Daily Subacute Paraquat Exposure Decreases Muscle Function and Substantia Nigra Dopamine Level

M. A. FAHIM1, S. SHEHAB2, A. NEMMAR1, A. ADEM3, S. DHANASEKARAN3, M. Y. HASAN3

1Department of Physiology, 2Department of Anatomy, 3Department of Pharmacology, College of Medicine, UAE University, Al Ain, United Arab Emirates

Received May 17, 2012
Accepted November 23, 2012
On-line March 14, 2013

Summary
The use of the herbicide paraquat (1,1′-dimethyl-4,4′-bipyridylium dichloride; PQ) which is widely used in agriculture is known to cause dopaminergic neurotoxicity. However, the mechanisms underlying this effect are not fully understood. This present study investigated the behavioral manifestations, motor coordination, and dopaminergic neurodegeneration following exposure to PQ. Male rats were injected with PQ (10 mg/kg i.p.) daily for three weeks. Rotarod systems were used for measuring locomotor activity and motor coordination. The effects of PQ on dorsiflexor, electrophysiologically-induced muscle contraction were studied. Dopamine concentrations in the ventral mesencephalon were measured by high performance liquid chromatography and the number of dopaminergic neurons in substantia nigra pars compacta was estimated by tyrosine hydroxylase immunohistochemistry. PQ induced difficulty in movement and significant reduction in motor activity and twitch tension at the dorsiflexor skeletal muscle. The number of tyrosine hydroxylase positive neurons was significantly less in the substantia nigra pars compacta and nigral dopamine level was significantly reduced in PQ treated animals (20.4±3.4 pg/mg) when compared with control animals (55.0±2.4 pg/mg wet tissue). Daily treatment of PQ for three weeks induces selective dopaminergic neuronal loss in the substantia nigra and significant behavioral and peripheral motor deficit effects.

Key words
Paraquat • Dopamine • Skeletal muscle • Locomotor activity

Introduction
Paraquat (PQ, 1,1′-dimethyl-4,4′-bipyridinium dichloride) is a widely used herbicide in agriculture whose chemical structure is very similar to the active form of MPTP (1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine), a neurotoxin that leads to parkinsonism in animals (Bloem et al. 1990) and humans (Langston et al. 1983). This suggests an association between the use of this pesticide in agriculture and incidence of Parkinson’s disease. Indeed, intraperitoneal (i.p.) administration of PQ in rodents causes loss of DA neurons in the substantia nigra (SN) as a key feature in parkinsonism with associated decrease in locomotor activity (Brooks et al. 1999, McCormack et al. 2002).

Epidemiologic studies indicate that exposure to PQ in human through agricultural usage can be a risk factor in the incidence of neurodegeneration in both animal and human models (Dinis-Oliveira et al. 2006, McCormack et al. 2005, Thiruchelvam et al. 2000a,b, 2003, Djukic et al. 2007). A strong correlation has been reported between exposure to PQ and Parkinson’s disease (PD) incidence (Berry et al. 2010) and confirmed by clinical studies conducted in Canada, Taiwan, and the United States (Liou et al. 1997). This correlation is supported by animal studies showing that PQ produces toxicity on dopaminergic neurons of the rat and mouse brain (McCormack et al. 2002, McCormack et al. 2005). However, it is unclear how PQ triggers toxicity in dopaminergic neurons. PQ exposure results in mitochondrial dysfunction and microglial activation leading to increased generation of reactive oxygen.
species (ROS), which in turn damages dopaminergic neurons. PQ also decreases the binding of dopamine (DA) to dopamine transporter (DAT) and inhibits DA uptake, thereby disturbing DA homeostasis (Ossowska et al. 2005). Paraquat mediates nigral dopaminergic neuronal apoptotic machinery through sequential phosphorylation of c-Jun N-terminal kinase and c-Jun and the activation of caspase-3 which induces sequential neuronal death (Peng et al. 2004).

PQ is one of the most widely used herbicides in the world. It is rapidly acting and nonselective herbicide. Occupational and professional exposure to PQ may occur by inhalation or dermal route and is considered as an etiological factor of PD (Moretto and Colosio 2011). Suicidal poisonings are related to ingestion of PQ (Gawarammana and Buckley 2011). Ingestion of concentrated solutions (12-20 %) of PQ leads to early death due to organs failure. Patients with acute PQ poisoning show damage to the lungs, liver, and kidneys, and some also show symptoms of central nervous system toxicity (Di Monte 2003). There is no specific treatment for PQ poisoning, thus management of poisonings is to relieve symptoms and complications (Gawarammana and Buckley 2011).

Similarly, PQ is toxic to animals and can cause damage to lungs and brain, among other tissues. Conspicuously, PQ has been reported to increase the risk for sporadic PD via its toxicity to DA neurons in the substantia nigra (Thiruchelvam et al. 2003, 2005). PQ toxicity is caused by oxidative stress due to redox cycling, a process in which it accepts an electron from an appropriate donor and subsequently reduces O$_2$ to produce superoxide anion radical (O$_2^-$) (Drechsel and Patel 2008). These observations emphasize the need to systematically monitor exposures and apply experimental approaches to understand and anticipate mechanisms that could result in PQ-induced neurotoxicity.

The present study aimed to explore the behavioral manifestations of PQ induced toxicity on the locomotor activity and motor coordination. We aimed also to investigate the skeletal muscle electrophysiological modifications and to determine the level of DA in substantia nigra following PQ treatment.

Materials and Methods

This project was reviewed and approved by the Institutional Review Board of the United Arab Emirates University, and experiments were performed in accordance with protocols approved by the Institutional Animal Care and Research Advisory Committee.

Animals and treatment

All the experiments were performed on Male Wistar rats (body weight, 210±15 g). Animals were housed in groups of 4 in polypropylene cages with a controlled light and dark cycle of 12 hours each at 24-26 °C. Food and water were available ad libitum. PQ (Sigma, St. Louis, MO), dissolved in normal saline, was injected at 10 mg/kg i.p. daily for 3 consecutive weeks to induce neurotoxicity. Equal number of rats served as control and received normal saline in similar way. At the end of three weeks of treatment and after 30 min of last treatment with PQ, the individual groups of rats were subjected to following tests.

Behavioral studies

Behavioral studies included measuring motor coordination in rats. Rotarod systems (Harvard apparatus, MA, USA) were used for measuring locomotor activity and motor coordination. The animals were placed on a rod with 3-cm diameter, which is rotating at a constant speed (20 RPM). The total time during which the animals remain by coordinating and balancing on the rod and continuously moving forward to show the forward gait to avoid falling off the rod was compared between control and PQ treated group of animals (n=10, in each group). The latency to fall represented a measure of motor activity and motor coordination of the animals. Prior to the actual test, all the animals were trained on rotarod twice a day for one week.

Electrophysiological recording

The electrophysiological recordings were performed by exposing dorsiflexor muscle with its motor nerve in-situ and stimulating electrically to observe the changes in twitch tension. At the time of experiments, rats (n=8, in each group) were anesthetized with urethane 25 % solution (2.5 mg/g bodyweight, i.p.) and the flexor digitorum superficialis muscle was dissected out. Care was taken not to damage the muscle. The dorsiflexor muscle was chosen because it encloses predominantly fast twitch fibers and its location makes in-situ physiological recording possible. Muscle contraction ability was investigated by measuring isometric twitch tensions. Isometric twitch tensions (evoked either directly by stimulation of the muscle or indirectly by stimulation of motor nerve) were measured after the tendinous
insertion of electrodes and was attached to a force displacement transducer (Model FT-03C, Grass Technologies, RI, USA). The output was differentially amplified and displayed on a chart recorder for analysis. Twitch responses to supramaximal stimuli delivered to the dorsiflexor nerve at 1 Hz were recorded in dorsiflexor muscle. Direct muscle stimulation was accomplished by placing two wide platinum wires underneath the muscle. Twitches were evoked either directly or indirectly using a stimulator (Model S44, Grass Technologies, RI, USA) delivering 5 VDC square wave pulses of 0.5 ms duration. The muscle was lengthened until a maximum twitch response was elicited. This was achieved usually when the muscle was stretched by 1.1 times its resting length. Normal Krebs solution was used to irrigate the exposed muscle and nerve.

**Biochemical studies – estimation of dopamine**

Animals were humanely decapitated and tissue samples from ventral mesencephalon were removed and placed on ice. The samples were weighed and transferred to pre-cooled lightproof Eppendorf tubes. Two milliliters of 0.1 M perchloric acid containing 0.1 M citric acid and 0.001 M ethylenediaminetetraacetic acid was added to each tube. The tubes were submerged in ice pellets and the tissues were homogenized using a motorized homogenizer (Ultra Turrax T25basic, IKA, Werke) for 2 min. The homogenized tissue was centrifuged in a refrigerated centrifuge (2 °C) at 5400xg for 10 min. The supernatant was aspirated into Eppendorf tubes and filtered through 0.45-µm mesh microfilter before being injected into the HPLC system.

The HPLC system consisted of a dual plunger pump (Waters® 616, Waters® Corporation, MA, USA), controller (Waters® 6000 S), autosampler (Waters® 717S), and a pulsed electrochemical detector (Decade II, Antec Leyden®, The Netherlands). The glassy carbon electrode was equipped with the applied potential of 800 mV and current of 10 nA, and with Empower® 2.0, the operating software, from Waters®. The standard catecholamine mobile phase from Chromsystems® (Mobile Phase Catecholamine Part No: 5001) was used at the flow rate of 0.8 ml/min and run overnight to stabilize the baseline. Calibration solutions (Chromsystems®, Plasma calibration standards) containing 386 pg/ml of DA were injected repeatedly to establish the integrity of the column, and the stability of the mobile phase and the reproducibility of the retention time. Peak areas of each component were recorded and averaged to calculate the final concentration of DA in the tissue sample.

**Tyrosine hydroxylase immunohistochemistry in substantia nigra pars compacta (SNc)**

The rats (n=6 in each group) were humanely killed with an over dose of urethane 25 % solution (2.5 g/kg bodyweight, i.p.) and perfused with 10 % formalin in phosphate buffer, transcardially. The brains were removed, postfixed in the same fixative solution overnight and then imbedded in paraffin. Coronal paraffin sections (10 µm) of the midbrain were cut and collected serially and processed for detection of tyrosine hydroxylase (TH) using the avidin-biotin-complex (ABC) method. Briefly, after microwave treatment for antigen retrieval, the sections were incubated with TH-antibody raised in rabbit (Millipore, diluted 1:10,000) overnight. After rinsing in phosphate buffered saline (PBS), the sections were incubated in biotinylated goat anti-rabbit IgG (Jackson, 1:500) for 1 h then in extravidin- peroxidase conjugate (Sigma, 1:1000) for another hour. To visualize any TH immunoreactivity the sections were incubated for 5 min in a solution containing 25 mg dianinobenzidine dissolved in 50 ml of 0.1 M phosphate buffer (PB, pH 7.4) with 7.5 µl hydrogen peroxide (30 %) and 1 ml nickel chloride (3.5 %) added to intensify the reaction. Finally, the sections were rinsed with water, dehydrated in graded alcohol, cleared in xylene and mounted with. All antibodies were diluted in PBS containing 0.3 % Triton.

Representative digital images were captured using a Zeiss AxioCamHRc digital camera with AxioVision 3.0 software (Carl Zeiss, Germany). The survival of DA producing neurons was determined by the number of TH positive (TH+) neurons in the SNc. Six sections from each animal (n =6) separated by at least 30 µm from the middle of nigra 5.2-5.8 mm behind bregma (Paxinos and Watson 2007) were counted. Only TH-positive profiles displaying obvious nuclei which were identified by the lack of cytoplasmic staining in the middle of the neurons were included in this analysis. The labels of immunohistochemical images were coded and these images were carefully and blindly (without the knowledge of animal treatment) assessed by an expert histopathologist and reported about the changes observed in the tissue sections.

**Statistical analysis**

The calculated mean of data derived from each experiment was presented as bar graphs and the standard
error of mean (S.E.M) was plotted as error bar (mean±S.E.M). The results from the control and PQ treated groups were compared using unpaired Student’s t-test in the software Graphpad Prism version 4. For all the experiments, the sample size was 6-10 and the significance level of 0.05 (95% confidence) was considered as a cut off.

**Results**

The weight of the rats were assessed and recorded during and after the treatment of PQ. No significant changes were observed in the weight of PQ treated group (204.0±2.7 g, n=10 initially and 247.2±2.4 g, n=10 after three weeks) when compared to the saline treated control group (204.9±3.4 g, n=10 initially and 257.8±6.3 g, n=10, after three weeks) (Fig. 1). No significant effect was found in feeding, drinking and ability of the animals to maintain normal growth and full health.

**Behavioral studies**

Behavioral manifestations were measured following exposure to PQ. These included measuring locomotor activity and motor coordination in rats. PQ treatment modified locomotor activity and motor coordination as investigated by performance on the rotarod instrument. PQ treated animals lost their coordination and the normal motor control and showed weakness when compared to the control group to walk continuously or walk forward to avoid falling off the rotarod. Statistical analysis showed that animals that received PQ stayed for much (P<0.05) shorter period (124±33 s, n=10) on the rotarod compared to control group (380±99 s, n=10) (Fig. 2).

**Electrophysiological studies**

Muscle contraction ability was investigated by measuring isometric twitch tensions (evoked either directly by stimulation of the muscle or indirectly by stimulation of motor nerve). Twitch tensions (n=10) were recorded after the tendinous insertions were attached to a force displacement transducer. Isometric force of contraction in response to indirect supramaximal nerve and direct muscle stimulation were reduced in PQ treated animals (Table 1). PQ treatment significantly (P<0.05) reduced force and tension of muscle contraction. Muscles from PQ treated rats generated a significantly smaller force of contraction upon both direct and indirect stimulation. However, PQ treatment had no effect on contractile speed, rise time or half time of decay (Table 1).

| Muscle characteristic | Control     | PQ treated  |
|-----------------------|-------------|-------------|
| **Indirect nerve stimulation** |             |             |
| Rise time (ms)        | 0.49±0.04   | 0.50±0.06   |
| ½ Decay time (ms)     | 0.44±0.03   | 0.43±0.04   |
| Twitch tension (g)    | 8.5±0.3     | 4.9±0.5*    |
| **Direct muscle stimulation** |         |             |
| Rise time (ms)        | 0.47±0.03   | 0.52±0.06   |
| ½ Decay time (ms)     | 0.37±0.04   | 0.48±0.08   |
| Twitch tension (g)    | 8.1±0.3     | 3.9±0.7*    |

Data in the table shown are mean±S.E.M, n=10, * P<0.05.
Biochemical studies – estimation of dopamine

PQ treatment reduced the DA level significantly in the ventral mesencephalon when compared to the control group which received saline only (P<0.01, n=8). The level of the DA in ventral mesencephalon in PQ treated group was 20.4±3.3 pg/mg while the control group measured 55.1±2.4 pg/mg of wet weight of the tissue (Fig. 3).

Fig. 3. Effects of paraquat on amount of dopamine estimated by HPLC in substantia nigra compared to control. Data in bar graph are mean±S.E.M, n=8, ** P<0.01.

Immunohistochemical studies – SNc dopamine

In order to determine whether PQ treatment could cause loss of DA neurons, quantification of TH+ neurons in SNc was carried out. The number of TH+ neurons (authentic marker of dopaminergic neurons) in the middle of SNc was 45.6±2.4/section and 33.8±3.4/section in control and PQ-treated rats respectively. Statistical analysis showed that chronic PQ exposure significantly reduced about one third of total number of TH+ neurons in SNc relative to sections from saline treated control rats (P<0.001, n=6) (Figs 4 and 5).

Fig. 4. Effect of paraquat on number of the TH+ neurons compared to control data in bar graph are mean±S.E.M, n=6, *** P<0.001.

Discussion

The present studies have demonstrated that PQ injection (10 mg/kg injected daily i.p. for three weeks) can cause a notable reduction in the amount of DA in SNc and a significant bradykinetic reaction in the rotarod experiment when compared to the control group. The degeneration in TH+ neurons in PQ treated group was up to 28% when compared to the control group in the SNc. This significant loss is mainly attributed to the treatment of PQ. Our in-situ experiment on twitch response on dorsiflexor muscle showed significant decrease in their twitch tensions. However, the rise time and the half decay time of the contraction have not shown a statistically significant change when compared to the control group.

This study also investigated the effects of subacute intraperitoneal injection of PQ. The results showed that PQ produced a decrement in rotarod performance. Animals received daily treatment of PQ for three weeks stayed on the rotarod for much shorter period compared with control. In agreement with previous study (Thiruchelvam et al. 2003) in which 10 mg/kg, twice per week for 6 weeks was used, the motor coordination was reduced in the PQ treated rats tested in the similar environment of rotarod, suggesting a strong relationship with the characteristics of neurotoxicity produced by PQ.

The present results demonstrated that the i.p. treatment of PQ, resulted in a significant reduction of muscle contraction when stimulated electrically on dorsiflexor muscle with no effect on contractile speed, rise time or half time of decay.

Presynaptically, effects of PQ treatment could result from blocking entry of Ca2+ into nerve terminals via voltage sensitive channels or it may have an action on the internal Ca2+ binding sites and consequently the level of Ca2+ sequestering activity inside the nerve terminal (Yoshimura et al. 1993, Tauskela et al. 2005, Bagatini et al. 2011). Postsynaptically, PQ may elicit modifications in the regulation of the myoplasmic transient that could explain altered twitch contractile properties. Indeed, muscle-twitch response after transmitter release from nerve terminals can be changed significantly by changing sarcoplasmic reticulum function with or without alterations in myosin characteristics. However, the unchanged rise and relaxation time of isometric twitch tension probably reflect an intact function of the sarcoplasmic reticulum, as opposed to an alteration in the intrinsic shortening properties of the myofibrils of the muscle. The physiological role of skeletal muscle
sarcoplasmic reticulum is the release and sequestration of Ca^{2+} during the contraction-relaxation cycle, thus regulating the level of contractile apparatus activation. Another possibility is that free radicals are elevated during PQ treatment and may cause muscle membrane damage, with the net results of contractility decrement (Huang et al. 2012). Recently, reported data indicated that PQ decreases the mitochondrial membrane potential and increases mitochondrial reactive oxygen species (ROS), supporting mitochondria as the target site of PQ (Huang et al. 2012).

A previous study on the neuromuscular function was conducted by directly applying PQ to the diaphragm (an isolated skeletal muscle preparation). The results showed that PQ inhibited acetylcholine contracture blocked the postsynaptic acetylcholine receptors which play a role in the inhibition of the skeletal muscle contracture. In addition, PQ resists the diaphragms from alpha-isometric force of contraction in response to indirect supramaximal nerve and direct muscle stimulation (Lin-
Shiau and Hsu 1994). Taken together with these findings and our results, suggest that the effect of PQ might be both locally mediated through neuromuscular junction and through indirect manifestation from the effect on central dopaminergic system.

The results obtained from histochemical studies depicted that chronic PQ exposure significantly reduced the number of TH+ neurons in the SNc relative to vehicle-treated rats. Although earlier studies showed no significant effects of PQ treatment on the number of dopaminergic neurons in SNc (Widdowson et al. 1996, Thiruchelvam et al. 2000a,b), our results are in agreement with those who reported 25-30 % loss of TH+ neurons (McCormack et al. 2002, Mangano et al. 2011).

Although the mechanism of action of PQ in destroying DA neurons in Parkinsonism is not fully understood several mechanisms have been proposed. It has been shown that PQ induces dopamine overflow and reduces DA synthesis by N-methyl-D-aspartate (NMDA) receptor activation, associated with Ca2+ penetration as a key feature of neurodegeneration. PQ has also been found to decrease the mitochondrial complex I activity of the brain (Tawara et al. 1996). Furthermore, it markedly induces alpha-synuclein up-regulation and aggregation as a consequence of toxicant insult leading to alpha-synuclein pathology in neurodegenerative disorders (Manning-Bog et al. 2002).

This study also investigated the effect of daily PQ exposure (i.p.) for 3 weeks. The reason for that is to try to mimic heavy human exposure scenarios to PQ. While this dosage regimen has affected the muscle function and SN dopamine level, it did not affect the body weight or the general appearance of the animals. Other researchers have also investigated different routes and dosage regimens. Mangano et al. (2011) demonstrated that PQ exposure (10 mg/kg, 3 times /wk. for three weeks) could conceivably contribute to motor and non-motor disturbances. McCormack et al. (2002) showed that PQ (10 mg/kg once /wk for three weeks) caused selective dopaminergic degeneration without significant decrease in DA level in the striatum. These authors explained their finding by a possible compensatory mechanism by which neurons that survive damage are capable of restoring neurotransmitter tissue levels (McCormack et al. 2002). However, Widdowson et al. (1996) reported that multiple oral dosing (5 mg/kg/day) for 14 days did not lead to changes in locomotor activity or grip strength or neuropathology or changes in neurochemistry in the nigrostriatal tract. These findings illustrate the importance of the route and dosage regimen in PQ-induced neuromuscular dysfunction.

One of the possibilities of having less TH+ neurons obtained in PQ treated animals in this study may be due to phenotypic down-regulation of TH+. However, this is unlikely the case because in two recent studies, in which an unbiased quantification technique was used, the findings indicated that PQ treatment in mice killed TH+ containing neurons selectively (McCormack et al. 2002, Mangano et al. 2011).

The results of the current study showed that PQ treatment produce 66 % reduction in the level of DA in ventral mesencephalon measured with HPLC compared with 28 % loss of TH+ neurons in SNC measured immunocytochemically. Interestingly, similar results have been previously reported which showed that the extent of MPTP-induced DA depletion is usually much greater that extent of neuronal loss in the substantia nigra of mice and monkey (Chan et al. 1997, Di Monte et al. 2000). This discrepancy might be explained by the usage of different techniques. Immunohistochemical staining is a very efficient technique to provide precise location and accurate estimate of the number of TH+ neurons in substantia nigra. However, this technique does not provide accurate estimate of the concentration of the neuronal transmitter in nigra. Degenerating neurons, which would very likely produce less amount of TH+ or DA, will still be stained positively and counted especially when a very sensitive peroxidase method with nickel intensification is employed as the one used in this study.

In these studies, an estimation of DA level resulted in a major decrease in the concentration suggesting a strong correlation to our histopathological reports. Several studies have authenticated the involvement of the DA from the neurons spread through SNC and other regions of mid brain. About sixty percent of reduction in the levels of DA was observed in this current study. Nigrostriatal DA regulates the tone and contraction in skeletal muscles through an influence on postsynaptic D1 and D2 receptors (Korchounov et al. 2010, Calabresi et al. 2007). To completely estimate the degree and the extent of the progressive neurotoxicity, it will require a long course of study to reproduce the nature of disease which occurs slowly in brain.

Conclusion

In conclusion, the results of the present study have demonstrated that i.p. daily treatment of rats for
3 weeks with PQ induces selective dopaminergic neuronal loss in the substantial nigra and significant behavioral and peripheral motor deficit effects. Additional studies are needed to uncover the mechanisms underlying these effects.

Conflict of Interest
There is no conflict of interest.

Acknowledgements
This work was financially supported by the Research Affairs at the UAE University under a contract no. 02-04-8-11/04. The technical assistance of Sarabjit Singh, Mohammed Shafiullah and Araf Abdul-Kareem is highly appreciated.

References

BAGATINI PB, SAUR L, RODRIGUES MF, BERNARDINO GC, PAIM MF, COELHO GP, DA SILVA DV, DE OLIVEIRA RM, SCHIRMER H, SOUTO AA, VIANNA MR, XAVIER LL: The role of calcium channel blockers and resveratrol in the prevention of paraquat-induced parkinsonism in Drosophila melanogaster: a locomotor analysis. Invert Neurosci 11: 43-51, 2011.

BERRY C, LA VECCHIA C, NICOTERA P: Paraquat and Parkinson’s disease. Cell Death Differ 17: 1115-1125, 2010.

BLOEM BR, IRWIN I, BURUMA OJ, HAAN J, ROOS RA, TETRUD JW, LANGSTON JW: The MPTP model: versatile contributions to the treatment of idiopathic Parkinson’s disease. J Neurol Sci 97: 273-293, 1990.

BROOKS AI, CHADWICK CA, GELBARD HA, CORY-SLECHTA DA, FEDEROFF HJ: Paraquat elicited neurobehavioral syndrome caused by dopaminergic neuron loss. Brain Res 823: 1-10, 1999.

CALABRESI P, PICCONI B, TOZZI A, DI FILIPPO M: Dopamine-mediated regulation of corticostriatal synaptic plasticity. Trends Neurosci 30: 211-219, 2007.

Di MONTE DA: The environment and Parkinson’s disease: is the nigrostriatal system preferentially targeted by neurotoxins? Lancet Neurol 2: 531-538, 2003.

DINIS-OLIVEIRA RJ, REMIÃO F, CARMO H, DUARTE JA, NAVARRO AS, BASTOS ML, CARVALHO F: Paraquat exposure as an etiological factor of Parkinson’s disease. Neurotoxicology 27: 1110-1122, 2006.

DJUKIC M, JOVANOVIC MC, NINKOVIC M, VASILJEVIC I, JOVANOVIC M: The role of nitric oxide in paraquat-induced oxidative stress in rat striatum. Ann Agric Environ Med 14: 247-252, 2007.

DRECHSEL DA, PATEL M: Role of reactive oxygen species in the neurotoxicity of environmental agents implicated in Parkinson’s disease. Free Radic Biol Med 44: 1873-1886, 2008.

GAWARAMMANA IB, BUCKLEY NA: Medical management of paraquat ingestion. Br J Clin Pharmacol 72: 745-757, 2011.

HUANG C-L, LEE Y-C, YANG Y-C, KUO T-Y, HUANG N-K: Minocycline prevents paraquat-induced cell death through attenuating endoplasmic reticulum stress and mitochondrial dysfunction. Toxicol Lett 209: 203-210, 2012.

KORCHOUÑOV A, MEYER MF, KRASNIANSKI M: Postsynaptic nigrostriatal dopamine receptors and their role in movement regulation. J Neural Transm 117: 1359-1369, 2010.

LANGSTON JW, BALLARD P, TETRUD JW, IRWIN I: Chronic Parkinsonism in humans due to a product of meperidine-analog synthesis. Science 219: 979-980, 1983.

LIN-SHIAU SY, HSU KS: Studies on the neuromuscular blocking action of commercial paraquat in mouse phrenic nerve-diaphragm. Neurotoxicology 15: 379-388, 1994.

LIOU HH, TSAI MC, CHEN CJ, JENG JS, CHANG YC, CHEN SY, CHEN RC: Environmental risk factors and Parkinson’s disease: a case-control study in Taiwan. Neurology 48: 1583-1588, 1997.

MANGANO EN, PETERS S, LITTLEJOHN D, SO R, BETHUNE C, BOBYN J, CLARKE M, HAYLEY S: Granulocyte macrophage-colony stimulating factor protects against substantia nigra dopaminergic cell loss in an environmental toxin model of Parkinson’s disease. Neurobiol Dis 43: 99-112, 2011.

MANNING-BOG AB, MCCORMACK AL, LI J, UVERSKY VN, FINK AL, Di MONTE DA: The herbicide paraquat causes up-regulation and aggregation of alpha-synuclein in mice: paraquat and alpha-synuclein. J Biol Chem 277: 1641-1644, 2002.
MCCORMACK AL, THIRUCHELVAM M, MANNING-BOG AB, THIFFAULT C, LANGSTON JW, CORY-SLECHTA DA, DI MONTE DA: Environmental risk factors and Parkinson’s disease: selective degeneration of nigral dopaminergic neurons caused by the herbicide paraquat. Neurobiol Dis 10: 119-127, 2002.

MCCORMACK AL, ATIENZA JG, JOHNSTON LC, ANDERSEN JK, VU S, DI MONTE DA: Role of oxidative stress in paraquat-induced dopaminergic cell degeneration. J Neurochem 93: 1030-1037, 2005.

MORETTO A, COLOSIO C: Biochemical and toxicological evidence of neurological effects of pesticides: the example of Parkinson’s disease. Neurotoxicology 32: 383-391, 2011.

OSSOWSKA K, WARDAS J, KUTER K, NOWAK P, DABROWSKA J, BORTEL A, LABUŚ L, Kwiecinski A, KRYGOWSKA-WAJS A, WOLFARTH S: Influence of paraquat on dopaminergic transporter in the rat brain. Pharmacol Rep 57: 330-335, 2005.

PAXINOS G, WATSON C: The Rat Brain in Stereotaxic Coordinates. Academic Press, London, 2007.

PENG J, MAO XO, STEVENSON FF, HSU M, ANDERSEN JK: The herbicide paraquat induces dopaminergic nigral apoptosis through sustained activation of the JNK pathway. J Biol Chem 279: 32626-32632, 2004.

TAUSKELA JS, BRUNETTE E, O’REILLY N, MEALING G, COMAS T, GENDRON TF, MONETTE R, MORLEY P: An alternative Ca²⁺-dependent mechanism of neuroprotection by the metalloporphyrin class of superoxide dismutase mimetics. FASEB J 19: 1734-1736, 2005.

TAWARA T, FUKUSHIMA T, HOJO N, ISOBE A, SHIWAKU K, SETOGAWA T, YAMANE Y: Effects of paraquat on mitochondrial electron transport system and catecholamine contents in rat brain. Arch Toxicol 70: 585-589, 1996.

THIRUCHELVAM M, BROCKEL BJ, RICHFIELD EK, BAGGS RB, CORY-SLECHTA DA: Potentiated and preferential effects of combined paraquat and maneb on nigrostriatal dopamine systems: environmental risk factors for Parkinson’s disease? Brain Res 873: 225-234, 2000a.

THIRUCHELVAM M, RICHFIELD EK, BAGGS RB, TANK AW, CORY-SLECHTA DA: The nigrostriatal dopaminergic system as a preferential target of repeated exposures to combined paraquat and maneb: implications for Parkinson’s disease. J Neurosci 20: 9207-9214, 2000b.

THIRUCHELVAM M, McCORMACK A, RICHFIELD EK, BAGGS RB, TANK AW, DI MONTE DA, CORY-SLECHTA DA: Age-related irreversible progressive nigrostriatal dopaminergic neurotoxicity in the paraquat and maneb model of the Parkinson’s disease phenotype. Eur J Neurosci 18: 589-600, 2003.

THIRUCHELVAM M, PROKOPENKO O, CORY-SLECHTA DA, RICHFIELD EK, BUCKLEY B, MIROCHNITCHENKO O: Overexpression of superoxide dismutase or glutathione peroxidase protects against the paraquat + maneb-induced Parkinson disease phenotype. J Biol Chem 280: 22530-22539, 2005.

WIDDOWSON PS, FARNWORTH MJ, UPTON R, SIMPSON MG: No changes in behaviour, nigro-striatal system neurochemistry or neuronal cell death following toxic multiple oral paraquat administration to rats. Hum Exp Toxicol 15: 583-591, 1996.

YOSHIMURA Y, WATANABE Y, SHIBUYA T: Inhibitory effects of calcium channel antagonists on motor dysfunction induced by intracerebroventricular administration of paraquat. Pharmacol Toxicol 72: 229-235, 1993.