

Experimental Study of Cerium Oxide Nanoparticles (CeNP) Against Malathion Induced Lung Oxidative Toxic Stress in Rats

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Received January 6, 2017; Revised February 2, 2017; Accepted May 25, 2017

This paper is available online at <http://ijpt.tums.ac.ir>

ABSTRACT

Regardless of toxicity of nanoparticles, cerium oxide nanoparticles (CeNPs) are emerging as a multi-functional agent for biomedical purposes. On the other hand, Organophosphorus pesticides, like malathion, are inevitably found in the environment. The common involving pathway CeNPs and malathion share is oxidative stress. Therefore, we conducted this study to find the possible neutralizing or synergistic effects of CeNPs on oxidative stress responses in malathion-induced toxicity by intraperitoneal (IP) injection. In this experimental study, 40 Wistar male rats with the weight range of 200-250 g were randomly selected and divided into eight groups. Group1 (control, normal saline), group2 (100 mg/kg/day malathion /IP), group3 (15 mg/kg/day CeNPs/IP), group4 (30 mg/kg/day CeNPs /IP), group5 (60 mg/kg/day CeNPs /IP), group6 (100 mg/kg/day malathion+15 mg/kg/day CeNPs /IP), group7 (100 mg/kg/day malathion+30 mg/kg/day CeNPs /IP) and group8 (100mg/kg/day malathion+60 mg/kg/day CeNPs /IP). After 4 weeks of treatment, the levels of lipid peroxidation (LPO), total antioxidant capacity (TAC), total thiol molecules (TTM) and activity of catalase (CAT) in lung tissue were measured. All data were analyzed by SPSS V16 and One way ANOVA with Tukey post hoc test. The results demonstrated that CeNPs caused significant increases in LPO and TAC, in a dose-dependent-manner. For TTM level, none of the groups presented any significant change compared to control. Significantly decreased levels of CAT, also, were seen in all treatment groups. Surprisingly, all animals of group 8 died. Worth of noting, groups receiving combined CeNPs and malathion showed severe responses for these parameters. These results discovered that CeNPs induces oxidative stress parameters and ROS production, especially combined with malathion in lung tissue. Groups receiving both CeNPs and malathion displayed synergistic toxic properties. LPO, TAC and CAT seem to be better parameters for measuring CeNPs-induced responses. Further investigations are required to shed light on clear mechanisms involved.

Keywords: *Cerium oxide nanoparticle, Lung, Oxidative Stress, Rat, Malathion*

Organophosphorus compounds are known to be one of the most widely utilized pesticides all over the world. Residual amounts of these pesticides can be detected in the water, soil, vegetables and other food products [1]. Among such compounds, malathion [O,O-dimethyl-S-(1,2-dicarboxy-ethyl) phosphorodithioate] is known to be the most extensively used organophosphate pesti-

cides in agriculture, industry, medicine and public health issues [1-3]. Wide application of malathion, however, brings potentially hazardous impacts on human toxicity [3]. Induction of oxidative stress has been represented as the main mechanism of malathion toxicity in subchronic exposition [4]. Oxidative damage predominantly occurs by increasing in the production of

reactive oxygen species (ROS), which during the reactions with biological molecules such as lipids, proteins and nucleic acid are generated [5]. ROS are highly reactive and unstable particles with unpaired electron(s) which attack to nearby molecules to get another electron, resulting in damaged molecular structures and inhibiting cellular functions [5].

There are so many hydrophobic pesticides, like malathion, that bind strongly to biological membranes, particularly phospholipid bilayers of cells, and are capable of damaging the membranes by induction of lipid peroxidation (LPO) [6-9]. In another words, oxidative stress can be described as an imbalance between the body antioxidant defense system and the production of free radicals [44]. If the latter conquers the former, or by any other reason antioxidant defense falls into decreased state, a condition of oxidative stress will be developed, that might cause long-term problems [10]. Moreover, the vital role of lung in facing ROS in daily life and its susceptibility to the variety of diseases cannot be denied [11].

Nowadays, nanomaterials have been chosen to meet the different requisites in an extent range including medical and industrial goals [12]. Cerium oxide nanoparticle (CeNPs) has gained its own place in applications for fuel cells, phosphor/luminescence, solar cells, oxygen pumps, gas sensors and acting as catalysts [12-14]. In line with this, for biomedical purposes, CeNPs were exhibiting antioxidant properties [15-17]. The unique ability to self-regeneration and switching, based on the physiological environment, between cerium (3+) and cerium (4+) oxidation states enables CeNPs to scavenge free radicals such as superoxide, hydrogen peroxide, and hydroxyl and nitric oxide [15]. Furthermore, it has been exploited as a mimicking catalase agent [16, 18] and is recognized to be non-toxic [15,18-21].

On the other hand, some concerns has raised according to the published reports about CeNPs toxicity [22-27], which with regards to oxidant/antioxidant effect of CeNPs, explains the controversial usage of this nanoparticle. There is still a lot to be understood [14, 28-29] and function of CeNPs needs to be determined much more closely. This study was conducted to find the possible neutralizing or synergistic effects of CeNPs on oxidative stress responses in malathion-induced toxicity by intraperitoneal (IP) injection.

MATERIALS AND METHODS

Preparation of cerium oxide nanoparticles

To evaluate the different doses for each group, based on average body weight of rats (220 g), CeNPs were suspended in deionized water. A sonication time of 10 minutes was considered. To avoid the separation of the particles and precipitation, suspension of particles was immediately prepared and vortexed vigorously, before each injection.

Chemicals

The CeNPs (30 nm, US Research Nanomaterials, Inc company), used in this study, were obtained from Notrino company. Dithionitrobenzoic acid (DTNB), malathion, ethylenediamine tetraacetic acid (EDTA), phosphate buffer solution (PBS), tetraethoxypropane (MDA), trichloroacetic acid (TCA), 2-thiobarbituric acid (TBA), n-butanol and 2, 4, tris base, H₂O₂, tripyridyl-s-tiazine (TPTZ) were purchased from Sigma Co.

Animals and experimental design

This study was an experimental one. All measures in this work were approved by the Ethics Committee of Vice-Chancellor for Research & Technology of Hamadan University of Medical Sciences. Forty male adult Wistar rats (weighing 200-240 g) were purchased from Pasteur Animal Breeding Center of Tehran and maintained in polypropylene cages under standard conditions of 12/12-h light and dark cycles at room temperature (25 ± 2°C). Rats had freely access to distilled water ad libitum. After one week acclimation, animals were randomly divided into 8 groups (each containing 5), as described below:

Group 1: Control, normal saline , Group 2: 100 mg/kg/day malathion , Group 3: 15 mg/kg/day CeNPs , Group 4: 30 mg/kg/day CeNPs , Group 5: 60 mg/kg/day CeNPs, Group 6: 100 mg/kg/day malathion + 15 mg/kg/day CeNPs, Group 7: 100 mg/kg/day malathion + 30 mg/kg/day CeNPs , Group 8: 100 mg/kg/day malathion + 60 mg/kg/day CeNPs. Handling and IP injection of all groups for the entire 4 weeks of the treatment were done by an expert laboratory technician.

Homogenizing the lung tissues

At the noontime of the twenty-ninth day, rats were sacrificed. Their lungs were quickly separated and rinsed with PBS (pH = 7.5). Tissues were all quickly dried and homogenized with 10 mL PBS (pH = 7.5), using a homogenizer.

Measurement of thiobarbituric acid reactive substances (TBARS)

The cellular LPO products in homogenized lung tissue samples were evaluated by measuring thiobarbituric acid reactive substances represented as the extent of malonaldehyde (MDA) productions during reaction activated by acid-heating protocol. After diluting the samples with 1.5 mL TCA (20 % w/v) and centrifuging in 3000g, the precipitation was mixed with 1.5 mL H₂SO₄ (0.05 M) and 1.5 mL TBA (0.2 % w/v). Then, it was incubated for 45 minutes in boiling water bath. After passing time, 2 mL n-butanol was added to each solution, followed by cooling and centrifuging. The absorptions were, eventually, recorded at 532 nm. A standard curve of tetraethoxypropane was used to find the concentrations [17].

Total antioxidant capacity (TAC)

The reduction of Fe³⁺ to Fe²⁺ in the biological samples was assayed as the indicator of TAC. Thereafter, by the formation of complex between Fe²⁺ and TPTZ, the maximum absorbance of blue color solution, at 593 nm, was measured [30].

Total thiol molecules (TTM)

By calorimetric method of Hu and Dillard and using DTNB (Ellman's reagent) as the reagent of the reaction, the lung homogenates TTM, in a manner briefly as this, were determined: 1 mL of tris buffer (250 mM and EDTA 2 mM, pH= 8.2) was mixed well with 50 μ L of each sample. Afterwards, with adding 20 μ L DTNB, absorbance were measured again at 412 nm [31].

Catalase (CAT) activity

The activity of CAT was gained by absorbance decrease in 240 nm for each sample, in a reaction medium comprising H₂O₂ (10 mM) and sodium phosphate buffer (50 mM, pH = 7.5). One unit of the enzyme was considered as one mol H₂O₂ as the substrate consumed per minute. Altogether, specific activity was then expressed as unit per milligram protein [32].

Statistical analysis

All results were expressed as the Mean \pm SE for each group. Statistical analysis was performed, by SPSS.16 software, using one-way analysis of variance (ANOVA), as followed by post hoc Tukey test. The differences were considered significant if p value was less than 0.05 (p < 0.05).

RESULTS

CeNPs and malathion effects on the rats' general health

During the experiment, all rats of 60 mg/kg group died, but in other groups no missing was observed. Meanwhile, some clinical signs of illness in malathion group were seen as salivation, lacrimation, head shaking, spasms of the muscles, weight loss and poor mobility. Also, these signs had the most manifestations in groups of combined CeNPs and malathion. However, there was less presentation of those symptoms in rats treated with only CeNPs.

LPO

As can be seen from Fig. 1, CeNPs with dose of 15 mg/kg in comparison with the control group caused a significant increase in lung LPO (p value = 0.004). Also, in accordance with that, LPO contents were found to have significant increase in the groups of CeNPs 30 mg/kg (P = 0.013), CeNPs 60 mg/kg (P = 0.013), CeNPs 15 mg/kg plus malathion (P < 0.001, with the highest TBARS level in all treated groups) and CeNPs 30 mg/kg plus malathion (P = 0.047), all compared with the control group.

To our surprise, the elevated level of LPO of lung tissue in the treatment group of malathion alone, however, compared to the control group was not statistically significant (P = 0.134).

TAC

Combination of malathion with CeNPs and malathion alone led to a significant increase in total antioxidant capacity level in lung homogenates of groups treated with malathion alone (P = 0.009), 15 mg/kg CeNPs plus malathion (P < 0.001, with the highest TAC level in all treated groups) and 30 mg/kg CeNPs plus malathion (P = 0.014), as compared to the control group shown in Fig 2. In line with this, significant increase was, furthermore, seen in TAC level of CeNPs 60 mg/kg group (Fig. 2). Moreover, CeNPs 15 mg/kg plus malathion group indicated significant increase compared to the group of CeNPs 30 mg/kg (P = 0.042).

TTM

The results of TTM are interesting in different aspects. Fig. 3 shows that after the entire 4 weeks of our study and measurement of total thiol molecules in lung of the animals, no significant changes were produced in any group, in comparison with the control. Malathion group showed reduced TTM levels about half of the control. The level of TTM in group of 15 mg/kg CeNPs was almost as the same as that of control group. It can be highlighted in the Fig. 3 that dose of 30 mg/kg CeNPs showed a significant increase compared to malathion group (P = 0.023). Also, this increase was significant (P = 0.021) for group of CeNPs 30 mg/kg plus malathion. Although malathion group resulted in a considerable reduce in TTM level, but it was not statistically significant (P = 0.826). Similarly, considerable but not significant change (this time increased level of TTM) in CeNPs 30 mg/kg group (P = 0.317) was observed, compared to the control group.

CAT activity

Interestingly, by subchronic injection of CeNPs and malathion, in all of the treated groups CAT activity of rat lung tissue, as described in Fig. 4, was detected significantly decreased: malathion (P < 0.001), CeNPs 15mg/kg (P < 0.001), CeNPs 30 mg/kg (P = 0.001), CeNPs 60 mg/kg (P < 0.001), CeNPs 15 mg/kg plus malathion (P < 0.001) and CeNPs 30 mg/kg plus malathion (P < 0.001).

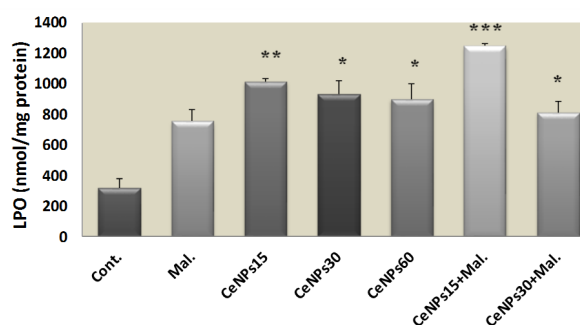


Fig 1. Lipid peroxidation (LPO) in lung tissue of rats. *Significantly different from control group at $p < 0.05$. **Significantly different from control group at $p < 0.01$. ***Significantly different from control group at $p < 0.001$. Cont, Control; Mal, malathion; CeNP, Cerium oxide nanoparticles.

DISCUSSION

The present study established administration of CeNPs induces oxidative stress parameters and ROS production, especially combined with malathion in lung homogenate. Malathion toxicity in lung homogenate seemed to be caused by oxidative stress. Also, oxidative stress was decreased by the treatment with CeNPs (Figs. 1 to 4).

ROS generated by malathion significantly reduced the levels of cellular antioxidants [33]. In this study we focused on the lung tissue, owing to its continuously and increasingly hazard of facing reactive derivatives of oxygen with the exogenous or endogenous sources.

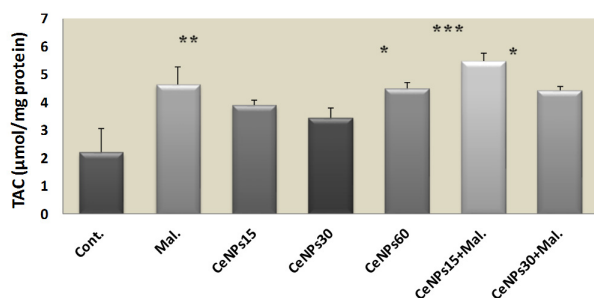


Fig 2. Total antioxidant capacity (TAC) in lung tissue of rats. *Significantly different from control group at $p < 0.05$. **Significantly different from control group at $p < 0.01$. ***Significantly different from control group at $p < 0.001$. Cont, Control; Mal, malathion; CeNP, Cerium oxide nanoparticles.

CeNPs have been applied in a variety of purposes from biomedical to industrial activities [34]. Likewise, because of limited and a very low absorption of nanoparticles' inhalation exposure and oral administration in animals, approximately 100% excreted in the feces [35-36], IP injection seems to be an appropriate approach to investigate the effects in a better setting.

This work was undertaken to determine whether CeNPs could attenuate some of the toxic effects of malathion [100 mg/kg/day = 1/20 LD50 [37] or a synergistic role can be found, in Wistar male rats treated for 4 weeks. During the experiment, all of the rats in group of 60 mg/kg CeNPs plus malathion died, which was explained as a primary sign of severe combined toxicity of CeNPs and malathion both together, before testing parameters. In comparison to the three groups receiving CeNPs alone, clinical signs of illness observed in other groups treated with malathion alone or combined with different doses of CeNPs were more severe.

As seen in Fig 1, groups with three different doses of CeNPs (15, 30 and 60 mg/kg) and combined injection of CeNPs and malathion confirmed significantly increased levels of MDA as a marker of LPO and cell membrane damage, among which the highest MDA level and cellular damage belongs with the combination of CeNPs 15 mg/kg plus malathion. Supporting this results, in previous studies it was found that MDA level in malathion exposed groups has increased [5, 38-40]. As discussed above, it is hypothesized that the missed group (CeNPs 60 mg/kg plus malathion) could not tolerate the oxidative damage which might have resulted in death. The lung is the first organ to come in contact with inhaled toxic chemicals especially organophosphate. OP insecticides can cause adverse effects in various organs such as the lungs [41]. Also, our results demonstrated that administration of malathion alone or with CeNPs led in significantly increase for TAC levels (Fig 2). This results are in the same line with findings reported previously and one explanation can be suggested that subchronic treatment in the present study confers the compensatory mechanisms activated through the effects of CeNPs and malathion on related progenitor cells. By regarding this results it seems reasonable to say that in subchronic treatment via overproduction of antioxidants, body is capable of defending against ROS. Presumably, as reviewed in publications of other researchers [14, 42], the aggregation of nanoparticles in part might play an essential role in development of toxicity. Thus, only in high concentrations (such as dose of 60 mg/kg in this study) increase in TAC levels, induced by toxic properties of CeNPs and potentially ROS, would occur. Interestingly, like MDA levels, combination of CeNPs 15 mg/kg plus malathion led in the highest level of TAC response. Additionally, from rats treated with CeNPs alone, only 60 mg/kg group revealed significant increase in TAC levels. Worthy of note, group received CeNPs 30 mg/kg displayed less increase and probably less response because of milder toxicity.

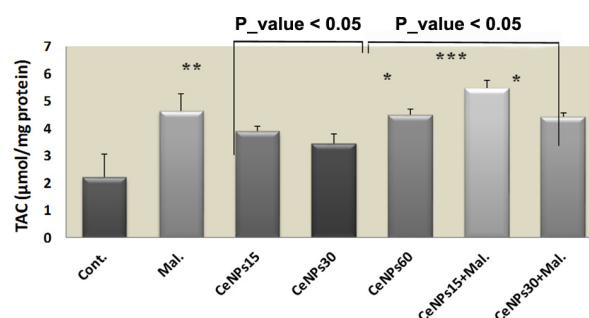


Fig 3. Total thiol molecules (TTM) in lung tissue of rats. Significant different TTM levels are elucidated. Cont, Control; Mal, malathion; CeNP, Cerium oxide nanoparticles.

TTM was assayed as an indicator of protein oxidation. Interestingly, results of TTM, in comparison with other parameters of study, in all treatment groups revealed no significant correlation, compared to the con-

control group in this subchronic design. Also, except 30 mg/kg CeNPs group others displayed decreased levels. Even though CeNPs 30 mg/kg caused a considerable (but not significant) increase, it is presumed that antioxidant enzymes containing thiol molecules such as glutathione are not affected as the same as other studied factors and there seems to be another mechanisms strongly involved in the alteration of TTM. From other side, LPO and TAC levels in lung tissues were changed significantly after subchronic treatment, suggesting that LPO and TAC is more affected by CeNPs and malathion exposure rather than protein oxidation. Possamai et al. showed similar finding only for malathion alone [1].

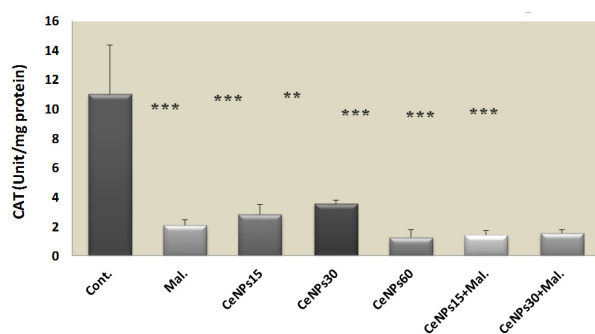


Fig 4. Catalase activity (CAT) in lung tissue of rats. **Significantly different from control group at $p < 0.01$. ***Significantly different from control group at $p < 0.001$. Cont, Control; Mal, malathion; CeNP, Cerium oxide nanoparticles.

In this study, activity of CAT enzyme was investigated as an antioxidant enzyme activity biomarker of primary defense against oxidative damage [43], by converting H_2O_2 produced as ROS free radicals to water and then blocking free radical-mediated damage. For CAT activity, all treatment groups showed significant decrease, which can be taken as a suitable biomarker for oxidative stress status. In contrast, Akhgari et al. has mentioned that by 4 weeks malathion administration activity of CAT in erythrocytes and liver was increased [44]. However, the reduced CAT activity may be resulted from the accumulation of the H_2O_2 and O_2 . Therefore, Loss of CAT activity will cause oxygen intolerance and triggers lots of deleterious reactions in the body [45]. As like TAC and TTM tests, CeNPs with dose of 30 mg/kg were detected with less decrease in CAT levels, promising less toxicity than other doses. Groups receiving both CeNPs (15 and 30 mg/kg) and malathion were seen with the greatest decreases in CAT level, suggesting this combination will cause the most severe damage in all assayed groups, in spite of the fact that rats receiving CeNPs 60 mg/kg plus malathion, due to potentially intolerable synergistic effects, were all dead. In this study by considering the highest responses of 15 mg/kg group in LPO and TAC tests and the most decreases in CAT activity of 30 mg/kg in groups treated with CeNPs alone, one can mention that CeNPs toxicity follows a dose-dependent-manner in this work. Some reports have claimed protective and antioxidant roles for CeNPs in lung and other tissues [16, 46-48]. Nonethe-

less, the results of this work are in agreement with that of previous studies having shown the pro-oxidant effects of malathion alone, whether in vivo or in vitro studies, especially in lung tissue [14, 49-50]; but for the first time this study reveals that using controversial CeNPs and malathion together, will cause much more deleterious behaviors over oxidative stress responses and CAT activity as an antioxidant enzyme, assayed in this study. Not only do not neutralize the toxic biological properties of malathion, but CeNPs also emerge their synergistic toxic and pro-oxidant function with malathion in rat lung tissue of male rats. One hypothesis can be stated as this: malathion-induced oxidative stress may decrease the cellular pH by destructing membranes of intracellular organelles. Reduced pH, described in other studies [49], is one of the main factors inducing harmful and pro-oxidant aspects of CeNPs.

In our study, only CeNPs with size of 30 nm were studied. Regarding discrepancy of results various methods of synthesis and shape [14,42], particle size [12,14,42,51-52], surface charge (also called zeta potential) [11,14,42,53-54] and agglomeration state [14,42] in different studies, were thought to be the reasons of varying range of pro- to anti-oxidant behavior. However, in the recent published paper of Pulido-Reyes et al. [55] only the percentage of Ce^{3+}/Ce^{4+} surface content sites was determined to cause the anti- or pro-oxidant behavior, the less Ce^{3+} sites the less pro-oxidant status will be achieved.

Our results have demonstrated that (1) CeNPs with size of 30 nm and malathion may both be directly involved in induction of deleterious oxidative stress responses, including elevated levels of LPO and TAC in rat lung tissue. (2) CeNPs can act as SOD enzyme. Therefore, excess H_2O_2 produced may result in depletion of CAT activity. (3) Combined treatment of CeNPs and malathion provoked synergistic, more toxic and oxidative damage responses on above-mentioned parameters. The other oxidative stress responses, LPO and TAC measurements, seem to give more consistent responses in the lung tissue examined rather than TTM after subchronic treatments. The toxic properties of CeNPs in groups treated with CeNPs alone, followed a dose-dependent-manner.

Further investigations using other oxidative stress and antioxidants parameters, different treatments periods (acute and chronic) after receiving CeNPs and malathion should be conducted to untangle and understand more aspects of CeNPs and its possible complementary properties with other chemicals.

REFERENCES

1. Possamai F, Fortunato J, Feier G, Agostinho F, Quevedo J, Wilhelm Filho D, et al. Oxidative stress after acute and sub-chronic malathion intoxication in Wistar rats. *Environ Toxicol Pharmacol* 2007; 23:198-204.

2. Ogutcu A, Suludere Z, Kalender Y. Dichlorvos-induced hepatotoxicity in rats and the protective effects of vitamins C and E. *Environ Toxicol Pharmacol* 2008; 26:355-61.
3. Elzoghby RR, Ahlam FH, Abdel-Fatah A, Farouk M. Protective role of vitamin C and green tea extract on malathion-induced hepatotoxicity and nephrotoxicity in rats. *Am J Pharmacol Toxicol* 2014; 9:177-188.
4. Lukaszewicz-Hussain A. Role of oxidative stress in organophosphate insecticide toxicity—Short review. *Pestic Biochem Physiol* 2010; 98:145-50.
5. Heikal T, Mossa A, Marei G, Abdel Rasoul M. Cyromazine and chlorpyrifos induced renal toxicity in rats: The Ameliorating effects of green tea extract. *J Environ Anal Toxicol* 2012; 2:1-7.
6. Mansour SA, Mossa A-TH. Lipid peroxidation and oxidative stress in rat erythrocytes induced by chlorpyrifos and the protective effect of zinc. *Pestic Biochem Physiol* 2009; 93:34-9.
7. Heikal T, Ghanem H, Soliman M. Protective effect of green tea extracts against dimethoate induced DNA damage and oxidant/antioxidant status in male rats. *Biohealth Science Bulletin* 2011; 3:1-11.
8. Celik I, Yilmaz Z, Turkoglu V. Hematotoxic and hepatotoxic effects of dichlorvos at sublethal dosages in rats. *Environ Toxicol* 2009; 24:128-32.
9. Kalender S, Uzun FG, Durak D, Demir F, Kalender Y. Malathion-induced hepatotoxicity in rats: the effects of vitamins C and E. *Food Chem Toxicol* 2010; 48:633-8.
10. Halliwell B. Free radicals, antioxidants, and human disease: curiosity, cause, or consequence? *Lancet* 1994; 344:721-4.
11. Win-Shwe T-T, Fujimaki H. Nanoparticles and neurotoxicity. *Int J Mol Sci* 2011; 12:6267-80.
12. Park E-J, Choi J, Park Y-K, Park K. Oxidative stress induced by cerium oxide nanoparticles in cultured BEAS-2B cells. *Toxicology* 2008; 245:90-100.
13. Wingard CJ, Walters DM, Cathey BL, Hilderbrand SC, Katwa P, Lin S, et al. Mast cells contribute to altered vascular reactivity and ischemia-reperfusion injury following cerium oxide nanoparticle instillation. *Nanotoxicology* 2011; 5:531-45.
14. Lin W, Huang Y-w, Zhou X-D, Ma Y. Toxicity of cerium oxide nanoparticles in human lung cancer cells. *Int J Toxicol* 2006; 25:451-7.
15. Arya A, Sethy NK, Singh SK, Das M, Bhargava K. Cerium oxide nanoparticles protect rodent lungs from hypobaric hypoxia-induced oxidative stress and inflammation. *Int J Nanomedicine* 2013; 8:4507-20.
16. Xu C, Qu X. Cerium oxide nanoparticle: a remarkably versatile rare earth nanomaterial for biological applications. *NPG Asia Materials* 2014; 6:e90.
17. Ranjbar A, Ghahremani MH, Sharifzadeh M, Golestani A, Ghazi-Khansari M, Baeeri M, et al. Protection by pentoxifylline of malathion-induced toxic stress and mitochondrial damage in rat brain. *Hum Exp Toxicol* 2010; 29:851-64.
18. Diaconeasa Z, Barbu-Tudoran L, Coman C, Leopold L, Mesaros A, Pop O, et al. Cerium oxide nanoparticles and its cytotoxicity human lung cancer cells. *Rom Biotech Lett* 2015; 20:10679.
19. Birbaum K, Brogioli R, Schellenberg M, Martinoia E, Stark WJ, Günther D, et al. No evidence for cerium dioxide nanoparticle translocation in maize plants. *Environ Sci Technol* 2010; 44:8718-23.
20. Pierscionek BK, Li Y, Schachar RA, Chen W. The effect of high concentration and exposure duration of nanoceria on human lens epithelial cells. *Nanomed Nanotech Biol Med* 2012; 8:383-90.
21. Lee SS, Zhu H, Contreras EQ, Prakash A, Puppala HL, Colvin VL. High temperature decomposition of cerium precursors to form ceria nanocrystal libraries for biological applications. *Chem Mater* 2012; 24:424-32.
22. Ould-Moussa N, Safi M, Guedeau-Boudeville M-A, Montero D, Conjeaud H, Berret J-F. In vitro toxicity of nanoceria: effect of coating and stability in biofluids. *Nanotoxicology* 2014; 8:799-811.
23. Watts W, Ische EE. Diesel Emissions Reference List: Health Effects, Measurement and Control.
24. Cassee FR, van Balen EC, Singh C, Green D, Muijser H, Weinstein J, et al. Exposure, health and ecological effects review of engineered nanoscale cerium and cerium oxide associated with its use as a fuel additive. *Crit Rev Toxicol* 2011; 41:213-29.
25. Karakoti AS, Munusamy P, Hostetler K, Kodali V, Kuchibhatla S, Orr G, et al. Preparation and characterization challenges to understanding environmental and biological impacts of ceria nanoparticles. *Surf Interface Anal* 2012; 44:882-9.
26. Walser T, Limbach LK, Brogioli R, Erismann E, Flamigni L, Hattendorf B, et al. Persistence of engineered nanoparticles in a municipal solid-waste incineration plant. *Nat Nanotechnol* 2012; 7:520-4.
27. Horie M, Kato H, Fujita K, Endoh S, Iwahashi H. In vitro evaluation of cellular response induced by manufactured nanoparticles. *Chem Res Toxicol* 2011; 25:605-19.
28. Kumari M, Singh SP, Chinde S, Rahman MF, Mahboob M, Grover P. Toxicity study of cerium oxide nanoparticles in human neuroblastoma cells. *Int J Toxicol* 2014; 33: :86-97.
29. Schubert D, Dargusch R, Raitano J, Chan S-W. Cerium and yttrium oxide nanoparticles are neuroprotective. *Biochem Biophys Res Commun* 2006; 342:86-91.
30. Iris F, Benzi F, Strain S. Ferric reducing antioxidant assay. *Methods Enzymol* 1999; 292:15-27.
31. Hu M, Dillard C. Plasma SH and GSH measurement. *Methods Enzymol* 1994; 233:385-387.
32. Spitz DR, Oberley LW. An assay for superoxide dismutase activity in mammalian tissue homogenates. *Anal Biochem* 1989; 179:8-18.
33. Farber JL, Kyle ME, Coleman JB. Mechanisms of cell injury by activated oxygen species. *Lab Invest* 1990; 62:670-679.
34. Khan MS, Jabeen F, Asghar MS, Qureshi N, Shakeel M, Noureen A, et al. Role of nano-ceria in the amelioration of oxidative stress: current and future applications in medicine. *Int J Biosci* 2015; 6:89-109.
35. Konduru NV, Jimenez RJ, Swami A, Friend S, Castranova V, Demokritou P, et al. Silica coating influences the corona and biokinetics of cerium oxide nanoparticles. *Part Fibre Toxicol* 2015; 12:31.
36. Yokel RA, Au TC, MacPhail R, Hardas SS, Butterfield DA, Sultana R, et al. Distribution, elimination, and biopersistence to 90 days of a systemically introduced 30 nm ceria-engineered nanomaterial in rats. *Toxicol Sci* 2012; 127:256-68.
37. Costa LG. Current issues in organophosphate toxicology. *Clin Chim Acta* 2006; 366:1-13.
38. Gultekin F, Delibas N, Yasar S, Kilinc I. In vivo changes in antioxidant systems and protective role of melatonin and a combination of vitamin C and vitamin E on oxidative damage in erythrocytes induced by chlorpyrifos-ethyl in rats. *Arch Toxicol* 2001; 75:88-96.
39. Ranjbar A, Solhi H, Mashayekhi FJ, Susanabdi A, Rezaie A, Abdollahi M. Oxidative stress in acute human poisoning with organophosphorus insecticides; a case control study. *Environ Toxicol Pharmacol* 2005; 20:88-91.
40. Abdollahi M, Mostafalou S, Pournourmohammadi S, Shadnia S. Oxidative stress and cholinesterase inhibition in saliva and plasma of rats following subchronic exposure to malathion. *Comp Biochem Physiol C Pharmacol* 2004; 137:29-34.
41. Hassani S, Sepand M, Jafari A, Jaafari J, Rezaee R, Zeinali M, et al. Protective effects of curcumin and vitamin E against chlorpyrifos-induced lung oxidative damage. *Hum Exp Toxicol* 2014; 34: 668-76.
42. Mittal S, Pandey AK. Cerium oxide nanoparticles induced toxicity in human lung cells: role of ROS mediated DNA damage and apoptosis. *BioMed Res Int* 2014; 2014.
43. El-Shenawy NS, El-Salmy F, Al-Eisa RA, El-Ahmary B. Amelioratory effect of vitamin E on organophosphorus insecticide

- diazinon-induced oxidative stress in mice liver. *Pestic Biochem Physiol* 2010; 96:101-7.
44. Akhgari M, Abdollahi M, Kebryaezadeh A, Hosseini R, Sabzevari O. Biochemical evidence for free radical-induced lipid peroxidation as a mechanism for subchronic toxicity of malathion in blood and liver of rats. *Hum Exp Toxicol* 2003; 22:205-11.
 45. Halliwell B, Gutteridge JM. *Free radicals in biology and medicine*: Oxford University Press, USA; 2015.
 46. Chen S, Hou Y, Cheng G, Zhang C, Wang S, Zhang J. Cerium oxide nanoparticles protect endothelial cells from apoptosis induced by oxidative stress. *Biol Trace Elem Res* 2013; 154:156-66.
 47. Niu J, Wang K, Kolattukudy PE. Cerium oxide nanoparticles inhibits oxidative stress and nuclear factor- κ B activation in H9c2 cardiomyocytes exposed to cigarette smoke extract. *J Pharm Exp Ther* 2011; 338:53-61.
 48. Hochella MF, Lower SK, Maurice PA, Penn RL, Sahai N, Sparks DL, et al. Nanominerals mineral nanoparticles earth systems science 2008; 319:1631-5.
 49. Wason MS, Zhao J. Cerium oxide nanoparticles: potential applications for cancer and other diseases. *Am J Transl Res* 2013; 5:126.
 50. Demokritou P, Gass S, Pyrgiotakis G, Cohen JM, Goldsmith W, McKinney W, et al. An in vivo and in vitro toxicological characterisation of realistic nanoscale CeO₂ inhalation exposures. *Nanotoxicology* 2013; 7:1338-50.
 51. Braakhuis HM, Gosens I, Krystek P, Boere J, Cassee FR, Fokkens P, et al. Particle size dependent deposition and pulmonary inflammation after short-term inhalation of silver nanoparticles. *Part Fibre Toxicol* 2014; 11:16.
 52. Ji Z, Wang X, Zhang H, Lin S, Meng H, Sun B, et al. Designed synthesis of CeO₂ nanorods and nanowires for studying toxicological effects of high aspect ratio nanomaterials. *Acs Nano* 2012; 6:5366-80.
 53. Patil S, Sandberg A, Heckert E, Self W, Seal S. Protein adsorption and cellular uptake of cerium oxide nanoparticles as a function of zeta potential. *Biomaterials* 2007; 28:4600-7.
 54. Asati A, Santra S, Kaittanis C, Perez JM. Surface-charge-dependent cell localization and cytotoxicity of cerium oxide nanoparticles. *ACS nano* 2010; 4:5321-31.
 55. Pulido-Reyes G, Rodea-Palomares I, Das S, Sakthivel TS, Leganes F, Rosal R, et al. Untangling the biological effects of cerium oxide nanoparticles: the role of surface valence states. *Sci Rep* 2015; 5:15613.

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