inhibiting the activation of caspase-3 and caspase-7 [35]. We confirmed that MMP of HaCaT cells was significantly affected by UVA radiation; moreover, ALA-PDT pretreatment can significantly protect HaCaT cells.

**Figure 4:** The expression level of 8-oxo-dG was inhibited with ALA-PDT pretreatment. Cells were treated with a sublethal dose of ALA-PDT, then these cells were irradiated with 10 J/cm² of UVA light. The expression level of 8-oxo-dG was detected by immunofluorescence. (a, b) Red fluorescence represented 8-oxo-dG-positive cells. Photographs were taken randomly under a fluorescence microscope, and the number of positive cells was counted; this represented the data for each group. Data were expressed as mean ± SD, n = 3 for each group, *p < 0.05.

**Figure 5:** ALA-PDT pretreatment increased the levels of p53, XPC, and OGG1 proteins. Cells were treated with a sublethal dose of ALA-PDT, then these cells were irradiated with 10 J/cm² of UVA light. A Western blot analysis was carried out to detect the expression levels of p53, XPC, and OGG1 proteins. Protein expression levels were quantified by using β-actin as control. Data were expressed as mean ± SD, n = 3 for each group, *p < 0.05.
cells against UVA-induced mitochondrial damage. This observation completely complies with a previous report, which states that ellagic acid protects keratinocytes against UVA-induced apoptosis through the mitochondrial apoptotic pathway [32].

Skin diseases are caused by UVA-induced oxidative damage and apoptosis [36–38]. In order to effectively prevent UVA-induced photodamage, endogenous antioxidants must be induced and DNA repair capacity must be improved [39]. Several studies have reported that T-oligos induced a protective DNA-damage response by activating p53, leading to the upregulation of antioxidant enzymes and DNA-repair enzymes. This protects the DNA from future insults [40–42]. The inducible DNA damage response, which is also known as SOS response, was first found in bacteria. Adaptive DNA damage responses are elicited in cells by administering sublethal doses of DNA-damaging agents [43, 44]. And a transient increase in DNA repair rate was observed by following acute sublethal DNA damage [45].

Reactive oxygen species (ROS)/free radicals were scavenged from a network of antioxidant enzymes, thereby maintaining cellular redox homeostasis [36, 46]. Superoxide dismutases (SODs), especially copper and zinc-dependent superoxide dismutase (SOD1) and the mitochondrial manganese-dependent superoxide dismutase (SOD2), efficiently catalyze the conversion of super oxides into oxygen and hydrogen peroxides. It is well known to be a major antioxidant enzyme that protects cells from oxidative stress, and it prevents carcinogenesis [47–49]. Effect of UVA irradiation on antioxidant enzymes has been reported. Skin cells prepare for subsequent exposure to damaging radiation by upregulating the activities of the antioxidant enzymes SOD1 and SOD2, which also demonstrated the existence of an SOS-like adaptive response [50]. Lee et al. reported that T-oligo can induce antioxidant defenses by upregulating the expression of SOD1 and SOD2 [40]. It is also reported that when chronically irradiated mouse skin was topicaly treated with T-oligo, the level of 8-oxo-dG reduced substantially [51]. Our data was completely compliant with the above observation: the expression of SOD1 and SOD2 was induced and activated with sublethal doses of ALA-PDT, which offered protection against oxidative stress. We speculate that ALA-PDT protects cells from UVA-induced damage by reducing the generation of ROS, O$_2^-$, and 8-oxo-dG, as well as diminishing the apoptosis of cells. We also elucidated the possible molecular mechanisms through which sublethal doses of ALA-PDT induced protective DNA damage responses in human keratinocytes. The inducible antioxidant responses are as follows: the p53-dependent upregulation of DNA repair capacity and the activation of antioxidant enzymes. These antioxidant responses can protect skin cells from oxidative photodamage, which is induced by UVA light. Thus, ALA-PDT might be used for the prevention of diseases due to oxidative damage. However, in addition to the inducible antioxidant responses, more detailed studies on their antioxidant mechanism are still needed. Wang and Sun have reported that ALA-PDT suppressed IFN-γ-induced K17 expression in HaCaT cells via the MAPK pathway [62]. The MAPK signaling pathway is involved in many biological processes, such as cell proliferation, differentiation, gene expression, and apoptosis [63]. Further experiments are required to determine whether the MAPK pathway participated in the process of ALA-PDT exerting antioxidative effects. Also, our present experiments have failed to fully confirm whether ALA-PDT can prevent UVA-induced photodamage in vivo. In subsequent studies, we will further confirm whether ALA-PDT exerts photoprotective effect by eliciting an SOS-like response in vivo. The possibility of using ALA-PDT for skin photoprotection or the prevention of oxidative damage in humans deserves further investigation.

In summary, our results prove that ALA-PDT pretreatment can exert antioxidative damage by reducing the generation of ROS, O$_2^-$, and 8-oxo-dG, as well as diminishing the apoptosis of cells. We also elucidated the possible molecular mechanisms through which sublethal doses of ALA-PDT induced protective DNA damage responses in human keratinocytes. The inducible antioxidant responses are as follows: the p53-dependent upregulation of DNA repair capacity and the activation of antioxidant enzymes. These antioxidant responses can protect skin cells from oxidative photodamage, which is induced by UVA light.
References

[1] M. K. Tripp, M. Watson, S. J. Balk, S. M. Swetter, and J. E. Gerstenwald, “State of the science on prevention and screening to reduce melanoma incidence and mortality: the time is now,” *CA: A Cancer Journal for Clinicians*, vol. 66, no. 6, pp. 460–480, 2016.

[2] Health, US Department of, and Human Services, “The surgeon general’s call to action to prevent skin cancer,” *Environmental Policy Collection*, vol. 5, Supplement 1, p. 192, 2014.

[3] R. E. B. Watson, N. K. Gibbs, C. E. M. Griffiths, and M. J. Sherrat, “Damage to skin extracellular matrix induced by UV exposure,” *Antioxidants & Redox Signaling*, vol. 21, no. 7, pp. 1063–1077, 2014.

[4] J. Moan, Z. Baturai, A. C. Porojnicu, A. Dahlback, and A. Juuzeniene, “UVA, UVB and incidence of cutaneous malignant melanoma in Norway and Sweden,” *Photochemical & Photobiological Sciences*, vol. 11, no. 1, pp. 191–198, 2012.

[5] L. R. Sklar, F. Almutawa, H. W. Lim, and I. Hamzavi, “Effects of ultraviolet radiation, visible light, and infrared radiation on erythema and pigmentation: a review,” *Photochemical & Photobiological Sciences*, vol. 12, no. 1, pp. 54–64, 2013.

[6] B. A. Gilchrest, “Photoaging,” *Journal of Investigative Dermatology*, vol. 133, no. E1, pp. E2–E6, 2013.

[7] T. M. Rünger, B. Farahvash, Z. Hatvani, and A. Rees, “Comparison of DNA damage responses following equimutagenic doses of UVA and UVB: a less effective cell cycle arrest with UVA may render UVA-induced pyrimidine dimers more mutagenic than UVB-induced ones,” *Photochemical & Photobiological Sciences*, vol. 11, no. 1, pp. 207–215, 2012.

[8] H. T. Wang, B. Choi, and M. S. Tang, “Melanocytes are deficient in repair of oxidative DNA damage and UV-induced photoproduts,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, no. 27, pp. 12180–12185, 2010.

[9] N. Maddodi, A. Jayanthy, and V. Setaluri, “Shining light on skin pigmentation: the darker and the brighter side of effects of UV radiation,” *Photochemistry and Photobiology*, vol. 88, no. 5, pp. 1075–1082, 2012.

[10] S. González, M. Fernández-Lorente, and Y. Gilaberte-Calzada, “The latest on skin photoprotection,” *Clinics in Dermatology*, vol. 26, no. 6, pp. 614–626, 2008.

[11] S. Q. Wang, Y. Balagula, and U. Osterwalder, “Photoprotection: a review of the current and future technologies,” *Dermatologic Therapy*, vol. 23, no. 1, pp. 31–47, 2010.

[12] S. C. Thompson, D. Jolley, and R. Marks, “Reduction of solar keratoses by regular sunscreen use,” *The New England Journal of Medicine*, vol. 329, no. 16, pp. 1147–1151, 1993.

[13] A. Green, G. Williams, R. Néale et al., “Daily sunscreen application and betacarotene supplementation in prevention of basal-cell and squamous-cell carcinomas of the skin: a randomised controlled trial,” *The Lancet*, vol. 354, no. 9180, pp. 723–729, 1999.

[14] H.-J. Kim, E. Lee, M. Lee et al., “Phosphodiesterase 4b plays a role in benzosphenone-3-induced phototoxicity in normal human keratinocytes,” *Toxicology and Applied Pharmacology*, vol. 338, pp. 174–181, 2018.

[15] S. Q. Wang, H. Xu, J. W. Stanfield, U. Osterwalder, and B. Herzog, “Comparison of ultraviolet a light protection standards in the United States and European Union through in vitro measurements of commercially available sunscreens,” *Journal of the American Academy of Dermatology*, vol. 77, no. 1, pp. 42–47, 2017.

[16] C. H. Kim, C. Chung, K. H. Choi et al., “Effect of 5-aminolevulinic acid-based photodynamic therapy via reactive oxygen species in human cholangiocarcinoma cells,” *International Journal of Nanomedicine*, vol. 6, pp. 1357–1363, 2011.

[17] L. W. Zhang, Y. P. Fang, and J. Y. Fang, “Enhancement techniques for improving 5-aminolevulinic acid delivery through the skin,” *Dermatologica Sinica*, vol. 29, no. 1, pp. 1–7, 2011.

[18] J. Ji, L. L. Zhang, H. L. Ding et al., “Comparison of 5-aminolevulinic acid photodynamic therapy and red light for treatment of photosaging,” *Photodiagnosis and Photodynamic Therapy*, vol. 11, no. 2, pp. 118–121, 2014.

[19] X. Ge, J. Liu, Z. Shi et al., “Inhibition of Mapk signaling pathways enhances cell death induced by 5-aminolevulinic acid photodynamic therapy in skin squamous carcinoma cells,” *European Journal of Dermatology*, vol. 26, no. 2, pp. 164–172, 2016.

[20] L. H. Goldberg, J. M. Landau, M. N. Moody et al., “Evaluation of the chemopreventative effects of ALA PDT in patients with multiple actinic keratoses and a history of skin cancer,” *Journal of Drugs in Dermatology*, vol. 11, no. 5, pp. 593–597, 2012.

[21] K. Togsverd-Bo, S. H. Omland, H. C. Wulf, S. S. Sørensen, and M. Haedersdal, “Primary prevention of skin dysplasia in renal transplant recipients with photodynamic therapy: a randomized controlled trial,” *American Journal of Transplantation*, vol. 15, no. 11, pp. 2986–2990, 2015.

[22] Z. Zhou, J. Song, L. Nie, and X. Chen, “Reactive oxygen species generating systems meeting challenges of photodynamic cancer therapy,” *Chemical Society Reviews*, vol. 45, no. 23, pp. 6597–6626, 2016.

[23] P. T. Schumacker, “Reactive oxygen species in cancer: a dance with the devil,” *Cancer Cell*, vol. 27, no. 2, pp. 156–157, 2015.

[24] B. R. Zhou, L. C. Zhang, F. Permatasari, J. Liu, Y. Xu, and D. Luo, “ALA-PDT elicits oxidative damage and apoptosis in...
UVB-induced premature senescence of human skin fibroblasts," *Photodiagnostics and Photodynamic Therapy*, vol. 14, pp. 47–56, 2016.

[25] M. V. Gozali, F. Yi, J.-a. Zhang et al., "Photodynamic therapy inhibit fibroblast growth factor-10 induced keratinocyte differentiation and proliferation through ROS in fibroblast growth factor receptor-2b pathway," *Scientific Reports*, vol. 6, no. 1, p. 27402, 2016.

[26] A. Svobodová and J. Vostálová, "Solar radiation induced skin damage: review of protective and preventive options," *International Journal of Radiation Biology*, vol. 86, no. 12, pp. 1099–1030, 2010.

[27] A. Valavanidis, T. Vlachogianni, and C. Fiotakis, "8-Hydroxy-2′-deoxyguanosine (8-ohdg): a critical biomarker of oxidative stress and carcinogenesis," *Journal of Environmental Science and Health*, Part C, vol. 27, no. 2, pp. 120–139, 2009.

[28] S. Hu, F. Chen, and M. Wang, "Photo-protective effects of oxy-resveratrol and kuwanon O on DNA damage induced by UVA in human epidermal keratinocytes," *Chemical Research in Toxicology*, vol. 28, no. 3, pp. 541–548, 2015.

[29] E. Maverakis, Y. Miyamura, M. P. Bowen, G. Correa, Y. Ono, and H. Goodarzi, "Light, including ultraviolet," *Journal of Autoimmunity*, vol. 34, no. 3, pp. J247–J257, 2010.

[30] M. S. Cooke, M. D. Evans, M. Dizdaroglu, and J. Lunev, "Oxidative DNA damage: mechanisms, mutation, and disease," *The FASEB Journal*, vol. 17, no. 10, pp. 1195–1214, 2003.

[31] N. Morley, A. Rapp, H. Dittmar et al., "UVA-induced apoptosis studied by the new apo-necro-Comet-assay which distinguishes viable, apoptotic and necrotic cells," *Mutagenesis*, vol. 21, no. 2, pp. 105–114, 2006.

[32] Y. C. Hseu, C. W. Chou, K. J. Senthil Kumar et al., "Ellagic acid protects human keratinocyte (HaCaT) cells against UVA-induced oxidative stress and apoptosis through the upregulation of the HO-1 and Nrf-2 antioxidant genes," *Food and Chemical Toxicology*, vol. 50, no. 5, pp. 1245–1255, 2012.

[33] M. Ichihashi, M. Ueda, A. Budiyanto et al., "U.V-induced skin damage," *Toxicology*, vol. 189, no. 1-2, pp. 21–39, 2003.

[34] C. Q. Yuan, Y. N. Li, and X. F. Zhang, "Down-regulation of apoptosis-inducing factor protein by RNA interference inhibits UVA-induced cell death," *Biochemical and Biophysical Research Communications*, vol. 317, no. 4, pp. 1108–1113, 2004.

[35] G. Petrak, F. di Lorenzo, P. Imbimbo et al., "Protective effect of Opuntia ficus-indica L. cladodes against UVA-induced oxidative stress in normal human keratinocytes," *Bioorganic & Medicinal Chemistry Letters*, vol. 27, no. 24, pp. 5485–5489, 2017.

[36] L. Chen, J. Y. Hu, and S. Q. Wang, "The role of antioxidants in photoprotection: a critical review," *Journal of the American Academy of Dermatology*, vol. 67, no. 5, pp. 1013–1024, 2012.

[37] A. Svozlová, A. Zdárnilová, J. Malísková, H. Mikulková, D. Walterová, and J. Vostálová, "Attenuation of UVA-induced damage to human keratinocytes by silymarin," *Journal of Dermatological Science*, vol. 46, no. 1, pp. 21–30, 2007.

[38] Y. Liu, F. Chan, H. Sun et al., "Resveratrol protects human keratinocytes HaCaT cells from UVA-induced oxidative stress damage by downregulating Keap1 expression," *European Journal of Pharmacology*, vol. 650, no. 1, pp. 130–137, 2011.

[39] L. Marrot, C. Jones, P. Perez, and J.-R. Meunier, "The significance of Nrf2 pathway in (photo)-oxidative stress response in melanocytes and keratinocytes of the human epidermis," *Pigment Cell & Melanoma Research*, vol. 21, no. 1, pp. 79–88, 2008.

[40] M. S. Lee, M. Yaar, M. S. Eller, T. M. Rünger, Y. Gao, and B. A. Gilchrest, "Telomeric DNA induces P53-dependent reactive oxygen species and protects against oxidative damage," *Journal of Dermatological Science*, vol. 56, no. 3, pp. 154–162, 2009.

[41] S. Arad, N. Konnikov, D. A. Goukassian, and B. A. Gilchrest, "T′-Oligos augment UV-induced protective responses in human skin," *The FASEB Journal*, vol. 20, no. 11, pp. 1895–1897, 2006.

[42] B. A. Gilchrest, "Telomere-based protective responses to DNA damage," *Journal of Investigative Dermatology Symposium Proceedings*, vol. 17, no. 1, pp. 15–16, 2015.

[43] S. Arad, N. Konnikov, D. A. Goukassian, and B. A. Gilchrest, "Quantification of inducible SOS-like photoprotective responses in human skin," *Journal of Investigative Dermatology*, vol. 127, no. 11, pp. 2629–2636, 2007.

[44] D. M. Smith and G. P. Raaphorst, "Adaptive responses in human glioma cells assessed by clonogenic survival and DNA strand break analysis," *International Journal of Radiation Biology*, vol. 79, no. 5, pp. 333–339, 2009.

[45] M. Radman, "SOS repair hypothesis: phenomenology of an inducible DNA repair which is accompanied by mutagenesis," in *Molecular Mechanisms for Repair of DNA*, Basic Life Sciences, P. C. Hanawalt and R. B. Setlow, Eds., pp. 355–367, Springer, Boston, MA, USA, 1975.

[46] Y. C. Hseu, H. W. Lo, M. Korivi, Y. C. Tsai, M. J. Tang, and H. L. Yang, "Dermato-protective properties of ergothioneine through induction of Nrf2/ARE-mediated antioxidant genes in UVA-irradiated human keratinocytes," *Free Radical Biology & Medicine*, vol. 86, pp. 102–117, 2015.

[47] V. C. Cullotta, M. Yang, and T. V. O’Halloran, "Activation of superoxide dismutases: putting the metal to the pedal," *Biochimica et Biophysica Acta (BBA) - Molecular Cell Research*, vol. 1763, no. 7, pp. 747–758, 2006.

[48] F. Johnson and C. Giulivi, "Superoxide dismutases and their impact upon human health," *Molecular Aspects of Medicine*, vol. 26, no. 4–5, pp. 340–352, 2005.

[49] I. N. Zelko, T. J. Mariani, and R. J. Folz, "Superoxide dismutase multigen family: a comparison of the CuZn-SOD (Sod1), Mn-SOD (Sod2), and EC-SOD (Sod3) gene structures, evolution, and expression," *Free Radical Biology & Medicine*, vol. 33, no. 3, pp. 337–349, 2002.

[50] M. T. Leccia, M. Yaar, N. Allen, M. Gleason, and B. A. Gilchrest, "Solar simulated irradiation modulates gene expression and activity of antioxidant enzymes in cultured human dermal fibroblasts," *Experimental Dermatology*, vol. 10, no. 4, pp. 272–279, 2001.

[51] S. Arad, E. Zattra, J. Hebert, E. H. Epstein Jr, D. A. Goukassian, and B. A. Gilchrest, "Topical thymidine dinucleotide treatment reduces development of ultraviolet-induced basal cell carcinoma in Pch-1+/− mice," *The American Journal of Pathology*, vol. 172, no. 5, pp. 1248–1255, 2008.

[52] B. Leuner, S. Ruhs, H. J. Brömmle et al., "RAGE-dependent activation of gene expression of superoxide dismutase and vanins by AGE-rich extracts in mice cardiac tissue and murine cardiac fibroblasts," *Food & Function*, vol. 3, no. 10, pp. 1091–1098, 2012.

[53] J. H. J. Hoeijmakers, "Genome maintenance mechanisms for preventing cancer," *Nature*, vol. 411, no. 6835, pp. 366–374, 2001.
[54] E. C. Friedberg, “DNA damage and repair,” Nature, vol. 421, no. 6921, pp. 436–440, 2003.
[55] E. Parlanti, M. D’Errico, P. Degan et al., “The cross talk between pathways in the repair of 8-oxo-7,8-dihydroguanine in mouse and human cells,” Free Radical Biology & Medicine, vol. 53, no. 11, pp. 2171–2177, 2012.
[56] M. D’Errico, E. Parlanti, M. Teson et al., “New functions of XPC in the protection of human skin cells from oxidative damage,” EMBO Journal, vol. 25, no. 18, pp. 4305–4315, 2006.
[57] K. L. Brown, M. Roginskaya, Y. Zou, A. Altamirano, A. K. Basu, and M. P. Stone, “Binding of the human nucleotide excision repair proteins XPA and XPC/HR23B to the 5R-thymine glycol lesion and structure of the cis-(5R,6S) thymine glycol epimer in the 5′-GTG-3′ sequence: destabilization of two base pairs at the lesion site,” Nucleic Acids Research, vol. 38, no. 2, pp. 428–440, 2010.
[58] S. Adimoolam and J. M. Ford, “P53 and DNA damage-inducible expression of the xeroderma pigmentosum group C gene,” Proceedings of the National Academy of Sciences of the United States of America, vol. 99, no. 20, pp. 12985–12990, 2002.
[59] M. Poletto, A. J. Legrand, S. C. Fletcher, and G. L. Dianov, “P53 coordinates base excision repair to prevent genomic instability,” Nucleic Acids Research, vol. 44, no. 7, pp. 3165–3175, 2016.
[60] S. Takeuchi, W. Zhang, K. Wakamatsu et al., “Melanin acts as a potent UVB photosensitizer to cause an atypical mode of cell death in murine skin,” Proceedings of the National Academy of Sciences of the United States of America, vol. 101, no. 42, pp. 15076–15081, 2004.
[61] S. Jiang, X.-M. Liu, X. Dai et al., “Regulation of DHICA-mediated antioxidation by dopachrome tautomerase: implication for skin photoprotection against UVA radiation,” Free Radical Biology & Medicine, vol. 48, no. 9, pp. 1144–1151, 2010.
[62] X. L. Wang and Q. Sun, “Photodynamic therapy with 5-aminolevulinic acid suppresses IFN-γ-induced K17 expression in HaCaT cells via MAPK pathway,” European Review for Medical and Pharmacological Sciences, vol. 21, no. 20, pp. 4694–4702, 2017.
[63] J. M. Kyriakis and J. Avruch, “Mammalian MAPK signal transduction pathways activated by stress and inflammation: a 10-year update,” Physiological Reviews, vol. 92, no. 2, pp. 689–737, 2012.