Toxicology Research

PAPER

View Article Online
View Journal | View Issue

Cite this: *Toxicol. Res.*, 2015, **4**, 1006

Neurobehavioral changes induced by di(2-ethylhexyl) phthalate and the protective effects of vitamin E in Kunming mice

Jiaqi Tang,†[a] Ye Yuan,†[a] Chenxi Wei,[a] Xiaomei Liao,[a] Junlin Yuan,[a] Eewa Nanberg,[b] Yinping Zhang,[c] Carl-Gustaf Bornehag*[b] and Xu Yang*[a]

Received 26th December 2014,
Accepted 7th April 2015

DOI: 10.1039/c4tx00250d

www.rsc.org/toxicology

Di(2-ethylhexyl) phthalate (DEHP) is a plasticizer commonly used in PVC that may leach into the environment, and has been shown to adversely affect the health of humans and animals. We undertook a study to ascertain the neurotoxicity of DEHP in Kunming mice. This study included three rounds of testing. In the first round, Kunming mice were exposed to different concentrations of DEHP (0, 5, 50, 500 mg kg^{-1} per day) after which their cognitive ability was assessed using the Morris water maze (MWM) test. The reactive oxygen species (ROS) content in tissue and the malondialdehyde (MDA) content of brains were also measured. In the second round, vitamin E (50 mg kg^{-1} per day) was given daily as an anti-oxidant *via* the intragastric route. Cognitive deficits and locomotor activity, as well as ROS and MDA contents were tested employing the same methods. In the third round, the depressive mood of mice after DEHP exposure (500 mg kg^{-1} per day) was measured using the open field test, the tail suspension test, and the forced swim test. The main findings of this study include: (1) a statistical association exists between DEHP oral exposure and spatial learning (DEHP 500 mg kg^{-1} per day) and memory (DEHP 50 mg kg^{-1} per day) dysfunction as ascertained by an MWM test of Kunming mice. (2) A statistical association was also found between DEHP oral exposure (50 and 500 mg kg^{-1} per day) and oxidative stress (ROS and MDA) of mouse brain tissue. (3) Co-administration of vitamin E (50 mg kg^{-1} per day) diminishes the elevation of ROS and MDA induced by DEHP (50 mg kg^{-1} per day) from significant levels to non-significant levels. (4) Co-administration of vitamin E (50 mg kg^{-1} per day) protects against mouse memory dysfunction induced by DEHP (50 mg kg^{-1} per day) from being significant to being not significant. (5) In the 5 mg kg^{-1} per day DEHP exposure groups, oxidative stress in brain tissue, and neurobehavioral changes were not found. (6) High dose DEHP exposure (500 mg kg^{-1} per day) may induce behavioral despair in mice. *Conclusions*: These data suggest that DEHP is neurotoxic with regard to cognitive ability and locomotor activity.

Introduction

Di(2-ethylhexyl) phthalate (DEHP) is a man-made chemical widely used in industry and commerce. This man-made chemical has a wide range of industrial applications, and ultimately appears in a wide range of consumer products, as well as in food processing and in medical applications.[1] DEHP is an endocrine disruptor and has been shown to disrupt reproductive tract development in male rodents in an anti-androgenic manner.[2] In addition, a number of non-reproductive endpoints have been reported in the literature, often at high doses, including hepatocellular carcinoma, anovulation and decreased fetal growth.[3]

DEHP is primarily used as a plasticizer in the manufacture of polyvinyl chloride (PVC), which is used extensively in consumer products, flooring and wall coverings, food and water contact applications, and medical devices.[4] DEHP has been measured in residential indoor environments in both house dust and indoor air,[5] and has also been measured in foods, milk and drinking water.[6] Humans are exposed to DEHP by multiple routes. Exposures can be oral: DEHP contaminated food, water and other liquids and in children through mouthing of toys and teethers. Exposure can also be *via* inhalation: DEHP volatilizes from PVC, nail polish and hair spray. Medical transfusion (haemodialysis, neonatal transfusion and parenteral nutrition) *via* DEHP-containing tubing and products is an

[a]*Section of Environmental Biomedicine, Hubei Key Laboratory of Genetic Regulation and Integrative Biology, College of Life Science, Central China Normal University, Wuhan, China. E-mail: yangxu@mail.ccnu.edu.cn; Tel: +86-13871361954*
[b]*Department of Health Sciences, Karlstad University, SE-651 88 Karlstad, Sweden. E-mail: carl-gustaf.bornehag@kau.se; Tel: +46-547002540*
[c]*Department of Building Science, Tsinghua University, Beijing, China*
† These two authors contributed equally to this work

important exposure route for DEHP, because *via* this route the DEHP exposure dose can reach very high levels.[7] The Center for Disease Control and Prevention (CDC) has published data on levels of phthalate metabolites in a large population-based sample of the US population over 6 years of age. These data demonstrate the ubiquitous nature of phthalates and variations in concentration by ethnicity, sex, and age.[8,9] The typical human exposure level to DEHP ranges from 3 to 30 μg kg^{-1} per day.[10] This dose can be exceeded under specific medical transfusions, reaching 1.5 mg kg^{-1} per day for haemodialysis patients[11] and 10 to 20 mg kg^{-1} per day during neonatal transfusion or parenteral nutrition.[12]

Since 2000, a number of epidemiological studies have found a series of health problems that are related to environmental DEHP exposure.[1] In addition, experimental results from some related toxicological studies also support these findings.[13] However, studies relating to DEHP-induced neurobehavioral, adverse effects are rare, with only one epidemiological study[14] and two animal toxicology studies[15,16] being found in the literature. The epidemiological study found a negative association between DEHP exposure and the Wechsler Intelligence Scale for Children vocabulary score; and the toxicology studies found that DEHP exposure at high doses (0.03 and 0.09% of diet) produced adverse effects in the neurobehavioural parameters in mice. However, the molecular mechanism of these neurobehavioural changes is still unclear.

Fortunately, scientific research related to the topic of DEHP-induced neurobehavioral adverse effects has made significant progress. (1) Adverse neurobehavioral changes may be caused by oxidative stress of brain tissue, especially hippocampus tissue;[17–19] (2) oxidative stress of body tissue and cells may be derived from environmental DEHP exposure.[20–22] Therefore, following the logic of syllogism we suspect that oxidative stress/damage may be the key event, *via* which DEHP exposure may cause damage to brain (hippocampus) tissue, and this in turn causes the neurobehavioral adverse effects. Vitamin E (Vit. E or Ve) is a common fat-soluble antioxidant.[23] Antioxidants protect cells from the oxidative damaging effects of free radicals, which are molecules that contain an unshared electron. Unshared electrons are highly energetic and react rapidly with oxygen to form reactive oxygen species (ROS).[24] As a medicine, Vit. E may help prevent or delay the chronic diseases associated with oxidative stress, for example heart disease[25] and cognitive decline.[26] As a molecular biological reagent, it may help us to make sure that a certain pathological change is mediated by oxidative stress/damage.[27] In such studies, Vit. E is often used in 50–100 mg kg^{-1} per day dose ranges.[28]

Hypotheses of the current study

(1) DEHP exposure at environmental levels may cause neurobehavioral changes to the body; (2) if vitamin E can relieve these pathological changes, then the oxidative stress induced by DEHP exposure may be one of the pathological mechanisms for these neurobehavioral changes.

Materials and methods

All protocols were approved by the Office of Scientific Research Management of Central China Normal University (8 November 2011; CCNU-SKY-2011-008), which is in Wuhan, China.

Animals

Male Kunming mice (7–8 weeks of age; 25–28 g) were purchased from the Hubei Experimental Animal Center (Wuhan, China). All mice were group housed in pathogen-free cages (5 mice to a cage) in rooms maintained at 20–25 °C with 50–70% humidity and a 12 h light–dark cycle. The cages we used were independent ventilation cages (IVC); each cage was equipped with a separate air inlet and outlet system. All mice were provided *ad libitum* access to a commercial diet and filtered water. The food for the animals was also purchased from the Hubei Experimental Animal Center (Wuhan, China).

Main reagents and equipment

DEHP (>99%; CAS: 117-81-7) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Tween-80 (CAS: 9005-65-6) was obtained from Amresco (Solon, OH, USA). Hydrocortisone (HC, CAS: 50-23-7) was obtained from Xiandai Hasen Pharmaceuticals (Shanghai, China). All other chemicals were of analytical grade and purchased from Sigma-Aldrich unless stated otherwise.

The equipment and biomarkers used in our study are shown in Table 1.

Table 1 Equipment for the neurobehavioral tests

Equipment (model)	Manufacture	Software used	Bio-effects tested	Endpoints tested
Morris water maze[a] (YH-WM-M/R)	Wuhan Yi-Hong Sci. & Tech. Co., Ltd (China)	ANY-Maze™ (Stoeling Co. USA)	Spatial learning and memory	Latency (learning); search-to-platform area (memory)
Open field test app. (YH-OF-M/R)	Wuhan Yi-Hong Sci. & Tech. Co., Ltd (China)	ANY-Maze™ (Stoeling Co. USA)	Anxiety-like behavior	Time spent in the center or border
Tail suspension test app. (YH-TS-M/R)	Wuhan Yi-Hong Sci. & Tech. Co., Ltd (China)	ANY-Maze™ (Stoeling Co. USA)	Depressive behavior	Immobility time
Forced swim test app. (YH-PFS-M/R)	Wuhan Yi-Hong Sci. & Tech. Co., Ltd (China)	ANY-Maze™ (Stoeling Co. USA)	Depressive behavior	Immobility time

[a] The diameter of the pool is 120 cm, the depth of the pool is 40 cm and the diameter of the platform is 5 cm. The equipment is located in a dedicated room.

Experimental design and animal exposure

The study comprised three rounds of testing, as described below.

First round of testing. The aims of the first round were to ascertain: (i) whether DEHP exposure affects the cognitive ability of mice; (ii) whether DEHP exposure can cause oxidative stress in the mouse brain; and (iii) to determine what the appropriate dose of DEHP should be for the second round. Thirty-six mice were randomly assigned to one of 4 dosage groups: vehicle control (0.9% NaCl/Tween 80 1 : 1), and 5, 50, or 500 mg kg^{-1} per day in a dosing volume of 10 mL per kg body weight. These DEHP exposure doses have been used in previous studies, and were considered reasonable.[11,29,30] Animals received daily intragastric intubations *via* a metal gastric tube for 10 consecutive days (once a day between 7:00 and 8:30 am).

Second round of testing. The aims of the second round were to investigate whether vitamin E can protect: (i) brain tissue from DEHP-induced oxidative stress; and (ii) the cognitive ability of mice from DEHP-induced weakening. Thirty-six mice were randomly assigned to one of 4 dosage groups: vehicle control (0.9% NaCl/Tween 80 1 : 1), DEHP (50 mg kg^{-1} per day); combined exposure (DEHP 50 mg kg^{-1} per day + Vit. E 50 mg kg^{-1} per day); and Vit. E control. Vit. E at 50 mg kg^{-1} per day is considered a good dosage choice for these types of studies.[28] Animals received daily intragastric intubations (DEHP and/or Vit. E) *via* a metal gastric tube for 10 consecutive days (once a day between 7:00 and 8:30 am).

Third round of testing. The aim of the third round was to investigate whether DEHP exposure may reduce locomotor activity ability in mice. Thirty mice were randomly assigned to one of 3 dosage groups: vehicle control (0.9% NaCl/Tween 80 1 : 1), DEHP (500 mg kg^{-1} per day) and depression-like symptom control (positive control, hydrocortisone 50 mg kg^{-1} per day for 10 days *via* intraperitoneal injection. All animals received daily intragastric intubations *via* a metal gastric tube for 10 consecutive days (once a day between 7:00 and 8:30 am).

Morris water maze (MWM)

The MWM test was designed to investigate the spatial cognitive abilities of laboratory mice. Rodents were placed in a circular, featureless pool of cool opaque water, where they had to swim until they discovered the escape platform (which was invisible and beneath the water surface). Mice were allowed to rest on the platform before returning to the water for another attempt. After several days of training, the rodents learned to swim directly onto the platform, presumably by using spatial cues from the room as a reference.[31] The biomarkers for neurobehavioral changes are "escape latency" (for learning) and "swimming time in the northeast quadrant (probe test)" (for memory) as measured by the Morris water maze test. The groups were subjected to the MWM to ascertain their learning ability from the 1st to the 7th day, to measure the memory ability by the search-to-platform on the 10th day, and then to determine the level of oxidative stress on the 11th day.

The training began 4 h after daily exposure of the mice. The mice were placed in the pool in the same order: SW quadrant, SE quadrant, NE quadrant, and then NW quadrant. Each mouse had three trials per day. The inter-trial period was ≤60 s. All trials had a maximum duration of 60 s, and the mice remained on the platform for 60 s at the end of each trial on the first day. Escape latency (time required to find the platform) was measured. If the animals did not find the platform within 60 s, they were gently pushed to the platform and allowed to stay there for 5 s, and the latency was recorded for 60 s. The mice were subjected to 7 days of training, on the 8th and 9th day the MWM was not used, and then on the 10th day, it was used again. The platform on the 10th day was taken away from the pool, and then each animal was released from the S point for the probe test. A pickup camera recorded their tracks for 60 s.

After the MWM test the whole brains were collected and the necropsy started 1 h later. The whole process must be completed within 1 h. Animals were kept in a holding facility and individually taken for necropsy in a separate room.

Measurements of oxidative stress in brain tissue

Preparation of tissue samples. Mice were killed by cervical dislocation. Brain tissue was collected, weighed in the completely automatic electronic balance, and homogenized in ice-cold 0.9% NaCl to produce 1 : 9 (weight/volume; g ml^{-1}) homogenates. Homogenates were centrifuged at 5000 rpm (100*g*) for 10 min at 4 °C. The supernatant was collected and frozen at −20 °C for assessment of the levels of reactive oxygen species (ROS) and malondialdehyde (MDA).

ROS content assay. Levels of ROS in the samples were determined based on the reactions between ROS and the byproducts of 2′,7′-dichlorofluorescein (DCFH)-DA.[32,33] After transfer into cells, DCFH-DA is cleaved to form DCFH, which in turn is transformed into highly fluorescent DCF upon reaction with ROS. DCF was quantified in each sample using a fluorescence monitor (FLx 800 Multi-Detection Microplate Reader; BioTek Instruments, Wisnooski, VT, USA). At first, 2 μL of sample solution was removed to a test tube, and 198 μL of phosphate-buffered saline (PBS) at pH 7.5 was added. Then, 100 μL of the sample solution was removed to a 96-well microplate, and 100 μL of DCFH-DA fluorescent dye was added, diluted 1000-fold by PBS (pH = 7.5). The level of ROS in the supernatant was detected using a fluorescent microplate spectrophotometer at an excitation wavelength of 485 nm and an emission wavelength of 525 nm.

MDA content assay. MDA content in mouse brain homogenates was measured using the Draper and Hadley method.[34] Briefly, 0.5 mL of each homogenate was mixed with 2 mL of a 0.6% (w/v) thiobarbituric acid solution in a glass test tube, placed in a boiling water bath for 15 min, and cooled immediately. The mixture was then centrifuged at 10 000*g* for 10 min and the absorbance of the resulting supernatants was read at 450, 532, and 600 nm in a PowerWave XS Microplate Spectro-

photometer (BioTek Instruments). The total protein for each sample was determined by the Lowry method.[35] The level of MDA (C_{MDA}) in each sample was calculated using the following equation (with total protein), which incorporates the value of protein content (both the total level [in mg] and the corresponding concentration [C_{pro}]) in the sample:

$$C_{MDA}\ (\text{nmol mg}_{pro}^{-1}) = (6.45 \times [OD_{532} - OD_{600}] - 0.56 \times OD_{450})/C_{pro}.$$

Experiments for locomotor activity

These experimental groups were subjected to the open field test (OFT) on the 7th day, a tail suspension test (TST) on the 8th day, and the forced swim test (FST) on the 10th day. All of these behavioral tests were administered from 11:00 to 12:30.

Open field test (OFT). The OFT is an animal test which may be used to assay anxiety-like behaviors in rodents in scientific research. The apparatus used consisted of a square base (40 × 40 cm) surrounded by a 35 cm wall, with the floor divided into 16 squares. The "border" is defined as the 12 outer periphery squares and the "center" as the 4 central squares. Each mouse was placed individually in the center of the open-field apparatus. Testing was conducted over 5 min (300 s) and recorded using a video tracking system. The walls and floors of the apparatus were cleaned thoroughly with 10% ethanol between tests. Time spent in the border and time spent in the center were the endpoints collected.

Tail suspension test (TST) and forced swim test (FST). The TST[36] is also an experiment used to assay anxiety-like behaviors in rodents. Changes in immobility time indicate changes in mood. It is widely used to detect depressive behavior induced by stress and the potential antidepressant effects of drugs. Briefly, mice were suspended individually on the edge of a shelf 58 cm above the floor by adhesive tape placed 1 cm from the tip of the tail. Mice were allowed to hang for 6 min and the duration of immobility during the final 4 min (240 s) was recorded using a video tracking system. "Immobility" was defined as hanging passively and completely motionless (depression-like symptom), and was automatically judged using the computer software ANY-Maze™ (Stoeling Co. USA).

The FST[37] is a test used to measure the depressive mood induced by stress and the effect of antidepressant drugs on the behavior of laboratory animals (typically rats or mice). FST was conducted using the method of Porsolt *et al.*[38] with minor modifications. Briefly, mice were forced individually to swim for 6 min (with the final 4 min being recorded) in a transparent glass cylinder (height, 45 cm; diameter, 20 cm) filled 30 cm high with water (22 ± 0.5 °C). "Immobility" was defined as the time spent floating in water without struggling and making only those movements necessary to keep the head above water, and automatically judged using the computer software ANY-Maze™ (Stoeling Co. USA).

Immobility has been described as a symptom of "behavioral despair", and both tests have been suggested as animal models of human depression (although this view is somewhat controversial). Nonetheless, these tests can be used to predict depressant-like symptoms and antidepressant-like activity.[36,37]

Statistical analyses

Data are means ± SEM. Statistical graphs were generated using Origin 6.0 (OriginLab, Northampton, MA, USA), which was also used for slope analyses in Fig. 1A and 2A. Statistical analyses were carried out using SPSS version 13.0 (SPSS, Chicago, IL, USA). A repeated measures ANOVA followed by a Tukey's *post-hoc* test (Tukey test) was used for WMWT escape latency analyses; and all other data were analyzed using a one-way ANOVA followed by a Tukey's test. A p-value of ≤ 0.05 was considered significant.

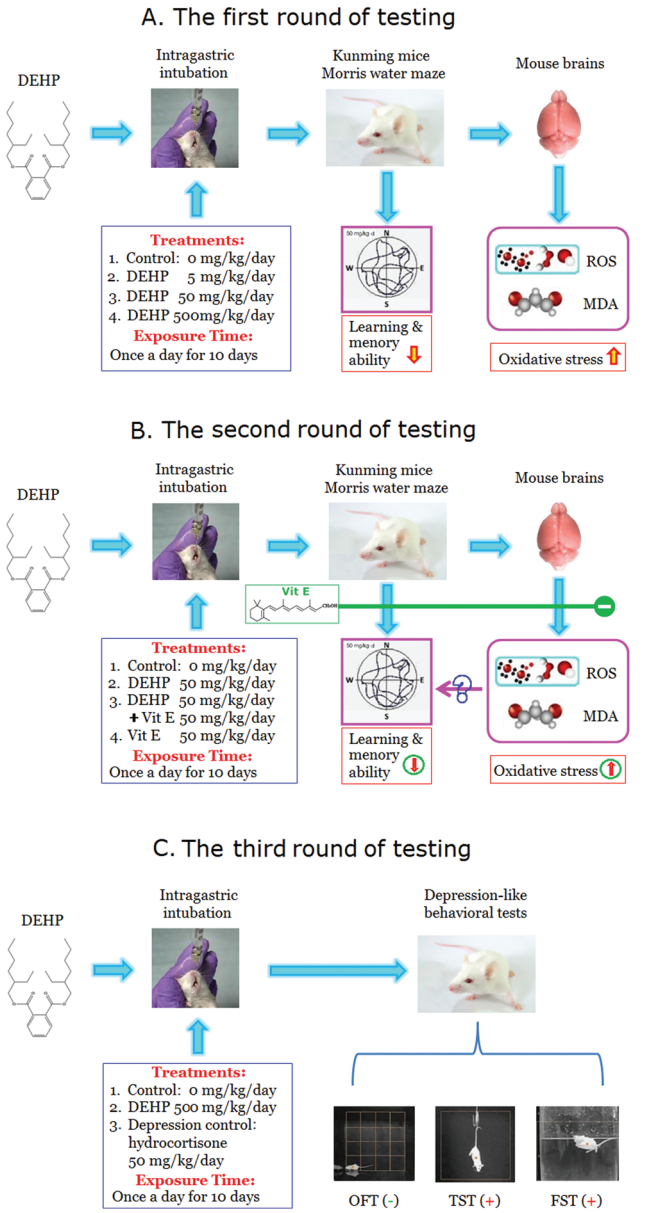

Fig. 1 Schematic diagram of the experimental design and animal exposure.

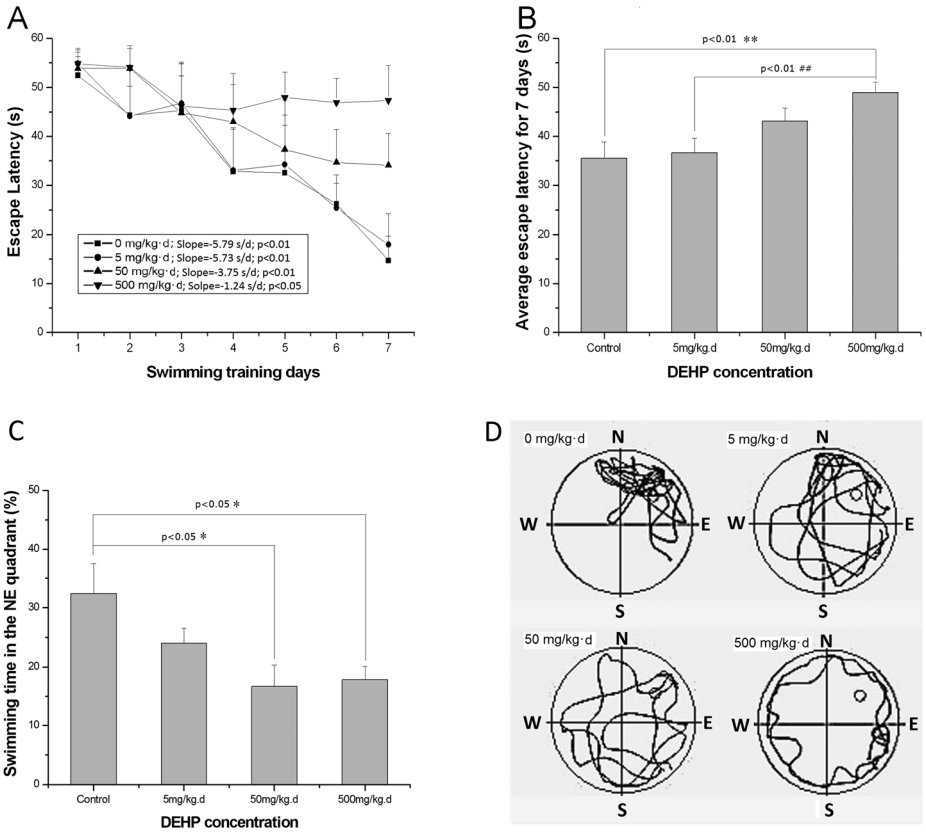

Fig. 2 Results of neurobehavioral tests in the first round of testing. (A) Escape latency of different DEHP groups on different days (slope analyses were taken using Origin 6.0). (B) Average escape latency of the four DEHP exposure groups for the 7 days (repeated measures ANOVA: $F_{(3,\ 20)} = 5.629$, $p = 0.006$; Tukey's *post-hoc* test: **: $p < 0.01$ compared with the control group; ##: $p < 0.01$ compared with the 500 mg kg^{-1} per day group). (C) Swimming time in the northeast (NE) quadrant (one-way ANOVA: $F_{(3,\ 20)} = 3.982$, $p = 0.022$; Tukey's *post-hoc* test: *: $p < 0.05$ compared with the control group). (D) The typical swimming pathway records of the four DEHP exposure groups by a probe test with a Morris water maze on the 10th day.

Results

The first round of testing

In the MWM, the hidden-platform acquisition test is applicable for investigating the spatial learning abilities of laboratory animals. Fig. 2A and B show the escape latency of different DEHP groups for all 7 days. Mice in each experimental group showed a clear decrease in escape latency over the 7 days of training. The latency of the control group showed the fastest decrease (fastest learning) (slope = −5.79 s d^{-1}, $p <$ 0.01), whereas that of the 500 mg kg^{-1} per day group showed the slowest decrease (slowest learning) (slope = −124 s d^{-1}, $p <$ 0.05).

The probe test can be used to evaluate the spatial memory of laboratory animals. The swimming time in the NE quadrant for the four DEHP exposure groups is shown in Fig. 2C. Mice in the control group spent more time in the NE quadrant (where the platform had been); the other groups with DEHP exposure spent less time in the NE quadrant. The swimming pathway on the 10th day is shown in Fig. 2D. The swimming pathway of the control group was purposeful and orderly with a focus on the NE quadrant. The swimming pathway of mice in the 500 mg kg^{-1} per day group was irregular and without purpose.

The levels of ROS and MDA after administration of DEHP are shown in Fig. 3A and B. Compared with the control group, a dramatic and dose-dependent elevation of ROS and MDA content was observed in each group. It was significantly increased in the 50 and 500 mg kg^{-1} per day groups ($p < 0.05$ or $p < 0.01$).

The second round of testing

Fig. 4A and B show that the latency of the mice that were exposed to DEHP had the slowest decrease (slowest learning, slope = −4.30 s d^{-1}, $p < 0.01$), and that the group with vitamin E (slope = −5.80 s d^{-1}, $p < 0.01$) was similar to the control group (faster learning, slope = −5.70 s d^{-1}, $p < 0.01$). Fig. 4C shows that when compared with the control group, mice in the DEHP exposure group spent less time ($p < 0.01$) in the NE quadrant (in which the escape platform was located).

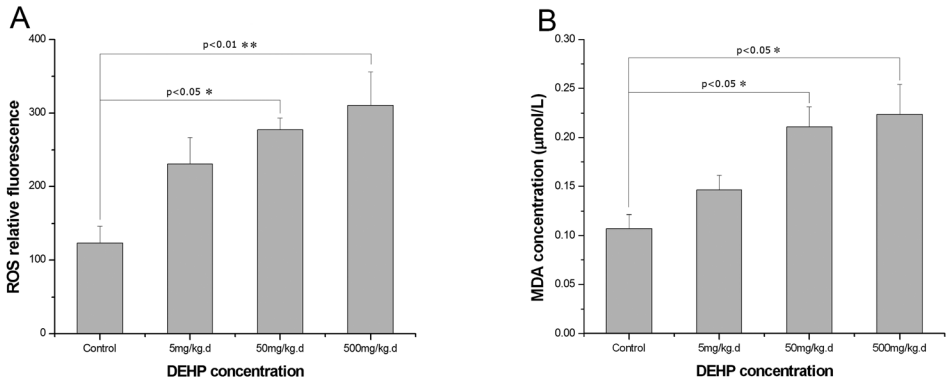

Fig. 3 Results of oxidative stress in mouse brains in the first round of testing. (A) ROS content in the brain tissue of the four DEHP exposure groups (one-way ANOVA: $F_{(3,\ 20)} = 6.399$, $p = 0.003$; Tukey's *post-hoc* test: *: $p < 0.05$, **: $p < 0.01$ compared with the control group). (B) MDA content in the brain tissue of the four DEHP exposure groups (one-way ANOVA: $F_{(3,\ 20)} = 4.501$, $p = 0.014$; Tukey's *post-hoc* test: *: $p < 0.05$ compared with the control group).

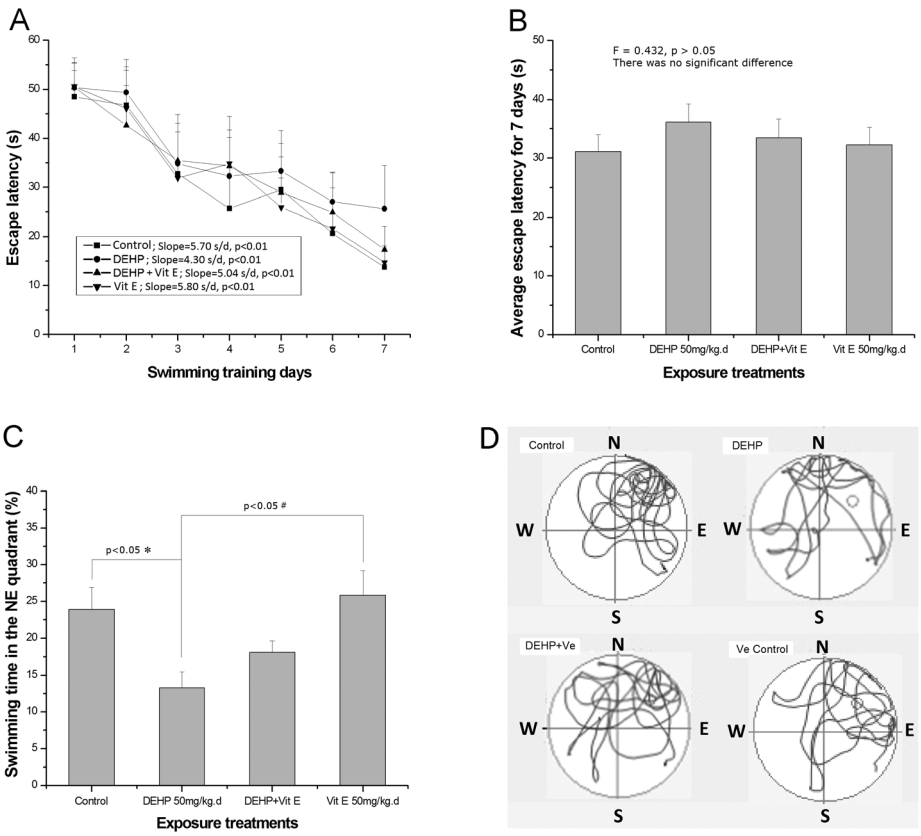

Fig. 4 Results of neurobehavioral tests in the second round of testing. (A) Escape latency of the four experimental groups on different days (slope analyses were taken using Origin 6.0). (B) Average escape latency of the four experimental groups for the 7 days (repeated measures one-way ANOVA: $F_{(3,\ 20)} = 0.432$, $p = 0.732$). (C) Swimming time in the northeast (NE) quadrant (one-way ANOVA: $F_{(3,\ 20)} = 4.702$, $p = 0.012$; Tukey's *post-hoc* test: *: $p < 0.05$ compared with the control group; Tukey's *post-hoc* test: #: $p < 0.05$ compared with the Vit. E group). (D) The typical swimming pathway records of four experimental groups by a probe test with a Morris water maze on the 10th day.

Fig. 5A and B show that ROS and MDA contents were significantly increased in the DEHP-only group ($p < 0.05$, $p < 0.01$), but not so in the vitamin E group. It is interesting that the DEHP + Vit. E combined exposure group showed a significant difference compared to the DEHP and control groups (#: $p < 0.05$, $p < 0.05$). This difference may indicate that vitamin E played a protective role in the brain tissue against oxidative stress.

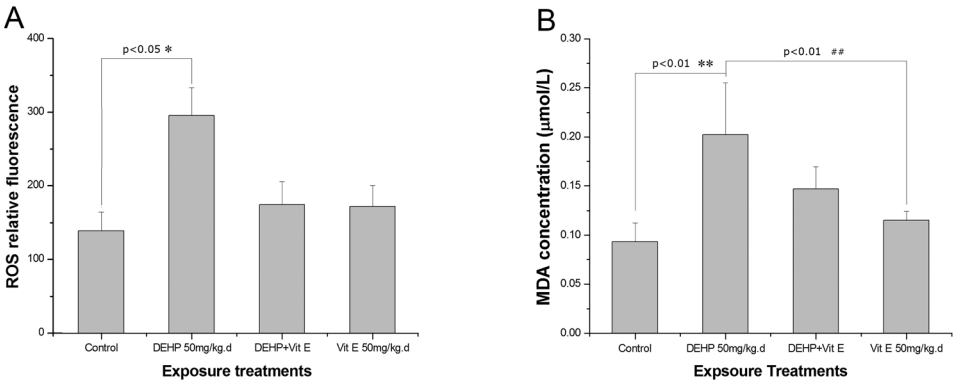

Fig. 5 Results of oxidative stress of mouse brains in the second round of testing. (A) ROS content in the brain tissue of the four experimental groups (one-way ANOVA: $F_{(3,\ 20)} = 3.267$, $p = 0.043$; Tukey's *post-hoc* test: *: $p < 0.05$ compared with the control group). (B) MDA content in the brain tissue of the four experimental groups (one-way ANOVA: $F_{(3,\ 20)} = 6.720$, $p = 0.003$; Tukey's *post-hoc* test: **: $p < 0.01$ compared with the control group; Tukey's *post-hoc* test: $^{\#\#}$: $p < 0.01$ compared with the Vit. E group).

The third round of testing

The results of the OFT are shown in Fig. 6. Mice in the control group spent more time in the center, while the DEHP (500 mg kg^{-1} per day) group was similar to the hydrocortisone group. However, the differences between the groups in the OFT were not significant ($p > 0.05$, $p > 0.05$).

In the TST (Fig. 7A) and the FST (Fig. 7B), the immobility time (seconds) showed significant increases in the DEHP group compared with the control group ($p < 0.01$ and $p < 0.05$); similar immobility times were observed in the DEHP and hydrocortisone dose groups.

Discussion

The main findings of this study include: (1) a statistical association exists between DEHP oral exposure and spatial learning (DEHP 500 mg kg^{-1} per day) and memory dysfunction (DEHP 50 mg kg^{-1} per day) as determined by the MWM test of Kunming mice. (2) A statistical association is also found between DEHP oral exposure (at 50 and 500 mg kg^{-1} per day levels) and oxidative stress (ROS and MDA) of mouse brain tissue. (3) Co-administration of vitamin E (50 mg kg^{-1} per day) diminishes the elevation of ROS and MDA induced by DEHP

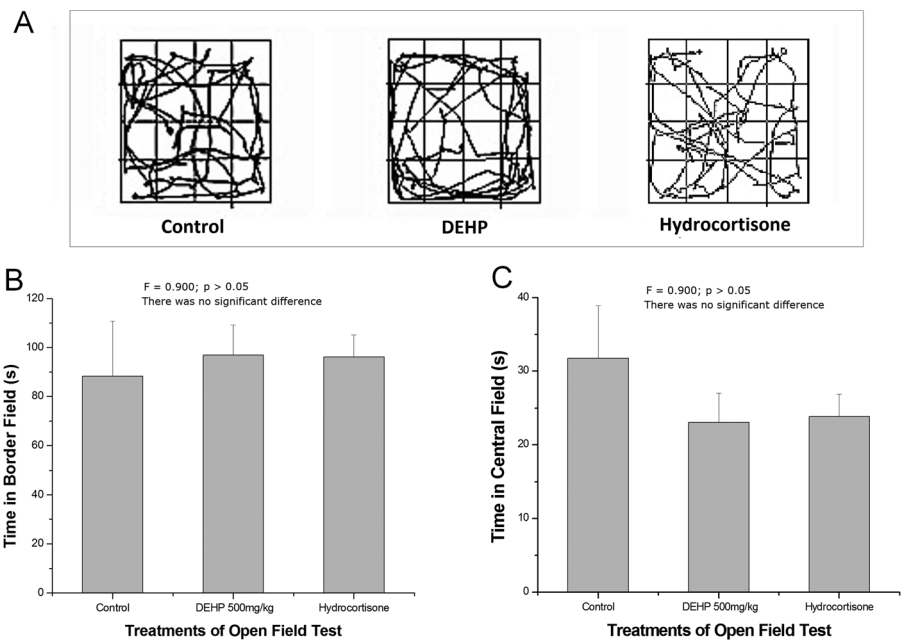

Fig. 6 Results of neurobehavioral OFT in the third round of testing. (A) The typical running pathway record of the three experimental groups using an OFT device. (B) Time in border field (one-way ANOVA: $F_{(2,\ 26)} = 0.900$, $p = 0.419$). (C) Time in the centre field (one-way ANOVA: $F_{(2,\ 26)} = 0.900$, $p = 0.419$).

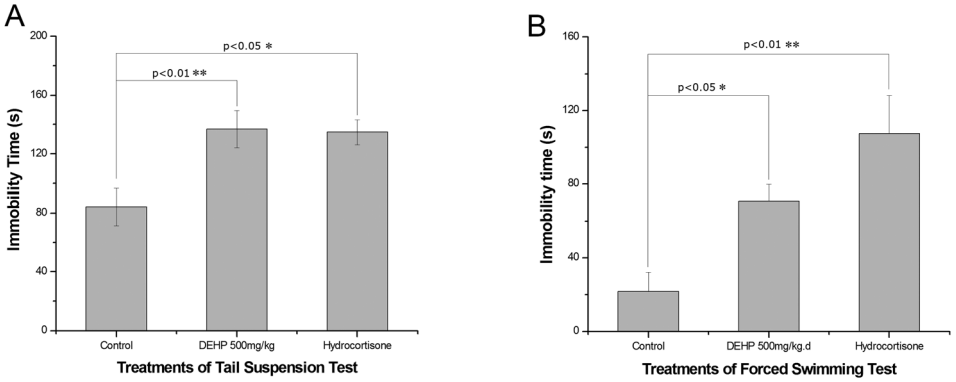

Fig. 7 Results of neurobehavioral TST and FST tests in the third round of testing. (A) Immobility time in the TST (one-way ANOVA: $F_{(2,\ 23)} = 6.735$, $p = 0.004$; Tukey's *post-hoc* test: *: $p < 0.05$, **: $p < 0.01$ compared with the control group). (B) Immobility time in the FST (one-way ANOVA: $F_{(2,\ 23)} = 9.639$, $p = 0.001$; Tukey's *post-hoc* test: *: $p < 0.05$, **: $p < 0.01$ compared with the control group).

(50 mg kg^{-1} per day) from significant to non-significant. (4) Co-administration of vitamin E (50 mg kg^{-1} per day) can protect mouse memory from dysfunction induced by DEHP (50 mg kg^{-1} per day), from weakly significant ($p = 0.044$) to non-significant. (5) Oxidative stress in brain tissue and neurobehavioral changes are not found in the 5 mg kg^{-1} per day DEHP exposure groups. (6) High dose DEHP exposure (500 mg kg^{-1} per day) may induce behavioral despair in mice.

Studies on DEHP-induced neurobehavioral adverse effects are rare; we found only three papers in the literature. The two animal experimental studies suggest that higher levels of DEHP (0.03 and 0.09% of diet) may have adverse effects as shown by neurobehavioral tests on mice (surface righting, negative geotaxis, cliff avoidance, swimming behavior and olfactory orientation).[15,16] The epidemiological study[14] found a negative association between DEHP exposure and the score obtained from the Wechsler Intelligence Scale for Children vocabulary test. Unfortunately the DEHP exposure level was assessed by measuring the level of urine MEHP, which is the main metabolite of DEHP. Our study has three main contributions in this area: (1) a lower DEHP exposure level (50 mg kg^{-1} per day) may induce adverse effects as demonstrated in the neurobehavioral test (probe test); (2) oxidative stress may be one of the biological mechanisms for mediating the DEHP-induced neurobehavioral adverse effects; and (3) antioxidants, such as vitamin E, may protect nerve cells from these adverse effects.

There is an association between learning and memory. Learning is the integration of all types of reactions, and memory is the storage of this integration. The MWM has been used widely in neuroscience, neurobehavior, and neuropharmacology studies of laboratory animals owing to the simplicity of the device and the procedures.[39]

Oxidative stress has been defined as a "disturbance in the pro-oxidant–antioxidant balance in favor of the former, leading to potential damage".[40] The brain consumes a large quantity of oxygen, making it particularly susceptible to oxidative stress.[41] ROS (which are generated excessively under oxidative stress) reversibly or irreversibly damage nucleic acids, proteins, free amino acids, lipids, lipoproteins, carbohydrates, and macromolecules in connective tissue.[42] Excess production of ROS in the brain has been implicated as a factor underlying the etiology of DEHP-induced neurotoxicity.

Studies have shown that ROS production is responsible for oxidative stress and that an increase in ROS induces the death of dopaminergic cells. In the present study, we found that ROS generation in the brains of mice in the DEHP-treatment groups increased significantly compared with that seen in the control group. Excess generation of ROS can damage a wide variety of cellular constituents (DNA, RNA, proteins, sugars, and lipids), thereby compromising cell viability. Typically, lipid peroxidation is the primary result of oxidative stress, and correlated effects on MDA levels are also observed. MDA is a metabolite of the lipid peroxidation of membranes.

Vitamin E is the primary fat-soluble, chain-breaking, antioxidant-protecting, lipid bilayer.[23] Administering vitamin E to rats caused a reduction in the serum level of MDA (a marker of lipid peroxidation). It has been reported that antioxidants such as vitamin E can improve Alzheimer's disease as well as chronic intermittent hypoxia caused by cognitive impairment and learning disabilities.[43]

The present study showed that DEHP increased MDA content in the brain. These results suggest that DEHP can induce excessive generation of ROS and could reinforce lipid peroxidation in the brain, thereby affecting oxidation–anti-oxidation homeostasis. We also showed that vitamin E protected the mouse brain from oxidative damage induced by DEHP, but the evidence was not strong enough to show that vitamin E protected a mouse's cognitive ability ($p > 0.05$).

In the OFT, mice exposed to DEHP spent a lot of time in the border area compared with control mice, but this difference was not significant. In the FST and TST, the immobility time was significantly increased in the DEHP group ($p < 0.05$); the results and behavior of the DEHP treated mice were similar to the mice in the hydrocortisone group. This result suggests that mice exposed to DEHP may have a greater risk of

developing depression-like symptoms than normal mice. The results of the behavior tests were consistent with those of previous studies.[44]

The DEHP exposure doses (5, 50, and 500 mg kg^{-1} per day) in this animal study were higher than typical human exposure levels of 3–30 μg kg^{-1} per day;[10] however, the dose of 5 mg kg^{-1} per day coincides with the exposure levels from specific medical transfusions 1.5 mg kg^{-1} per day to 20 mg kg^{-1} per day.[11,12] For testing the non-reproductive endpoints of DEHP exposure, high exposure doses such as 500 mg kg^{-1} per day[29] and 0.03 and 0.09% of daily diet[15,16] have been reported in the literature.

Limitations of this study

Our study did not include an analysis of the MWM pathway for additional semi-quantitative evaluation. For example, (1) both 60 s probe trial and 30 s epoch, (2) swimming speed, and (3) swimming distance. Further studies by our group will take these analyses into account.

In conclusion, the MWM demonstrated the toxic effects of DEHP on cognition, and the TST and FST demonstrated the risk of development of depression-like symptoms caused by exposure to DEHP. These results also support the notion that oxidative stress may be one of the mechanisms contributing to injury of the CNS. Long term exposure experiments are needed to investigate the role of oxidative stress in DEHP-induced neurotoxicity and in particular the related mechanism.

Acknowledgements

This work was funded by the Key Project of International Cooperation of the Chinese Ministry of Science and Technology (2010DFA31790) and the Key Project of the National Natural Science Foundation of China (51136002).

References

1 S. H. Swan, Review article: Environmental phthalate exposure in relation to reproductive outcomes and other health endpoints in humans, *Environ. Res.*, 2008, **108**(2), 177–184.
2 L. G. Parks, *et al.*, The plasticizer diethylhexyl phthalate induces malformations by decreasing fetal testosterone synthesis during sexual differentiation in the male rat, *Toxicol. Sci.*, 2000, **58**, 339–349.
3 R. Hauser and A. M. Calafat, Review article: Phthalates and human health, *Occup. Environ. Med.*, 2005, **62**, 806–818.
4 ATSDR, Agency for Toxic Substances and Disease Registry, Division of Toxicology, Atlanta, GA, 2002, Toxicological profile for di(2-ethylhexyl)phthalate (DEHP).
5 R. A. Rudel, *et al.*, Phthalates, alkylphenols, pesticides, polybrominated diphenyl ethers, and other endocrine-disrupting compounds in indoor air and dust, *Environ. Sci. Technol.*, 2003, **37**, 4543–4553.
6 M. Wormuth, *et al.*, What Are the Sources of Exposure to Eight Frequently Used Phthalic Acid Esters in Europeans?, *Risk Anal.*, 2006, **26**, 803–824.
7 FDA. U.S., Food and Drug Administration, Center for Food Safety and Applied Nutrition, Office of Plant and Dairy Foods and Beverages, Rockville, MD. Food and Drug Administration Total Diet Study; summary of residues found ordered by pesticide market baskets 91-3–99-1, 2001.
8 CDC. U.S., Department of Health and Human Services, Centers for Disease Control and Prevention. National Center for Environmental Health, Division of Laboratory Sciences, Atlanta, GA. Second national report on human exposure to environmental chemicals, 2003.
9 CDC. U.S., Department of Health and Human Services, Centers for Disease Control and Prevention. National Center for Environmental Health, Division of Laboratory Sciences, Atlanta, GA, 2005. Third national report on human exposure to environmental chemicals, 2005.
10 J. Doull, R. Cattley, C. Elcombe, B. G. Lake, J. Swenberg, C. Wilkinson, G. Williams and M. van Gemert, A cancer risk assessment of di (2-ethylhexyl) phthalate: application of the new US EPA risk assessment guidelines, *Regul. Toxicol. Pharmacol.*, 1999, **29**, 327–357.
11 S. Loff, F. Kabs, K. Witt, *et al.* Polyvinylchloride infusion lines expose infants to large amounts of toxic plasticizers, *J. Pediatr. Surg.*, 2000, **35**(12), 1775–1781.
12 R. Kavlock, D. Barr, K. Boekelheide, W. Breslin, P. Breysse, R. Chapin, K. Gaido, E. Hodgson, M. Marcus and K. Shea, NTP-CERHR expert panel update on the reproductive and developmental toxicity of di (2-ethylhexyl) phthalate, *Reprod. Toxicol.*, 2006, **22**, 291–399.
13 C. G. Bornehag and E. Nanberg, Phthalate exposure and asthma in children, *Int. J. Androl.*, 2010, **33**, 333–345.
14 S. C. Cho, S. Y. Bhang, Y. C. Hong, *et al.*, Relationship between environmental phthalate exposure and the intelligence of school-age children, *Environ. Health Perspect.*, 2010, **118**(7), 1027–1032.
15 T. Tanaka, *et al.*, Reproductive and neurobehavioural toxicity study of bis(2-ethylhexyl) phthalate (DEHP) administered to mice in the diet, *Food Chem. Toxicol.*, 2002, **40**(10), 1499–1506.
16 T. Tanaka, *et al.*, Reproductive and neurobehavioural effects of bis(2-ethylhexyl) phthalate (DEHP) in a cross-mating toxicity study of mice, *Food Chem. Toxicol.*, 2005, **43**(4), 581–589.
17 S. Murakami and H. Murakami, The effects of aging and oxidative stress on learning behavior in C. elegans, *Neurobiol. Aging*, 2005, **26**(6), 899–905.
18 X. Li, Y. Tang, Y. L. Wu, X. L. Yu, *et al.*, Effects of brominated diphenyl ethers-209 exposure on learning memory behaviors, oxidative damage and apoptosis in hippocampal neurons of adult rats, *Chin. Occup. Med.*, 2011, **38**(6), 463–466.
19 X. D. Liu, *et al.*, Cognitive deficits and decreased locomotor activity induced by single-walled carbon nanotubes and neuroprotective effects of ascorbic acid, *Int. J. Nanomed.*, 2014, **9**, 823–839.

20 E. Kasahara, E. F. Sato, M. Miyoshi, *et al.*, Role of oxidative stress in germ cell apoptosis induced by di(2-ethylhexyl) phthalate, *Biochem. J.*, 2002, **365**(Pt 3), 849–856.
21 J. Ghosh, J. Das, P. Manna, *et al.*, Hepatotoxicity of di-(2-ethylhexyl) phthalate is attributed to calcium aggravation, ROS-mediated mitochondrial depolarization, and ERK/NF-κB pathway activation, *Free Radicals Biol. Med.*, 2010, **49**(11), 1779–1791.
22 W. J. Chen, H. Dai, M. Chen, *et al.* Hepatotoxic effect and lipid oxidative damage of diethylhexyl phthalate (DEHP) on mice, *Asian J. Ecotoxicol.*, 2012, **7**(1), 93–98.
23 M. G. Traber and E. Vitamin, *Modern Nutrition in Health and Disease*, ed. M. E. Shils, M. Shike, A. C. Ross, B. Caballero and R. Cousins, Lippincott Williams & Wilkins, Baltimore, MD, 10th edn, 2006, pp. 396–411.
24 H. Verhagen, B. Buijsse, E. Jansen and B. Bueno-de-Mesquita, The state of antioxidant affairs, *Nutr. Today*, 2006, **41**, 244–250.
25 M. J. Stampfer, C. H. Hennekens, J. E. Manson, G. A. Colditz, B. Rosner and W. C. Willett, Vitamin E consumption and the risk of coronary disease in women, *N. Engl. J. Med.*, 1993, **328**, 1444–1449.
26 M. Sano, C. Ernesto, R. G. Thomas, M. R. Klauber, K. Schafer, M. Grundman, *et al.*, A controlled trial of selegiline, alpha-tocopherol, or both as treatment for Alzehimer's disease, *N. Engl. J. Med.*, 1997, **336**, 1216–1222.
27 K. H. Alzoubi, O. F. Khabour, B. A. Rashid, *et al.*, The neuroprotective effect of vitamin E on chronic sleep deprivation-induced memory impairment: The role of oxidative stress, *Behav. Brain Res.*, 2012, **226**(1), 205–210.
28 D. Rocksen, B. Ekstrand-Hammarstrom, L. Johansson and A. Bucht, Vitamin E Reduces Transendothelial Migration of Neutrophils and Prevents Lung Injury in Endotoxin -Induced Airway Inflammation, *Am. J. Respir. Cell Mol. Biol.*, 2003, **28**, 199–207.
29 J. S. Schmidt, K. Schaedlich, N. Fiandanese, *et al.*, Effects of di(2-ethylhexyl) phthalate (DEHP) on female fertility and adipogenesis in C3H/N mice, *Environ. Health Perspect.*, 2012, **120**(8), 1123–1129.
30 P. Erkekoglu, W. Rachidi, O. G. Yuzugullu, *et al.*, Evaluation of cytotoxicity and oxidative DNA damaging effects of di(2-ethylhexyl)-phthalate (DEHP) and mono(2-ethylhexyl)-phthalate (MEHP) on MA-10 Leydig cells and protection by selenium, *Toxicol. Appl. Pharmacol.*, 2010, **248**, 52–62.
31 Z. Lu, C. M. Li, Y. Qiao, *et al.*, Inhaled formaldehyde on learning and memory of mice, *Indoor Air*, 2008, **18**(2), 77–83.
32 D. Wu, J. Lu, Y. Q. Zhang, *et al.*, Ursolic acid improves domoic acid-induced cognitive deficits in mice, *Toxicol. Appl. Pharmacol.*, 2013, **271**(2), 127–136.
33 J. Bejma and L. L. Ji, Aging and acute exercise enhance free radical generation in rat skeletal muscle, *J. Appl. Physiol.*, 1999, **87**(1), 465–470.
34 H. H. Draper and M. Hadley, Malondialdehyde determination as index of lipid peroxidation, *Methods Enzymol.*, 1990, **186**(3), 421–431.
35 O. H. Lowry, N. J. Rosebrough, A. L. Farr, *et al.*, Protein measurement with the Folin phenol reagent, *J. Biol. Chem.*, 1951, **193**(1), 265–275.
36 L. Steru, R. Chermat, B. Thierry, *et al.*, The tail suspension test: A new method for screening antidepressants in mice, *Psychopharmacology*, 1985, **85**(3), 367–370.
37 B. Petit-Demouliere, F. Chenu and M. Bourin, Forced swimming test in mice: a review of antidepressant activity, *Psychopharmacology*, 2005, **177**(3), 245–255.
38 R. D. Porsolt, A. Bertin and M. Jalfre, Behavioral despair in mice: A primary screening test for antidepressants, *Arch. Int. Pharmacodyn Ther.*, 1977, **229**(2), 327–336.
39 R. D'Hooge and P. P. DeDeyn, Applications of Morris water maze in the study of learning, *Brain Res. Rev.*, 2001, **36**(1), 60–90.
40 H. Sies, Oxidative stress: from basic research to clinical application, *Am. J. Med.*, 1991, **91**(3), 31–38.
41 J. K. Andersen, Oxidative stress in neurodegeneration: cause or consequence, *Nat. Neurosci. Rev.*, 2004, **10**(1), S18–S25.
42 V. Voitkun and A. Zhitkovich, Analysis of DNA–protein crosslinking activity of malondialdehyde in vitro, *Mutat. Res.*, 1999, **424**(1–2), 97–106.
43 J. A. Joseph, B. Shukitt-Hale, N. A. Denisova, *et al.* Long-term dietary strawberry, spinach, or vitamin E supplementation retards the onset of age-related neuronal signal-transduction and cognitive behavioral deficits, *J. Neurosci.*, 1992, **18**(19), 8047–8055.
44 J. Boberg, S. Christiansen, M. Axelstad, *et al.*, Reproductive and behavioral effects of diisononyl phthalate (DINP) in perinatally exposed rats, *Reprod. Toxicol.*, 2011, **31**(2), 200–209.