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Aqueous Extract from Taiwanese *Agrocybe cylindracea* strain B Protects DNA against $\cdot\text{OH}$ - mediated Strand Breaks

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ABSTRACT

Water extract from *Agrocybe cylindracea* strain B (ACE), an edible mushroom produced in Taiwan, has previously been studied for its antioxidative activities. ACE is an efficient antioxidant *in vitro*. Since oxidative alterations of DNA can be linked to the development of cancer, we decided to study whether ACE protects DNA against oxidative stress. We report here that pUC18 plasmid DNA and HepG2 cells' DNA are damaged by $\cdot\text{OH}$ radicals generated from Cu (II) plus H_2O_2 . The DNA damage was quantified by determining the diminution of supercoiled DNA forms and the DNA migration after oxidative attack using agarose gel electrophoresis. The IC_{50} values of ACE were 69.7 $\mu\text{g}/\text{mL}$ and 91.6 $\mu\text{g}/\text{mL}$ for cupric-mediated $\cdot\text{OH}$ formation by determining the diminution of supercoiled DNA forms and Comet assay, respectively. The antioxidant capacity of ACE was significantly higher than that of *Lentinus edodes* extract (LEE) and the two known scavengers of hydroxyl radical, mannitol and thiourea. ACE and LEE could also inhibit the oxidative degradation of 2'-deoxyribose caused by $\cdot\text{OH}$ radicals generated from metal ions plus H_2O_2 . The malondialdehyde (MDA) inhibition effect of active fractional protein from ACE was better than that of LEE. The major protein components of ACE were different from LEE.

Key words: *Agrocybe cylindracea*, DNA damage, hydroxyl radical, antioxidative activity

INTRODUCTION

Oxidative DNA damage by reactive oxygen species (ROS) has been hypothesized to play a critical role in several diverse biological processes including mutagenesis, carcinogenesis, aging, radiation damage, and cancer chemotherapy⁽¹⁻²⁾. Cellular metabolism has been shown to generate oxygen species such as hydrogen peroxide (H_2O_2), hydroxyl radical ($\cdot\text{OH}$), singlet oxygen ($^1\text{O}_2$), superoxide anion (O_2^-), and hydroperoxyl radical⁽³⁾. They attack biological molecules and induced damage to cell or tissue injury⁽⁴⁾.

The limitation of synthetic antioxidants such as BHA, BHT, TBHQ and others have been shown in reviews of toxicity, cancer and promutagenic activity. This has resulted in increased demand for natural antioxidants. Much attention has been focused on antioxidant mechanism from natural sources⁽⁵⁾. Recently, research on phytochemicals in food materials and their effects on health, especially the suppression of active oxygen species by natural antioxidants from teas⁽⁶⁾, spices⁽⁷⁾, and mushrooms⁽⁸⁻¹¹⁾,

had been intensively studied. It has been shown that certain species of mushrooms have the capacity to lower plasma cholesterol level⁽¹²⁻¹⁴⁾ and blood pressure⁽¹⁵⁾, antitumor activity⁽¹⁶⁻¹⁷⁾ and antidiabetic activity⁽¹⁸⁾. Also, antioxidant and free radical scavenging activities of mushrooms and their constituents have been demonstrated using *in vitro* systems^(5,19-22).

Agrocybe cylindracea (DC: Fr.) Mre. [*syn. Agrocybe cylindracea* (Briganti) Singer] strain B is a newly cultured edible mushroom in Taiwan⁽²²⁾. It was introduced from Japan into Taiwan by Lung-Kuo Mushroom Farm, Taichung, since 1986⁽²²⁾. It has been reported that *A. cylindracea* had antitumor activity⁽²³⁾ and free radical scavenging activity⁽²⁴⁾. We recently demonstrated that water extract from *A. cylindracea* strain B (ACE) has antioxidant activity against iron-mediated lipid peroxidation of liposome⁽²⁵⁾. However, a few data are available about the protective activity of ACE on DNA damage induced by ROS. In the present study investigates the protection effects of ACE and its protein fraction on DNA damage induced by ROS. The water extract of shiitake mushroom *L. edodes* (LEE) used as a control for comparison of protection effect of ACE was also investigated.

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MATERIALS AND METHODS

I. Preparation of Mushroom Extracts

The strain B of *A. cylindracea* was cultivated at Lung-Kuo Mushroom Cultivation Farm, (Taichung, Taiwan). *L. edodes* was purchased at a supermarket in Taichung. Mushrooms were harvested before the veils broke, and sliced and ground with Waring Blender. Then the antioxidants were extracted as follows: 200 g of mushroom was extracted with 400 mL of deionized water for 30 min, and then centrifuged at 12,000 rpm for 30 min at 4°C. All extracts were filtered using Whatman No. 1 filter paper. Extraction was repeated twice, and the combined filtrates were dried with lyophilizer.

II. Assay of DNA Breakage

DNA breaks were detected using an adaptation of the method described above⁽²⁾. Supercoiled plasmid DNA (pUC18, 0.1 μ g) in 0.145 M NaCl, 0.01 M sodium phosphate, pH 7.0, was incubated for 1 hr at 37°C with 10 μ M CuSO₄ / 1 mM H₂O₂ and /or mushroom extracts in a total volume of 4 μ L. DNA damage occurred with 250 μ M H₂O₂ plus 2.5 μ M Cu (II). The reaction was stopped by addition of 1 μ L of 0.5 M EDTA (pH 8.0). One microliter of loading buffer [0.025% bromophenol blue, 0.025% xylene cyanole, 40% sucrose in 0.4 M Tris, 0.2 M sodium acetate, 0.02 M EDTA, pH 7.8 (10 \times TAE buffer)] was added and the samples were analyzed by carrying out electrophoresis for 60 min at 50 V in 1% agarose in 1 \times TAE buffer. The gel was stained with ethidium bromide and photographed.

III. Electron Paramagnetic Resonance (EPR) Spectrometry

The hydroxyl radical was detected using an adaptation of the method previously described⁽²⁶⁾. The hydroxyl radical rapidly reacts with the nitron spin trap 5,5-dimethyl pyrrolidine-N-oxide (DMPO) and the resultant DMPO-OH adduct was detected with an Electron Paramagnetic Resonance (EPR) spectrometry. The EPR spectrum was recorded for 2.5 min after mixing sample with phosphate buffer (0.1 M, pH 7.4), 10 mM EDTA, 10 mM H₂O₂, 0.3 M DMPO and 5 mM FeSO₄ using an EPR spectrometer (Bruker EMX-10/12, Germany) set at the following conditions: 3480-G magnetic field, 1.0 G modulation amplitude, 0.5 S time constant and 200 S scan period.

IV. Cell Culture

The HepG2 cells were obtained from American Type Culture Collection (ATCC). The cells were routinely grown in Dulbecco's Modified Eagle Medium (DMEM, Gibco BRL) supplemented with 10% (v/v) fetal bovine serum (FBS, Gibco BRL), 2 mM glutamine, 10 mM non-essential amino acid, 100 mM sodium pyruvate solution,

5.5% bicarbonate, 100 U/mL penicillin and 100 μ g/mL streptomycin. The cultures were incubated at 37°C in a humidified atmosphere containing 5% CO₂. The cells were subcultured every 3 to 4 days.

V. CuSO₄ / H₂O₂-induced DNA Damage in HepG2 Cells

To induce DNA damage, HepG2 cells (5×10^5) grown in 5 cm dishes were exposed to 10 μ M CuSO₄ / 1 mM H₂O₂ in the presence or absence of mushroom extracts (0.05, 0.1 or 0.2 mg/mL) in DMEM medium for 2 hr at 37°C in 5% CO₂ / 95% air. The cells were washed twice with phosphate buffer saline (1 \times PBS), pH 7.4, and trypsinized. The cells were centrifuged at 3,500 rpm for 5 min at 4°C and suspended in low melting point agarose (1%) for Comet assay.

V. Single Cell Gel Electrophoresis Assay (Comet Assay)

DNA breaks were detected using an adaptation of the method previously described⁽²⁷⁾. HepG2 cells treated with 10 μ M CuSO₄ / 1 mM H₂O₂ and / or mushroom extract were suspended in 80 μ L 1% (w/v) low melting point agarose in PBS (pH 7.4) at 37°C. The treated cells were immediately pipetted onto frosted glass microscope slides precoated with a layer of 1% (w/v) normal melting point agarose similarly prepared in PBS. The agarose was allowed to set for 10 min on ice and then the slides were immersed in lysis solution (2.5 M NaCl, 100 mM Na₂EDTA, 10 mM Tris, 1% sodium lauroylsarcosinate, pH 10.0 with NaOH, 10% v/v dimethyl sulfoxide and 1% v/v Triton X-100) at 4°C for 1 hr to remove cellular proteins. Slides were then placed in a horizontal electrophoresis tank containing electrophoresis buffer (300 mM NaOH and 1 mM Na₂EDTA) for 15 min before electrophoresis at 25 V, 300 mA for 25 min. Then the slides were washed 3 times for 5 min each with neutralizing solution (0.4 M Tris-HCl, pH 7.5) at room temperature before they were stained with 20 μ g/mL ethidium bromide. Ethidium bromide-stained slides were examined under a Nikon Eclipse TE-200 fluorescence microscope (Nikon, Japan). Fifty comets on 3 slides were quantified by computerized image analysis Inspectrox 2.1 (Matrox Electronic System Ltd., Canada) on the basis of DNA migration (tail length). The untreated HepG2 cells (blank control) and cells treated with benzo[a]pyrene (BaP), a known inducer of DNA migration, were included in each Comet assay. The DNA migrations of blank controls were very low. This showed that no DNA damage was caused by the comet assay. Each data represents the means \pm SD of three separate experiments.

VI. ACE Fraction and SDS-PAGE Analysis

The fraction analysis was performed according to the method previously described⁽²⁸⁾. Mushroom extract protein was isolated as follows: the ACE solution was applied to a carboxymethyl-cellulose (CM cellulose) column (2.2 \times 30

cm) which was previously equilibrated with 10 mM sodium acetate (pH 5.2). The column was first washed with 10 mM equilibration buffer and then eluted with 100 mL of 0.5N NaCl in 10 mM sodium acetate (pH 5.2). The LEE solution was applied to a DEAE - cellulose column (2.2 × 30 cm) which was previously equilibrated with 10 mM phosphate buffer (pH 7.8). The column was first washed with 10 mM equilibration buffer and then eluted with 100 mL of 0.5N NaCl in 10 mM phosphate buffer (pH 7.8). Collection was eluted by fraction collector at a rate of 1 tube / min and then detected protein content and total carbohydrates with spectrophotometer at 280 nm and 490 nm, according to the ultraviolet absorption assay⁽²⁹⁾ and the phenol-sulfuric acid method⁽³⁰⁾, respectively. Mushroom protein fractions and crude extracts were resolved using SDS-PAGE with 10% polyacrylamide gel at 100 V for 100 min on a Hoefer mini slab gel apparatus. The gel was then stained with Coomassie brilliant blue R solution. Its antioxidative activity was measured by TBA method as described in the following section.

VII. Determination of Damage to 2'-Deoxyribose

The inhibition effect on oxidative degradation of 2'-deoxyribose was determined by the thiobarbituric acid

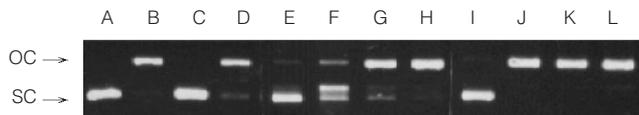


Figure 1. Typical agarose gel of pUC18 DNA showing bands of supercoiled (SC) and open circular (OC) forms. Experimental conditions are as described in Materials and Methods. Lanes on the gel represent: (A) control (no H₂O₂ or Cu²⁺), (B) 250 μM H₂O₂ + 2.5 μM Cu²⁺, (C) 2.5 mM mannitol alone, (D) 250 μM H₂O₂ + 2.5 μM Cu²⁺ plus 2.5 mM mannitol, (E) 62.5 μg/mL ACE alone, (F-H) 250 μM H₂O₂ + 2.5 μM Cu²⁺ plus ACE (F) 62.5, (G) 25.0, or (H) 12.5 μg/mL, (I) 62.5 μg/mL LEE alone, (J-L) 250 μM H₂O₂ + 2.5 μM Cu²⁺ plus LEE (J) 62.5, (K) 25.0, or (L) 12.5 μg/mL. Abbreviations: ACE, water-extract from *A. cylindracea*. LEE, water-extract from *L. edodes*.

(TBA) methods⁽³¹⁻³²⁾ after incubating the reaction mixture for 1 hr at 37°C. Hydroxyl radical was generated by a mixture of ascorbic acid, H₂O₂ and metal ions-EDTA, attacking 2'-deoxyribose to degrade into fragments that give rise to a chromogen upon heating with thiobarbituric acid under acidic condition. Therefore, 1 mM 2'-deoxyribose in 0.1 M sodium phosphate (pH 7.4) was incubated for 1 hr at 37°C with 10 μM EDTA, 10 μM ascorbic acid, 1 mM H₂O₂, 10 μM Cu²⁺ and / or ACE, LEE, other scavengers and mushroom protein fractions in a total volume of 1 mL. The reaction was stopped by addition of 0.1 mL of 20 mg/mL BHT. Damage to 2'-deoxyribose caused by H₂O₂ plus Cu (II) (in 100 mM PBS buffer, pH 7.4) was determined by quantification of TBARs at 532 nm. All test data are presented as an average of triplicate analyses.

VIII. Statistical Analysis

Results are expressed as the mean ± SD, with n = 3. Statistical evaluations were performed by analysis of variance followed by Duncan's test for dose-response data; *p* < 0.05 was considered significant.

RESULTS

I. Preparation of Mushroom Extracts

All extracts were combined and dried with lyophilizer. The yields of powder of ACE and LEE were 44.13% (dry basis) and 42.35% (dry basis), respectively.

II. Prevention of DNA Damage by ACE and Other Scavengers

To understand whether ACE could prevent DNA damage induced by oxidative stress, another known scavenger, mannitol, was selected as positive control. As shown in Figure 1, control preparations of pUC18

Table 1. Protection against oxidative damage to pUC18 by ACE and other chelators

Treatment	SC DNA (%) ^a	Protection (%) ^b	IC ₅₀ (μg/mL)
Solvent control	88.75 ± 3.38	100	
250 μM H ₂ O ₂ / 2.5 μM CuSO ₄	47.91 ± 3.02	0	
+ ACE 62.5 μg/mL	65.45 ± 6.79*	42.95	
+ ACE 25.0 μg/mL	55.52 ± 2.05*	18.65	69.7
+ ACE 12.5 μg/mL	46.05 ± 4.13	0	
+ LEE 62.5 μg/mL	54.31 ± 14.22	15.67	
+ LEE 25.0 μg/mL	53.36 ± 16.48	13.35	326.18
+ LEE 12.5 μg/mL	51.28 ± 14.67	8.26	
+ mannitol 2.5 mM	56.34 ± 2.08*	20.64	
mannitol 2.5 mM alone	87.15 ± 3.88	–	
ACE 62.5 μg/mL alone	86.03 ± 4.68	–	
LEE 62.5 μg/mL alone	85.42 ± 3.21	–	

^aExperimental conditions are as described in Materials and Methods. Values are means ± SD (n = 3). SC DNA (%) = percentage of supercoiled form DNA.

^bThe % protection was calculated as: % protection = 100 × [1 - (% SC of control - % SC of scavenger) / (% SC of control - % SC of H₂O₂ / Cu (II))].

*Significantly different from positive control at *p* ≤ 0.05. Abbreviations are the same as Figure 1.

Table 2. Effect of ACE and LEE on EPR signal intensity of DMPO-OH spin adducts

Sample	Relative EPR signal intensity ^a			IC ₅₀ ($\mu\text{g/mL}$)
	(IP % ^b)			
	Extract dose (mg/mL)			
	0.1	0.5	2.0	
Control	100	100	100	
Mannitol	–	–	51.3 \pm 0.2*(49)	N.D.
Thiourea	–	32.3 \pm 0.4*(68)	–	N.D.
ACE	49.0 \pm 0.5*(51)	8.2 \pm 0.6*(92)	3.2 \pm 0.3*(97)	< 100
LEE	105.5 \pm 0.8 (-5)	86.0 \pm 0.4*(14)	53.1 \pm 0.6*(47)	> 2000

^aExperimental conditions are as described in Materials and Methods. Relative EPR signal intensity (%) = {[h Δ H2(sample) / h Δ H2 (dpph)] / [h Δ H2 (control) / h Δ H2 (dpph)]} \times 100. h = the width of the peak, Δ H = the length of the peak stress. Values are means \pm SD (n = 3).

^bIP (%) = Percentage of inhibition = [relative EPR signal intensity of solvent control- relative EPR signal intensity of treatment]

*Significantly lower than solvent control at $p \leq 0.05$. Each value is the means of 4 peaks. Abbreviations are the same as Figure 1.

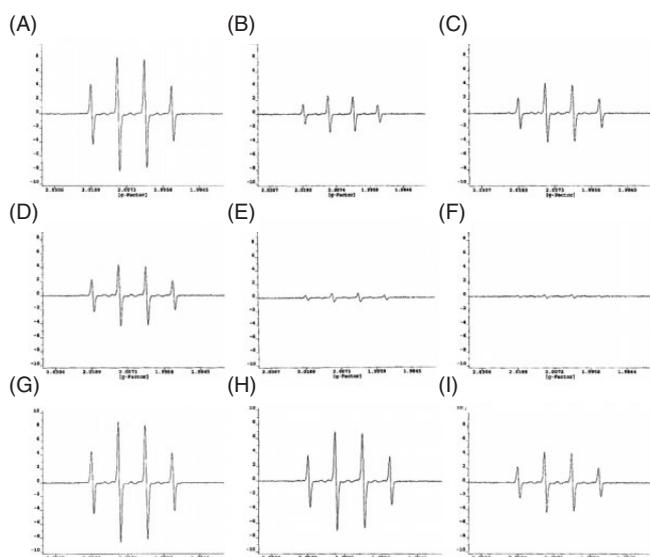


Figure 2. Typical EPR signal of DMPO-OH spin adduct. (A) control; (B) 0.5 mg/mL thiourea; (C) 2.0 mg/mL mannitol; (D-F) 0.1, 0.5 and 2.0 mg/mL of ACE, respectively; (G-I) 0.1, 0.5 and 2.0 mg/mL of LEE, respectively. Abbreviations are the same as Figure 1.

contained 88.75 \pm 3.38% supercoiled (SC) DNA (lane A), and the levels of which were not affected by incubation with 2.5 mM mannitol, 62.5 $\mu\text{g/mL}$ ACE or LEE for 1 hr (lane C, E and I, respectively). ACE at a concentration of 62.5 $\mu\text{g/mL}$ and 25 $\mu\text{g/mL}$ protected pUC18 DNA from damage while hydroxyl radicals were generated by 2.5 μM Cu (II) plus 250 μM H₂O₂ (lane F-G). However, addition of increasing concentrations of ACE caused the protection effect on breakage of pUC18. More protection occurred with ACE than LEE under the same concentrations. A quantitative comparison of the protective effect of ACE or LEE against the DNA damage induced by $\cdot\text{OH}$ -mediated reagents is shown in Table 1. IC₅₀ is the concentration of scavengers required to inhibit the DNA damage of oxidative stress by 50%. These values were derived from extrapolation of the dose-response curves. Although all scavengers had little efficiency in protecting against DNA damage, ACE was more effective than LEE. On the basis of IC₅₀, the protection effect of ACE was 5-fold greater than that of LEE.

Table 3. Effect of ACE and other chelators on the 2'-deoxyribose damage induced by H₂O₂/ Cu²⁺

Treatment	OD 532 nm \pm SD (IP % ^a)	IC ₅₀ ($\mu\text{g/mL}$)
Solvent control	0.661 \pm 0.009 (0.0)	---
ACE		
2000 $\mu\text{g/mL}$	0.033 \pm 0.005* (95.0)	
500 $\mu\text{g/mL}$	0.077 \pm 0.004* (88.4)	
100 $\mu\text{g/mL}$	0.223 \pm 0.026* (66.3)	49.12
LEE		
2000 $\mu\text{g/mL}$	0.034 \pm 0.009* (94.8)	
500 $\mu\text{g/mL}$	0.202 \pm 0.007* (69.5)	
100 $\mu\text{g/mL}$	0.461 \pm 0.009* (30.3)	358.26
Mannitol		
2000 $\mu\text{g/mL}$	0.329 \pm 0.015* (50.3)	
500 $\mu\text{g/mL}$	0.422 \pm 0.007* (36.1)	
100 $\mu\text{g/mL}$	0.520 \pm 0.006* (21.4)	1903.31
Thiourea		
2000 $\mu\text{g/mL}$	0.068 \pm 0.007* (89.7)	
500 $\mu\text{g/mL}$	0.135 \pm 0.008* (79.6)	
100 $\mu\text{g/mL}$	0.457 \pm 0.005* (30.9)	256.77

^aIP (%): inhibition percentage = [1-(OD₅₃₂ of treatment/ OD₅₃₂ of solvent control)] \times 100%. 2-Deoxyribose was treated with H₂O₂/Cu(II) plus various concentrations of ACE or LEE at 37°C for 1 hr. Abbreviations are the same as Figure 1.

*Significantly lower than solvent control at $p \leq 0.05$. The mean \pm SD is given for 3 independent experiments.

II. ACE Prevents the Formation of Hydroxyl Radicals

We demonstrated that ACE inhibits oxidative DNA damage caused by Cu (II) plus H₂O₂. The EPR studies using DMPO as a spin trap indicated that ACE can inhibit the generation of $\cdot\text{OH}$ radicals *via* the Fenton reaction. ACE had better inhibition effect than LEE and thiourea (Table 2 and Figure 2). As shown in Table 2, 0.5 mg/mL ACE inhibited 92% of DMPO-OH adduct caused by Fe (II) plus H₂O₂, while only 14% and 68% of DMPO-OH adduct was inhibited by LEE and thiourea under the same concentration of 0.5 mg/mL, respectively.

ACE and LEE could also significantly inhibit the oxidative degradation of 2'-deoxyribose caused by $\cdot\text{OH}$ radicals generated from Cu (II) plus H₂O₂. The inhibition effect on oxidative degradation of 2'-deoxyribose caused by $\cdot\text{OH}$ radicals is shown in Table 3. IC₅₀ values were derived from interpolation and extrapolation of the dose-

response curves. IC_{50} of ACE was 49 $\mu\text{g}/\text{mL}$ which was lower than that of LEE (358 $\mu\text{g}/\text{mL}$), thiourea (257 $\mu\text{g}/\text{mL}$) and mannitol (1903 $\mu\text{g}/\text{mL}$). On the basis of IC_{50} , the protection effect of ACE was 7-, 5- and 38-fold greater than that of LEE, thiourea and mannitol, respectively.

III. Effect of ACE on DNA Strand Breakage in HepG2 Cells

We also investigated the inhibitory effect of ACE in HepG2 cells on Cu (II)/ H_2O_2 -induced DNA damage using the single cell electrophoresis (Comet) assay. The DNA migrations of blank controls were the same as the solvent controls. This showed that no DNA damage was caused by Comet assay. As shown in Figure 3, ACE (200 $\mu\text{g}/\text{mL}$) significantly inhibited 10 μM Cu (II)/ 1 mM H_2O_2 -induced DNA damage (Figure 3F) and did not itself produce DNA damage (Figure 3E). A quantitative comparison of the protective effect of ACE or LEE against the DNA damage induced by $\cdot\text{OH}$ -mediated reagents is shown in Table 4. ACE (200 $\mu\text{g}/\text{mL}$) inhibited 67% of DNA damage caused by Cu (II) plus H_2O_2 in HepG2 cells, while only 47% of DNA damage was inhibited by LEE under the same conditions employed as shown in Table 4. IC_{50} is the concentration of scavengers required to inhibit the DNA damage of oxidative stress by 50%. These values were derived from interpolation and extrapolation of the dose-response curves. IC_{50} of ACE was 91.58 $\mu\text{g}/\text{mL}$ which was lower than that of LEE (214.14 $\mu\text{g}/\text{mL}$). Based on the IC_{50} , the protection effect of ACE was 2.3-fold greater than that of LEE.

IV. Effect of ACE Fractions on Oxidation of 2'-Deoxyribose

To further verify whether the inhibition activity of ACE on oxidative DNA damage induced by hydroxyl

radicals is mediated through protein or other carbohydrates, ACE was fractionated with CM-cellulose column. The fraction profiles (such as protein content and total carbohy-

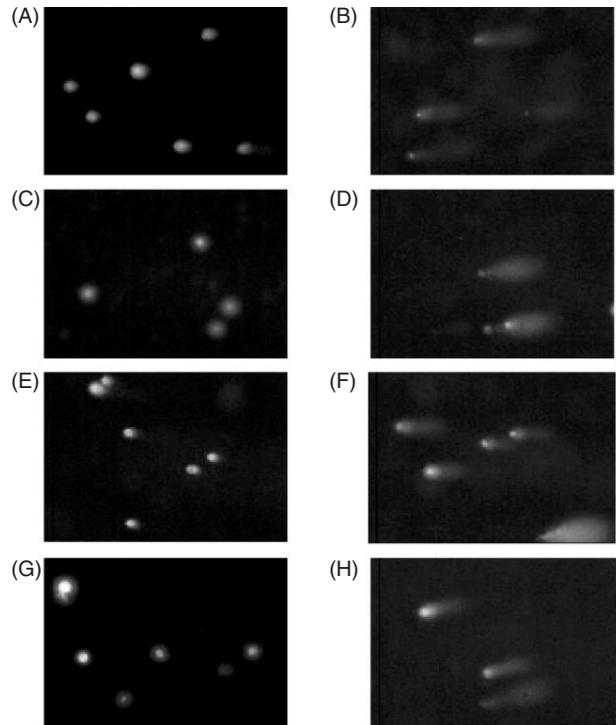


Figure 3. Representative comet images of HepG2 cells following treatment with mushroom extracts and/or 1 mM H_2O_2 plus 10 μM Cu (II). Cells were treated with sample with or without H_2O_2 plus Cu (II) at 37°C for 2 hr. (A) DMSO; (B) Bap 20 μM ; (C) control; (D) 1 mM H_2O_2 + 10 μM Cu(II); (E) ACE 200 $\mu\text{g}/\text{mL}$ alone; (F) 1 mM H_2O_2 + 10 μM Cu(II) + ACE 200 $\mu\text{g}/\text{mL}$; (G) LEE 200 $\mu\text{g}/\text{mL}$ alone; (H) 1 mM H_2O_2 + 10 μM Cu(II) + LEE 200 $\mu\text{g}/\text{mL}$. Abbreviations are the same as Figure 1.

Table 4. Protection effect of ACE and LEE on DNA migration induced by oxidative stress in HepG2 cells

Treatment	DNA migration ^a ± SD (μm)	Percent of grade ^b					Protection ^c (%)	IC_{50} ($\mu\text{g}/\text{mL}$)
		1	2	3	4	5		
Blank	19.04 ± 6.34	64	36	0	0	0		
1 mM H_2O_2 /10 μM CuSO_4	80.37 ± 19.42	0	0	0	32	68		
+ ACE 200 $\mu\text{g}/\text{mL}$	39.43 ± 9.74*	5	38	57	0	0	66.75	91.58
+ ACE 100 $\mu\text{g}/\text{mL}$	49.26 ± 9.76*	1	15	74	10	0	50.72	
+ ACE 50 $\mu\text{g}/\text{mL}$	62.76 ± 6.34	0	2	33	65	0	28.97	
+ LEE 200 $\mu\text{g}/\text{mL}$	51.44 ± 5.76*	0	3	92	5	0	47.17	214.14
+ LEE 100 $\mu\text{g}/\text{mL}$	55.02 ± 4.61*	0	0	89	11	0	41.33	
+ LEE 50 $\mu\text{g}/\text{mL}$	62.31 ± 7.46	0	0	45	54	1	29.45	
ACE 200 $\mu\text{g}/\text{mL}$ alone	25.39 ± 10.9	48	50	2	0	0		
LEE 200 $\mu\text{g}/\text{mL}$ alone	29.27 ± 13.37	37	42	21	0	0		
DMSO (solvent control)	16.69 ± 8.97	77	20	0	0	0		
Bap 20 μM	70.22 ± 4.53	0	0	5	93	2		

^aThe average DNA migration (DM) ± SD is given for 3 independent experiments.

^bThe grade of DNA migration as following: Grade 1 = 0~20 μm , Grade 2 = 21~40 μm , Grade 3 = 41~60 μm , Grade 4 = 61~80 μm , Grade 5 > 80 μm .

^cThe percent of protection was calculated as: protection (%) = $100 \times [(\text{DM of } \text{H}_2\text{O}_2/\text{Cu (II)} - \text{DM of scavenger}) / (\text{DM of } \text{H}_2\text{O}_2/\text{Cu (II)} - \text{DM of blank})]$.

*Significantly lower than $\text{H}_2\text{O}_2/\text{Cu(II)}$ treatment at $p \leq 0.05$. Cells were treated with $\text{H}_2\text{O}_2/\text{Cu (II)}$ plus various concentrations of ACE or LEE at 37°C for 2 hr. Abbreviations are the same as Table 1.

drate content) and their inhibition properties were detected with SDS-PAGE electrophoresis, phenol-sulfuric acid and 2'-deoxyribose method, respectively. As shown in Figure 4, the protein contents were higher between ACE fraction No.1-20 and No.80-110, whereas the total carbohydrate contents were higher between ACE fraction No.1-20 and No.56-63. However, the inhibition properties of ACE fraction were higher between No.1-20, No.55-70 and No.80-110, which were 74.2%, 49.8% and 54.9%, respectively. Moreover, the MDA inhibition effect of fraction No. 80-110 was better than that of fraction No. 1-20 under the same concentration. Therefore, we hypothesized the protein fraction to be the major active compound of ACE, which may not be similar as LEE. The major active proteins of ACE or LEE are shown in Figure 5. The molecular mass of the antioxidative proteins in ACE was estimated to be about 43 kDa and 29 kDa by SDS-PAGE (Figure 5, lane C), which were different from those in LEE (Figure 5, lane B). The protein fractions from ACE or LEE could also inhibit the oxidative degradation of 2'-deoxyribose caused by $\cdot\text{OH}$ radicals generated from Cu (II) plus H_2O_2 (Figure 6). The antioxidative capacity of ACE protein fraction was significantly higher than LEE fraction under the same concentration (Figure 6).

DISCUSSION

Active oxygen species may be involved in the etiology of diverse human diseases, such as coronary heart disease, stroke, rheumatoid arthritis and cancer⁽³³⁻³⁴⁾. The limitation of synthetic antioxidants such as BHA, BHT, and TBHQ, etc. have been shown in reviews of toxicity, cancer and pro-mutagenic activity. This would result in increased demand for natural antioxidants. Much attention has been focused on antioxidant mechanism from natural sources⁽⁵⁾. Trace metals such as copper and iron may interact with active oxygen species, ionizing radiation, or microwaves to damage DNA⁽²⁾. Iron and copper are ubiquitous metals in cells, as well as many enzymes and proteins. Their ionic forms are prone to participate in one-electron transfer reactions, and this is one important attribute for their use as prosthetic groups in enzyme that catalyze redox reactions. However, this capacity enables iron and copper to generate radical species as well. For example, copper and iron participate in the Fenton reaction, in which the reactive hydroxyl radical is generated:



The rate constant for the Fenton reaction is higher for copper than for iron⁽³⁵⁾. The hydroxyl radical is an extremely reactive free radical formed in biological systems. It reacts rapidly with almost every molecule in living cells, such as sugars, amino acids, DNA bases and organic acids. An example of a detector for hydroxyl radical is the sugar 2'-deoxy-D-ribose⁽³²⁾, which is also a component of DNA.

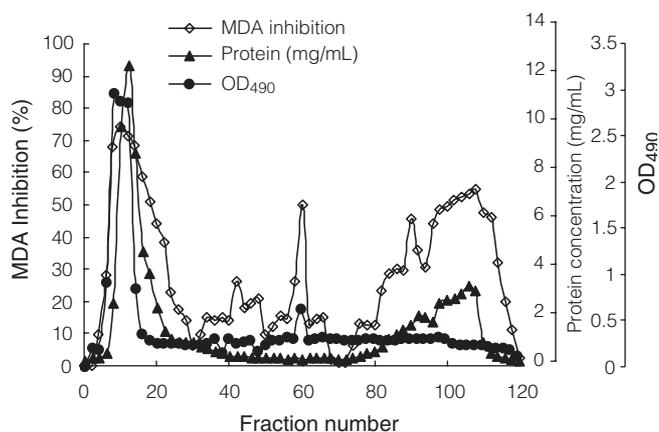


Figure 4. The MDA inhibition effect of ACE CM-fractions on oxidative degradation of 2'-deoxyribose induced by hydroxyl radicals and its protein (mg/mL) or total carbohydrate concentrations (OD₄₉₀). Abbreviations are the same as Figure 1.

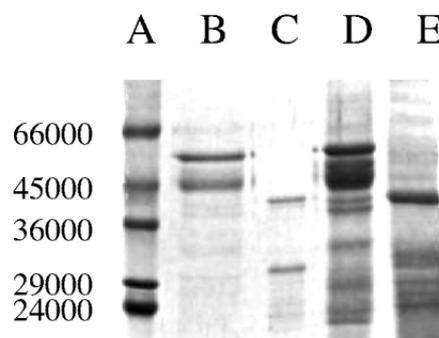


Figure 5. Electrophoretic analysis of active protein from CM fraction of ACE and DEAE fraction of LEE. Lane A: molecular mass markers from Sigma: (66 kDa), (45 kDa), (36 kDa), (29 kDa) and (24 kDa); Lane B: active fraction from LEE (LE 100) with DEAE-cellulose column chromatography; Lane C: active fraction from ACE (AC 107) with CM-cellulose column chromatography; Lane D: LEE (25 mg/mL), Lane E: ACE (25 mg/mL). Abbreviations are the same as Figure 1.

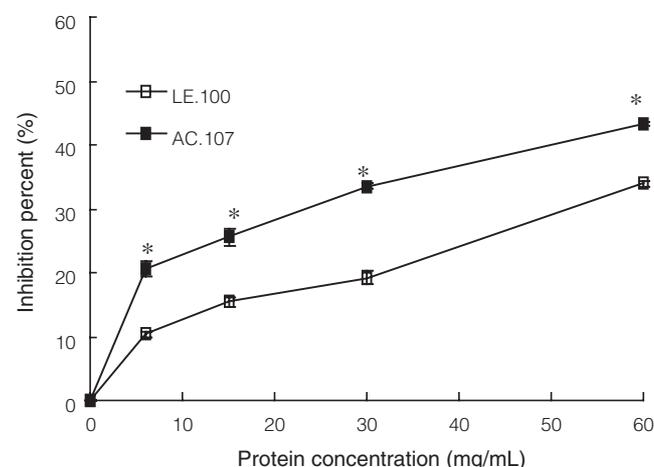


Figure 6. The inhibition activity of AC107 and LE100 on oxidative degradation of 2'-deoxyribose induced by hydroxyl radicals. *Significantly higher than *L. edodes* at $p \leq 0.05$. Abbreviations are the same as Figure 1.

In the “deoxyribose method”, the hydroxyl radical was generated by a mixture of ascorbic acid, H₂O₂ and metal ions–EDTA, attacking deoxyribose to degrade into fragments that give rise to a chromogen upon heating with thiobarbituric acid⁽³⁶⁻³⁷⁾ under acidic condition.

A variety of compounds from mushrooms have been found as antioxidants, including polysaccharides⁽³⁸⁾, melanin⁽³⁹⁻⁴⁰⁾, SOD-mimic compounds⁽⁴¹⁾, SOD⁽⁴²⁻⁴³⁾, and triterpene⁽⁴⁴⁾, which have a direct effect on free radical scavenging activities. In a previous report, several extracts of mushrooms prepared by using ethanol, particularly those from the mushroom, *Suillus bovinus*(L.: Fr.) *O. Kuntze*, were shown to have strong antioxidative activity^(5,19). Moreover, it has been demonstrated that methanol extract of *A. cylindracea* contained two indole extracted derivatives that had free radical scavenging activities⁽²⁴⁾.

The extract from *A. cylindracea* strain B, an edible mushroom produced in Taiwan, has previously been studied for its antioxidative activities. It is an efficient *in vitro* antioxidant. Our previous study has shown that ACE inhibit lipid peroxidation caused by Fe³⁺/H₂O₂/ascorbate, and the antioxidant activity of ACE may also be due to its scavenging activity on the hydroxyl radical⁽²⁵⁾. In this study, the protection effect of ACE on DNA damage was attributed to its capacity to scavenge free radicals, especially on hydroxyl radical. As shown in Table 3, the protective capacity of ACE was significantly higher than that of LEE.

It has been reported that mushrooms contain substances with chemical properties similar to ascorbic acid⁽⁴⁵⁾. Our preliminary data indicated that ACE has less reducing capacity than LEE (data not shown), which cannot fully explain the higher scavenging activity of ACE. Since tocopherol contents of mushrooms were approximately 150 µg/100 g dry matter, it seemed that tocopherol was not the main antioxidant component of mushrooms⁽¹⁹⁾. Mushroom polysaccharide extracts had superoxide and hydroxyl radical scavenging activities⁽³⁸⁾, but polysaccharide was less dissolved in cool water. Moreover, the two indole derivatives of *A. cylindracea* were extracted with methanol. Therefore, we hypothesize that the protein components of ACE appeared to contribute to free radical scavenging activity⁽³⁸⁾. It had been demonstrated that 107 KDa protein dimer, extract from shiitake mushroom, has scavenging activity and protection effect on DNA damage induced by ROS. We also found that the water-soluble protein isolated from the fruit body of *A. cylindracea* was as effective in protecting against hydroxyl radical-induced oxidation of 2'-deoxyribose (Figure 6), indicating that the protein compound is associated with the protective properties. We hypothesized that the protein profile of ACE was different from that of LEE. According to the result of SDS-PAGE as shown in Figure 5, we demonstrated that the active proteins of ACE were different from that of LEE.

Using agarose gel electrophoresis, we have evaluated the potential of ACE as an antioxidant defense against oxygen radical-mediated damage. Although the evidence presented here is based on *in vitro* experiment using

isolated DNA, the results clearly demonstrate that the water extract of *A. cylindracea* shows good antioxidative activity, as well as protection against DNA damage induced by metal-catalyzed Fenton reactions. As shown in Figure 6, the results indicated that fractional protein of ACE exhibited rapidly at a concentration-dependent increase in hydroxyl radical scavenging activity up to a concentration of 60 µg/mL. The scavenging activity was 44.6% at a concentration of 60 µg/mL ACE fractional protein. The hydroxyl radical scavenging activity of fractional protein from ACE was significantly stronger than that of LEE and also that of methanol extract of *G. tsugae*, which scavenged 53.4% of hydroxyl radical at a higher concentration of 5000 µg/mL⁽¹¹⁾.

According to the results described above, we suggest that edible *A. cylindracea* may be a potential chemoprevention foodstuff against oxidative stress. Therefore, further studies are needed to compare the activity of different solvent extracts from *A. cylindracea* and to identify the active component, and to study the protective mechanisms at the molecular level.

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