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Potential Oxidative Stress in the Bodies of Electric Arc Welding Operators: Effect of Photochemical Smog

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Objective To investigate whether photochemical smog emitted during the process of electric arc welding might cause oxidative stress and potential oxidative damage in the bodies of welding operators. **Methods** Seventy electric arc welding operators (WOs) and 70 healthy volunteers (HVs) were enrolled in a randomized controlled study design, in which the levels of vitamin C (VC) and vitamin E (VE) in plasma as well as the activities of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX), and the level of lipoperoxide (LPO) in erythrocytes were determined by spectrophotometry. **Results** Compared with the average values of the above experimental parameters in the HVs group, the average values of VC and VE in plasma as well as those of SOD, CAT and GPX in erythrocytes in the WOs group were significantly decreased (P<0.005-0.0001), while the average value of LPO in erythrocytes in the WOs group was significantly increased (P<0.0001). The findings from the partial correlation analysis on the controlling of age suggested that with a prolonged duration of exposure to photochemical smog the values of VC, VE, SOD, and GPX, except for CAT, in the WOs were decreased gradually (P<0.05-0.005), the value of LPO in the WOs was increased gradually (P<0.001), and that with the ozone dose increased in the air in each worksite VC, VE, SOD, CAT and GPX decreased (P<0.005-0.001), but LPO increased (P<0.001). The findings from the reliability analysis for the VC, VE, SOD, CAT, GPX, and LPO values which were used to reflect oxidative stress and potential oxidative damage in the WOs showed that the reliability coefficients' alpha (6 items) was 0.8021, P<0.0001, and that the standardized item alpha was 0.9577, P<0.0001. **Conclusion** Findings in the present study suggest that there exists an oxidative stress induced by long-term exposure to photochemical smog in the bodies of WOs, thereby causing potential oxidative and lipoperoxidative damages in their bodies.

Key words: Oxidative stress; Oxidative damage; Electric arc welding; Welder; Photochemical smog; Ozone; Nitrogen dioxide; Oxidation; Lipoperoxidation; Antioxidant; Antioxidase

INTRODUCTION

Electric arc welding is widely used in many fields such as welding engineering, architectural engineering, automotive industry, boat and ship engineering, aerospace

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engineering, weaponry industry, and so on. Photochemical smog emitted, however, during the process of electric arc welding may become a risk factor causing oxidative stress and potential oxidative damage in the bodies of electric arc welding operators[1,2]. Photochemical smog emitted during this process not only contains a large amount of ozone (O_3), a well-known oxidant pollutant and a major oxidant present in photochemical smog[1-11], but also includes a considerable variety of volatile organic compounds like nitrogen dioxide (NO_2) and other nitrogen oxides (NOx) playing an important role in catalyzing lipoperoxidative reactions of polyunsaturated fatty acids (PUFAs), other lipids and lipid-contained organic compounds, and a crowd of gases, carbon monoxide, hydrocarbons threatening the human health[1,2,12-27]. Up to now, however, there are neither reports on changes of free radical reactions in the bodies of electric arc welding operators, nor reports about relationship between electric arc welding and potential oxidative damage induced by photochemical smog. This research was designed to investigate whether photochemical smog emitted during the process of electric arc welding might cause oxidative stress and potential oxidative damage in the bodies of welding operators, and to explore the mechanisms by which photochemical smog might cause oxidative stress and potential oxidative damage in the welders.

MATERIALS AND METHODS

Study Design

Seventy electric arc welding operators (WOs) and seventy healthy volunteers (HVs) were enrolled in a randomized controlled study design, in which the levels of vitamin C (VC) and vitamin E (VE) in plasma as well as the activities of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX), and the level of lipoperoxide (LPO) in erythrocytes were determined by spectrophotometry. Differences between the average values of the above experimental parameters in the WOs group and the HVs group were compared. Partial correlation analysis on controlling of age between the duration of exposure to photochemical smog and the ozone dose in the air in each worksite on one hand and each of the experimental parameters on the other was carried out. Reliability analysis for the experimental parameters used to reflect oxidative stress and potential oxidative damage in the WOs was computed.

Subjects

Electric arc welding operators (WOs) Seventy WOs were randomly sampled from 131 WOs engaged in electric arc welding in two architectural worksites in Hangzhou, Zhejiang Province, China, with “Select Cases-Random Sample” of “SPSS 11.0 for Windows”. Forty three males and twenty seven females were aged from 21 to 45 (31.9±7.6) years . Their duration of exposure to photochemical smog (DEPS) ranged from 2 to 27 (13.2 ±7.2) years. They were all volunteers with informed consent to participate in this study.

Healthy volunteers (HVs) Seventy HVs whose age, gender, hemoglobin, serum albumin, body-mass index, annual earning, education level, and residence region were matched with the WOs were randomly sampled from 120 healthy volunteers who were architectural workers in the above same two architectural worksites in Hangzhou, Zhejiang Province, China, and confirmed by comprehensive physical examination at the Second Affiliated Hospital, College of Medicine, Zhejiang University, with “Select Cases-Random Sample” of “SPSS 11.0 for Windows”. Forty five males and twenty five females were aged

from 21 to 45 (31.5±6.9) years. They were not engaged in electric arc welding and other welding, and were all volunteers with informed consent to participate in this study.

There was no significant difference in the average values of age, hemoglobin, serum albumin and body-mass index between the WOs group and the HVs group, and in the gender, annual earning, education level, and residence region between the two groups.

The demographic and health data of these WOs and HVs are presented in Table 1.

TABLE 1

Demographic and Health Data in WOs and HVs Groups

Item	WOs (*n*=70)	HVs (*n*=70)	*P* Value
Age (years)	21–45 (31.9±7.6)	21–45 (31.5±6.9)	0. 744*
Gender	M = 47 F = 23	M = 45 F = 25	0.861**
Systolic Pressure (mm Hg)	88–132 (110.0±11.6)	85–134 (109.4±11.2)	0.750*
Diastolic Pressure (mm Hg)	60–86 (74.9±6.8)	62–85 (74.8±6.4)	0. 942*
Hemoglobin (g/L)	117–150 (136.7±6.8)	122–143 (136.3±7.1)	0.709*
Albumin (g/L)	35.21–50.22 (42.55±2.31)	38.46–46.84 (42.86±2.24)	0.430*
Body-Mass Index	19.34–25.36 (23.26±1.33)	20.75–25.51 (23.22±1.26)	0.873*

Note. *Independent samples *t* test, **Pearson Chi-square test (Exact Sig.).

Disorders associated with brain, heart, lung, liver, kidney and other organs as well as blood, circulatory, respiratory, digestive and other systems of the operators and healthy volunteers were all excluded by their routine blood, urine and feces examinations as well as radiographs, cardiogram and other necessary tests in this study. Any episodes of inflammation, hypertension, hyperlipidemia, acute or chronic bronchitis, autoimmune disease, diabetes, atherosclerosis, tumors and other diseases, and subnutrition, malnutrition, supernutrition and other nutritional diseases were also all excluded in this study. In addition, there were no smoking and excessive drinking histories in the above subjects in this study.

The above subjects had never been exposed to radiation, or engaged in work with exposure to intoxicating materials or pesticides. Within the preceding month when they were enrolled as volunteers in the study, none of them had taken any antioxidant supplements such as vitamin C, vitamin E, ginkgo biloba, tea polyphenols or other similar substances.

Methods

Measurement of ozone dose in the worksites An ozone-analyzer, LIDA DCS-1 ozone-analyzer, made in Shanghai LIDA Instrument Factory, China, was used to determine directly the ozone dose in the air in 70 worksites. The ozone dose was measured on 60 cm above the ground in each badly-ventilated worksite of 1.0 m^3 space in which a welder was working for 1.0 min at 10 a.m. and 3 p.m., lasting for three days on end, and the average value of ozone doses was expressed as mg/m^3. The weather in measuring ozone doses was fine, the wind speed was from zero to one on the wind scale, and the temperature was from 22℃ to 26℃[1,2].

Collection and pretreatment of blood samples Fasting venous blood samples were

collected in the morning and heparin sodium was added as anticoagulant, and the plasma and erythrocytes promptly separated were stored at -50℃ immediately, and the blood samples did not undergo any hemolysis[1,2,13].

Measurement of each biochemical constituent and enzyme The methods used in determining various biochemical constituents and enzymes were outlined below, with details provided in references 1, 2, and 13. Two different methods for spectrophotometry of ferrozine coloration were used to determine plasma VC and VE levels expressed as μmol/L, respectively[1,2,13]. Spectrophotometry of inhibiting pyrogallol auto-oxidation was used to determine erythrocyte SOD activity expressed as U/g •Hb[1,2,13]. Spectrophotometry of coloration of hydrogen peroxide and acetic acid-potassium dichromate was used to determine erythrocyte CAT activity expressed as K/g•Hb[1,2,13]. Improved Hafeman's spectrophotometry was used to determine erythrocyte GPX activity expressed as U/mg•Hb[1,2,13]. Spectrophotometry of thiobarbituric acid reactive substances (TBARS) was used to determine erythrocyte LPO level expressed as nmol/g•Hb[1,2,13].

In the above experiments, the main analytical reagents, such as vitamin C, vitamin E, 5,6-diphenyl-3-(2-pyridyl)-1,2,4-triazinedisulfonic acid disodium salt (ferrozine), Cu/Zn-superoxide dismutase, catalase, 1,2,3-trihydroxybenzene (pyrogallol), 1,1,3,3-tetraethoxypropane, 2-thiobarbituric acid, were all purchased from SIGMA® Chemical Company, USA. The other analytical reagents were all produced in China. The fresh quadruply distilled water was prepared with a quartz glass distilling apparatus. In the above experiments, the main analytical instruments included HP 8453-spectrophotometer, U. S. A.[1,2,13]. The instrument used to determine the ozone doses was LIDA DCS-1 ozone- analyzer, Shanghai LIDA Instrument Factory, China[1,2].

In the determination of the above biochemical substances and enzymes, all experiments were standardized by using the same batch number of each reagent, the same quality control and the same laboratory assistant. The identical analytical apparatus and instruments were strictly applied for each experiment in order to control and minimize errors and bias, and to ensure its analytical quality[1,2,13].

Statistical Analysis

All experimental data in this study were statistically analyzed with SPSS 11.0 for Windows statistic software using a Compaq Pentium Ⅳ/2.4 GHz computer. The experimental parameters all presented the normal distributions by Kolmogorov-Smirnov *Z* test, and were expressed as $\bar{x} \pm s$ and 95% confidence interval (95% CI). Hypothesis testing methods included independent-samples *t* test, Pearson chi-square test (χ^2 test), partial correlation analysis, and reliability analysis. In the statistical analysis of this study, the level of hypothesis testing (α) was$\leqslant$0.05 in order to avoid false positives (α-error), and the power of hypothesis testing (*power*) was $\geqslant$0.85 to avoid false negatives (β-error)[1,2,13].

RESULTS

Ozone Dose in the Air of the Worksites

The ozone doses in the air of the 70 worksites ranged from 0.159 to 0.371 (0.252± 0.056) mg/m^3, and the 95% confidence interval was from 0.2384 mg/m^3 to 0.2653 mg/m^3.

Comparison Between the Average Values ($\bar{x} \pm s$) of Experimental Parameters in the WOs and HVs Groups, and 95% Confidence Interval

Compared with the average values of above experimental parameters in the HVs group, the average values of VC and VE in plasma as well as those of SOD, CAT, and GPX in erythrocytes in the WOs group were significantly decreased (P<0.005-0.0001), while the average value of LPO in erythrocytes in the WOs group was significantly increased (P<0.0001) (Table 2). The upper limits of 95% confidence interval (95% CI) of the average values of VC and VE in plasma as well as those of SOD, CAT, and GPX in erythrocytes in the WOs group were less than the lower limits of 95% CI of those in the HVs group, while the lower limit of 95% CI of the average value of LPO in erythrocytes in the WOs group was greater than the upper limit of 95% CI of that in the HVs group (Table 2).

TABLE 2

Comparison of the Average Values of the Experimental Parameters Between the WOs and HVs Groups ($\bar{x} \pm s$)

Group	n	Antioxidative Constituents					Oxidative Constituents
		Plasma		Erythrocyte			Erythrocyte
		VC (μmol/L)	VE (μmol/L)	SOD (U/g•Hb)	CAT (K/g•Hb)	GPX (U/mg•Hb)	LPO (nmol/g•Hb)
WOs	70	45.37±12.44 (42.41-48.34)	20.08±5.78 (18.70-21.46)	1862±146 (1827-1897)	267.2±71.7 (250.1-284.2)	24.86±7.25 (23.13-26.59)	32.19±4.67 (31.08-33.30)
HVs	70	56.07±14.97 (52.50-59.64)	25.86±6.65 (24.27-27.44)	2033±161 (1994-2071)	309.8±82.1 (290.2-329.4)	28.76±8.12 (26.82-30.70)	28.61±4.14 (27.62-29.60)
P^*		<0.0001	<0.0001	<0.0001	0.0013	0.0032	<0.0001

Note. *Independent-samples t test. The figures in parentheses are 95% confidence interval (95% CI).

Partial Correlation Analysis of the Duration of Exposure to Photochemical Smog (DEPS) and Each Experimental Parameter of 70 Electric Arc Welding Operators

The findings from the controlling of age in the partial correlation analysis of the DEPS and each experimental parameter for 70 WOs suggested that with prolonged DEPS in the WOs, the values of VC, VE, SOD, and GPX, except for CAT, were decreased gradually (P<0.05-0.005), and the value of LPO was increased gradually (P<0.001) (Table 3).

TABLE 3

Partial Correlation Analysis of DEPS, ODAEW and Each Experimental Parameter for 70 Welding Operators

Partial Correlation Coefficients on Controlling for Age							
Correlative Item	n	r	P	Correlative Item	n	r	P
DEPS and VC	70	– 0.3674	0.002	ODAEW and VC	70	– 0.3446	0.004
DEPS and VE	70	– 0.3360	0.005	ODAEW and VE	70	– 0.3643	0.002
DEPS and SOD	70	– 0.2794	0.020	ODAEW and SOD	70	– 0.6233	<0.001
DEPS and CAT	70	– 0.2345	0.052	ODAEW and CAT	70	– 0.3845	0.001
DEPS and GPX	70	– 0.2660	0.027	ODAEW and GPX	70	– 0.5792	<0.001
DEPS and LPO	70	0.4694	<0.001	ODAEW and LPO	70	0.5803	<0.001

Partial Correlation Analysis of Ozone Dose in the Air of Each Worksite (ODAEW) and Each Experimental Parameter for 70 Electric Arc Welding Operators

The findings from the controlling of age in the partial correlation analysis of ODAEW and each experimental parameter for 70 WOs suggested that with increased ODAEW in the WOs, the values of VC, VE, SOD, CAT, and GPX were decreased gradually ($P<0.005$-0.001), and the value of LPO was increased gradually ($P<0.001$) (Table 3).

Reliability Analysis of Experimental Parameters Used to Reflect Oxidative Stress and Potential Oxidative Damage in the Electric Arc Welding Operators

The findings from the reliability analysis for the levels of VC and VE in plasma as well as the activities of SOD, CAT, and GPX in erythrocytes, and the level of LPO in erythrocytes, which were used to reflect oxidative stress and potential oxidative damage in the electric arc welding operators, suggested that the reliability coefficients' alpha (6 items) was 0.8021, $P<0.0001$, and that the standardized item alpha was 0.9577, $P<0.0001$.

DISCUSSION

VC and VE are the most important antioxidants, and SOD, CAT and GPX are the most important antioxidases in the human body[1,2,4,5,12-19,22-24,28-30]. LPO and its metabolites like malondialdehyde and conjugated diene, etc., play an important role in the metabolism in the human body[1,2,12-19,22-24,28,29]. Both significantly decrease antioxidant levels and antioxidasive activities, and markedly increased LPO level may cause metabolic disorders and pathological aggravation of a series of free radical chain reactions in the human body, thus inducing a variety of diseases related to abnormal reactions of free radicals[1,2,4,5,12-19,22-24,28-30].

The findings in this study showed that there existed, in all likelihood, an imbalance between oxidation and antioxidation, and an oxidative stress and a potential oxidative damage in the bodies of electric arc welding operators. There might be several interpretations.

The simplest reason was that the photochemical smog emitted during the process of electric arc welding could not be apace and adequately exhausted to exoteric air due to badly-ventilated working conditions, especially in the conditions of low air pressure, which led to long-term exposure of the welding operators to a large amount of ozone, nitrogen dioxide, and other volatile inorganic and organic compounds in the photochemical smog[1,2,27]. The data we measured with an ozone-analyzer displayed that the concentration of ozone in a badly-ventilated worksite of 1.0 m^3 space in which a welder was working ranged actually from 0.16 mg/m^3 to 0.37 mg/m^3, and such data were beyond the recommended maximum exposure limit of 0.1 mg/m^3 in the hygienic standard of public places[1,2], and far exceeded the ozone olfact (olfactory threshold of ozone) of 0.018 mg/m^3[1,2].

Ozone is one of the main components and the most abundant oxidants in the photochemical smog emitted during the process of electric arc welding[27]. As a strong oxidant, ozone or its reactive products may cause DNA damage by interacting directly with DNA and linearizing circular DNA, inducing ozone-sensitive mutant, inhibiting or depressing DNA replication[1,2,6]. Ozone and ozonizative process may generate a large amount of superoxide anion radicals ($O_2^{\cdot-}$), hydxoyl radicals ($\cdot OH$) and others as well as singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2) and other reactive oxygen species[1,2,6]. Ozone *per se* may attack strongly the active sites and active groups in the molecular structures of antioxidants and antioxidases[1,2]. High doses of ozone inhaled by the welders, therefore, might lead to a significant decrease in the synthesis or regeneration of SOD, CAT,

and GPX, deactivating or inactivating them, and resulting in a marked decrease of their activities in the welders[1,2]. Excessive O_2^- , ·OH, $^1O_2$, H_2O_2 and others might also cause DNA damage and attack strongly the structures of VC, VE, SOD, CAT and GPX by combining with some active groups, deactivating them, resulting in significantly decreased VC and VE levels, and SOD, CAT, and GPX activities in the welders[1,2,4,12-19,22-24,27,29]. At the same time, ozone could cause oxidative decomposition, peroxidative modification and lipoperoxidative reactions of PUFAs, unsaturated phospholipids, glycolipids, cholesterol, and other lipids and lipid-containing organic compounds in blood, tissues and cellular membranes, and accelerate these reactions , especially lipoperoxidative reactions, resulting in a marked increase of LPO in the welders who inhaled a large amount of photochemical smog, and leading to potential lipoperoxidative damage in their bodies[1,2,4,12-19,22-24,27,29]. In addition, significant decrease and/or loss of GPX activity induced by DNA damage as well as decrease of VE level derived from high ozone doses might also result in lipoperoxidation, causing increase of LPO level, inducing lipoperoxidative damage to cells, and cytoclasis[1,2,4,12-19,22-24,27,29]. Nitrogen dioxide (NO_2) and other nitrogen oxides (NOx) play a very important role in catalyzing peroxidative reactions of PUFAs, and other lipids and lipid-containing organic compounds in humans[1,2,4,13-20,23-25,28,29,31-35]. A large amount of NO_2 and other NOx in the photochemical smog emitted during the process of electric arc welding inhaled by the welders who are operating at some badly-ventilated worksites can catalyze, in all likelihood, lipoperoxidative reactions, and further increase LPO level in their bodies[1,2,4,13-20,23-25,28,29].

Bivariate correlation analysis, *viz* a simple linear correlation, can not really reflect relationships of both DEPS and ODAEW and each experimental parameter in the electric arc welding operators owing to a close correlation between age and above parameters in humans[1,2,13-19,22-24,28-30]. In this study, therefore, partial correlation analysis was used to analyze the correlation between both DEPS and ODAEW and each parameter for 70 electric arc welding operators, controlling of their age in order to eliminate the effect of age upon each of the parameters during correlation analysis[36]. The findings from the partial correlation analysis on controlling of age suggest that with prolonged DEPS the values of VC, VE, SOD and GPX, except for CAT, in the WOs are decreased gradually (P<0.05-0.005), the value of LPO in the WOs is increased gradually (P<0.001), and that with increased ODAEW those of VC, VE, SOD, CAT and GPX decreased (P<0.005-0.001), and LPO increased (P<0.001). In other words, the longer the exposure to photochemical smog is, the severer the oxidative stress and potential free radical damage are. At the same time, the findings suggest that it is very important to use correct statistic analyses in calculating the correlation between multiple variables, especially when two or multiple variables are disturbed by another variable. Under such conditions, partial correlation analysis, controlling of certain variables, should be used to replace bivariate correlation analysis in order to obtain a true statistic conclusion[36].

The findings of reliability analysis in this study showed that the above experimental parameters were, to a large extent, comparatively satisfactory and reliable (the reliability coefficients' alpha of 6 items was 0.8021, P<0.0001, and the standardized item alpha was 0.9577, P<0.0001), and that a large amount of photochemical smog inhaled by welders for a long time could induce, in all likelihood, oxidative stress and potential oxidative damage in their bodies.

In conclusion, the findings in the present study suggest that long-term exposure to photochemical smog can induce oxidative stress in electric arc welding operators, thereby causing potential oxidative and lipoperoxidative damages in their bodies. We, therefore,

recommend that well-ventilated equipment should be provided at any welding worksites in order to minimize the concentration of photochemical smog when welding, and to protect welders against damage from photochemical smog. Undoubtedly, this is only an preliminary conclusion because in the present study we did not determine the concentrations of nitrogen dioxide, other nitrogen oxides, and volatile inorganic and organic compounds in the photochemical smog emitted during the process of electric arc welding associated with generation of excessive free radicals and reactive oxygen species in the worksites.

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