Continuous MPTP intoxication in the Göttingen minipig results in chronic parkinsonian deficits

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INTRODUCTION

Parkinson’s disease (PD) is a common neurodegenerative disorder, resulting from progressive loss of dopaminergic neurons in the substantia nigra pars compacta (SNc). Neuroprotective therapies in PD are still not available, perhaps because animal models do not imitate the chronic and progressive nature of the clinical state of PD. To address this, we performed a feasibility study aimed at establishing a chronic non-primate large animal PD model in Göttingen minipigs based on continuous infusion of the neurotoxin 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP). Twelve female Göttingen minipigs were divided into groups of 2-4 animals and implanted with infusion pumps for continuous intramuscular MPTP delivery of 4-24 mg MPTP/day for 11 weeks. The animals showed parkinsonian symptoms with bradykinesia, rigidity, coordination and chewing difficulties. Symptoms were stable in the 12 and 18 mg MPTP/day groups, whereas the remaining groups showed partial or full behavioral recovery. Digital gait analysis, high performance liquid chromatography (HPLC) measurements and stereological counts of tyrosine hydroxylase-positive (TH+) neurons in the SNc revealed a dose-related decrease in gait velocity, striatal metabolite levels and neuron numbers with increasing doses of MPTP. No neuronal inclusions were observed, but alpha-synuclein staining intensified with increased cumulative MPTP dosages. We conclude that this large-animal model of chronic MPTP administration in Göttingen minipigs shows trends of stable parkinsonian deficits at 18 mg MPTP/day in all modalities examined. This PD model shares many of the characteristics seen in patients and, although preliminary, holds considerable promise for future pre-clinical trials of neuroprotective therapies.

Key words: 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP), animal model, behavior, minipig, neuropathology, Parkinson’s disease

Received 21 November 2015, accepted 11 July 2016

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To address the need of a non-primate large animal model for neuroprotective studies in PD we set out to develop, thoroughly describe and validate a modified model of parkinsonism in the Göttingen minipig based on continuous MPTP-infusion. In this feasibility study we included few animals in each group for the purpose of providing preliminary evidence of optimal MPTP doses and methods for evaluating parkinsonian deficits and degrees of nigro-striatal damage. This study represents the first of its kind in a large animal and its results are of importance to future large-scale validation studies, aimed at developing an animal model of PD more closely imitating the clinical state and course of PD seen in patients.

MATERIALS AND METHODS

Animals

A total of 16 female Göttingen minipigs (Ellegård Göttingen Minipigs A/S, 4261 Dalmose, Denmark) approximately 1-year-old were used for this study approved by the Danish National Council for Animal Research Ethics (DANCARE). Twelve animals were chronically MPTP intoxicated as described below, and the remaining 4 were kept as normal controls. The animals were kept in pairs in a stable with an air temperature of 21 +/- 1°C, a relative humidity of 50 +/- 2% and an air change of 12 times/hour. The stable was artificially illuminated with 12 h light and 12 h darkness. The animals were allowed to acclimate for 3–4 weeks before the surgical pump implantation.

MPTP stability.

Prior to the experiment the stability of the MPTP HCl (M-0896, Sigma-Aldrich, St. Louis, Missouri) was tested with high performance liquid chromatography (HPLC), confirming its stability at 39°C (the body temperature of the minipig) for 5 months. Briefly, HPLC was performed employing a reverse-phase column Supelcypak-100 (4.6×150 mm, 5 µm; Supelco Inc., Bellefonte, Pennsylvania). The mobile phase was a mixture of 25% acetonitrile and 75% 25 mM potassium phosphate (pH 7.4) at a flow rate of 1 ml/min and monitoring was performed at 265 nm. See Yoshihara and others (2000) for details.

MPTP intoxication

On the day of surgery, the animals were deeply anesthetized with a combination of ketamine (125 mg im+62.5 mg iv), midazolam (25 mg im+12.5 mg iv) and isoflurane (inhalation, 5% for 2 minutes, then reduced to 1.5%). Under sterile conditions, a Medtronic Synchromed II 8637-40 (40 mL) programmable pump (Medtronic, Minneapolis, Minnesota) filled with MPTP HCl 10 mg/ml was implanted subcutaneously on the right side of the back of each pig (Figs 1A and 1B). A Medtronic catheter 8709SC was connected to the pump, cut to an appropriate length and its tip placed intramuscularly in the back of the animal. The skin was sutured tightly in three layers. Antibiotics (benzylpenicillin 300,000 IE im) were administered 1 day pre-operatively, on the day of the surgery and 5 days postoperatively. Analgetics (flunixin 50 mg im) were administered 3 days postoperatively. Each pump was programmed with an external Medtronic En’Vision unit for continuous MPTP delivery. The twelve animals in the MPTP group were divided into 5 groups, receiving 4 mg MPTP/day (n=2), 6 mg MPTP/day (n=2), 12 mg MPTP/day (n=2), 18 mg MPTP/day (n=4) or 24 mg MPTP/day (n=2). When required, the pumps were refilled transcutaneously under sterile conditions in animals anesthetized with azaperone (200 mg) and midazolam (25 mg+25 mg pn) im. The ten pigs receiving 4–18 mg MPTP/day had the infusion protocol last 11 weeks. The two animals receiving 24 mg MPTP/day had the infusion stopped after 11 days as the animals expressed severe parkinsonian deficits compromising food and water intake, and levodopa (L-dopa) (levodopa 50 mg/carbidopa 12.5 mg p.o., 1–3 times daily) was administered to these animals as supportive measures for the remainder of the study. These two minipigs were sacrificed at the end of the 11 weeks’ protocol i.e. after 11 days of intoxication followed by 9 weeks of recovery. Two animals in the 18 mg MPTP/day group also received L-dopa substitution therapy due to severe parkinsonism, but without cessation of the MPTP infusion.
Two animals developed a skin infection over the pump area, and this was managed with antibiotics (benzylpenicillin 300,000 IE im) and transcutaneous drainage under general anesthesia with azaperone (200 mg) and midazolam (25 mg) im. The pumps were not removed and the infusions continued throughout the treatment.

The remaining four control animals were anesthetized as described above and received a skin incision and were sutured in a location similar to the location of the pump in the MPTP group. However, due to the high cost of the pumps, the control animals did not have pumps implanted.

**Behavioral analysis**

The pigs were observed for the next 11 weeks at 0, 1 week, 2, 2.5, 4, 5, 7 and 10–11 weeks. Evaluations were performed in the stable with at least 10 minutes of observation by authors MSN and AM according to a behavioral score scheme modified from Mikkelsen and others (1999) to include motility (0–5), coordination (0–5), rigidity (0–2), chewing (0–2) and vocalization (0–2), with 0 denoting the normal state and 5/2 the most severe expression. Motility was evaluated in degree of bradykinesia; coordination in crossing of hind or front limbs or both; rigidity by flexion/extension of the hind limb; chewing by time spent to eat chocolate treats; and vocalization by the ability to make normal sounds, a pathological high pitch sound or by loss of ability to vocalize. A total score of 0 was normal, 1–5 was regarded mild, 6–11 moderate and 12–16 indicated severe parkinsonism. L-dopa substitution therapy was paused for at least 18 hrs prior to behavioral evaluation.

**Gait analysis**

Digital gait analysis was modified from previous clinical studies (Johsen et al. 2009, Mogensen and Jakobsen 2001) and performed for each pig pre-operatively and after 4 and 11 weeks of MPTP intoxication. Each pig served as its own internal control, comparing its pre- and post-operative gait velocities. Prior to the first analysis the animals were trained to walk in a flat, fenced area with author MSN using chocolate (e.g., M&M’s”) as treats (Fig. 1C). Animals in need of L-dopa therapy did not receive the drug for at least 24 hrs prior to the gait analysis. Six infrared Vicon cameras were placed on tripods around the fenced area. Reflective ball-shaped markers were placed with double-stick tape distally on both hind limbs and the right fore limb, on the right thigh and between the highest point of the shoulders. The cameras recorded the positions of the markers in space. The 2D coordinates from each camera were digitalized and transformed to one set of 3D coordinates and from this, gait velocity was calculated.

**Euthanasia**

At the end of the 11 weeks of infusion or observation, the animals were anesthetized with ketamine and midazolam as described above and through a burr hole in the skull biopsies for HPLC were taken from the left striatum and snap frozen in liquid nitrogen. Each animal was then euthanized with intracardial pentobarbital injection (2 g) before transcardial perfusion with 5 L 4% paraformaldehyde (PFA). The brains were removed and the brain stem containing SNc dissected according to the method described in Nielsen and others (2009). The right striatum was cut coronally and divided in a rostral and caudal part. The pumps were removed and their function verified.

**Histology**

The brain stems and right striatae were paraffin embedded and serial 30-µm-thick sections mounted on glass slides before immunohistochemical staining for tyrosine hydroxylase (TH) or α-syn. Immunohistochemistry was
performed directly on the slides as described previously (Nielsen et al. 2009), using monoclonal rabbit anti-tyrosine hydroxylase (P 40101-0, Pel Freez, Rogers, Arkansas) diluted 1:600 or polyclonal sheep anti-alpha-synuclein (ab6162, Abcam, Cambridge, UK) diluted 1:100 as primary antibodies. Visualization was performed by use of a biotinylated secondary antibody (anti-rabbit Ig, Amersham, Buckinghamshire, UK diluted 1:200, or anti-sheep Ig, diluted 1:400) followed by strepavidin horseradish peroxidase (Sigma) and final exposure to diaminobenzidine (DAB). α-syn stained sections were counter-stained with toluidine blue. Omission of both primary antibodies resulted in lack of staining. In addition, separate nigral sections were stained with hematoxylin-eosin (HE).

**Metabolite measurements**

To determine the concentration of dopamine (DA), 3,4-dihydroxyphenylacetic acid (DOPAC), homovanillic acid (HVA) and 3-methoxythyramine (3-MT) the left striatal samples were thawed and homogenized with a Teflon pistil, adding 0.5 ml ice-cold 0.5 M/l perchloric acid containing 0.05% w/v sodium thiosulfate (Pharmacy, Aarhus University Hospital, Aarhus, Denmark). The homogenate was centrifuged for 5 min at 13000 rpm. The supernatant was analyzed by HPLC using Perkin-Elmer Series 200 HPLC pump (Titan) connected in series with a Rheodyne 7025 injector (80 µl loop), a Phenomenex Sphereclone 5µ ODS (2) (250×4.6 mm, Phenomenex, Torrance, California), a Dionex PED II electrochemical detector in amperometry mode (sensitivity 1 µA). For data acquisition Dionex Chromeleon Software 6.8 was used. The mobile phase was a mixture of 80% buffer containing 0.1 M NaH₂PO₄·H₂O (13.8 g/l), 2.6 mM octanesulphonic acid sodium salt (0.6 g/l), 0.1mM EDTA (38 mg/l), pH 3.3 adjusted with acetic acid and 20% methanol. At a flow rate of 1 ml/min, DOPAC eluted around 9 min, dopamine around 15 min, HVA around 21 min and 3-MT around 36 min. Further details can be seen in Gamache and others (1993) and Mikkelsen and colleagues (1999). Metabolite concentrations were determined by comparison to the peaks produced by injection of the respective standards at the fixed concentration of 2 µg/ml each.


Stereology

The total number of TH-positive (TH+) neurons in the SNc was estimated on both the right and left sides on TH-stained sections according to our previous study (Nielsen et al. 2009), utilizing the optical fractionator technique (West 1999), using a Zeiss AxioPlan microscope interfaced with MicroBrightField StereoInvestigator software. A 40× air lens was used. The final section thickness was measured to 28 µm. \( \sum Q^- \) represents the total counts from each SNc, and the total number of neurons, \( N \), was calculated as follows: Every 10th section of the SNc was used, making the section sampling fraction, \( ssf=1/10 \). The counting frame had an area of 7,000 µm², and the area associated with each step made by the computer over the section surface was 22,500 µm² or 160,000 µm², depending on the MPTP dose of the animal (the larger the dose, the smaller the step due to assumed fewer neurons), making the area sampling fraction, \( asf=0.311 \), \( asf=0.078 \), or \( asf=0.044 \), respectively. The relation between the section thickness (\( t=28 \) µm) and the height of the optical dissector (\( h=15 \) µm), \( t/h \), was 28/15. Thus \( N=\sum Q^-\times(1/ssf)\times(1/asf)\times(t/h) \).

RESULTS

Behavior

Abnormal behavior was observed in all groups of MPTP-intoxicated animals. Initially, the animal would lean its thigh against the wall. Then followed lack of coordination, primarily of the hind limbs and in severe cases the front limbs. General bradykinesia and freezing episodes could progress to akinesia in the most extreme cases. We also observed prolonged chewing and disturbances in normal vocalization (normal sounds progressing to abnormal sounds and finally to inability to vocalize). Only severely affected animals displayed reliably assessable rigidity of the limbs. There was no tremor, except in the acute stage of intoxication in the 24 mg MPTP animals. For the 4–12 mg MPTP pigs, mild symptoms were observed after 10–21 days of intoxication, with most of the animals showing partial or full behavioral recovery after 7 weeks of intoxication, despite the on-going active infusion (Figs 2A and 2B). The four 18 mg MPTP animals developed symptoms of moderate to severe PD after approximately 2 weeks and all but one (pig #10) showed moderate and stable

Fig. 3. Average behavioral scores compared to the daily MPTP dose and the cumulative MPTP dosage at 4 and 11 weeks of observation. Note the recovery of the 6 mg MPTP animals, despite high cumulative dosage compared with the 24 mg animals, where infusion was stopped after just 11 days. Also note that the 12 and 18 mg groups as the only groups show stable behavioral scores from the 4- to the 11-week observations (A and C). The numbers 4–24 in B and D refer to mg MPTP/day.
behavioral deficits. In three animals, progressive impairments and behavioral scores was seen towards the end of the observation period (Fig. 2C). The two most severely affected animals in this group received L-dopa to ensure proper food intake. The 24 mg MPTP animals employed severe parkinsonism after just 11 days of intoxication. Their pumps were turned off to prevent further progression of the symptoms and the animals were administered L-dopa therapy. They quickly recovered and stabilized into moderate PD without any signs of progression (Fig. 2D). Comparing the average behavioral scores at 2 and 11 weeks with the daily MPTP doses confirmed full recovery in the 4 and 6 mg groups overall and partial recovery of the 24 mg group (Figs 3A and 3C). The 12 and 18 mg groups showed stable scores. When comparing the average behavioral scores with the total cumulative MPTP dosage, stable scores were again seen in the 12 and 18 mg MPTP groups from 2 to 11 weeks (Figs 3B and 3D). The 24 mg animals demonstrated the classical behavioral feature of acute toxicity; initial severe scores with partial recovery following interruption of MPTP administration. These animals were rated moderately parkinsonian at 11 weeks despite the much lower cumulative dose compared with the continuously infused animals.

Digital gait analysis

The digital gait analysis pointed to decreased gait velocity in the 12 and 18 mg MPTP groups after 4 and 11 weeks of intoxication (Fig. 4), most distinctly demonstrated in the 18 mg MPTP group. Results from a representative 24 mg animal showed an initial decrease in gait velocity at 4 weeks with recovery to normal values at the 11-week test, consistent with the observed behavioral recovery. The 4–6 mg MPTP animals displayed normal gait velocity throughout the observation period and are not shown in Fig. 4. We did not observe any effect of training, learning or exercise i.e. normal animals did not increase or decrease their gait velocity significantly during the course of the observation period.

HPLC

HPLC analysis of striatal DA and its metabolites at the end of the 11-week study presented in Figs 5A–5D suggested decreased concentrations of DA and its metabolites in response to exposure to increasing doses of MPTP, with occasional outliers. The relative increase in metabolites in the 4 animals receiving 18 mg MPTP/day in comparison with the further decrease in DA at that dose suggested an increase in turnover. This is supported by Fig. 5E graph in which a routinely used index of DA turnover, DA metabolites/DA, suggested an increase in the 18 mg daily dose animals as well as the animals with the acute moderate to severe lesion.

Histopathology

A trend of dose-dependent neuron loss in the SNc was demonstrated on TH-stained sections (Figs 6A–6D). The neuron loss was most prominent in the rostral and lateral 2/3 of the SNc in the lower daily dose groups, but the 18 and 24 mg MPTP animals displayed a neuronal loss in all parts of the SNc. Surviving neurons appeared smaller and more heavily stained than in normal animals. In the striatum, the 12 and 18 mg animals showed swollen TH+ terminals with fewer fibers and terminals in the 18 mg group (Figs 6F–6G). Some sense of direction of the fibers remained in the 18 mg animals, but was lost in the 24 mg animals, which also displayed smaller, fewer terminals (Fig. 6H). These changes were most prominent in the rostral part of the striatum corresponding to the rostral nigral projection.

The SNc and striatae of MPTP intoxicated animals stained positive for α-syn (Fig. 7). α-syn was mostly visible in the neuropil, but occasional neuronal staining
in the SNc was also observed, primarily confined to the cytoplasm and the cell membrane (Fig. 7B). There were no neuronal inclusions. α-syn stained most intense in 12 and 18 mg animals receiving continuous MPTP infusion compared with the acutely intoxicated 24 mg animals. This finding was most prominent in the striatum (Figs 7E and 7F). Control animals were devoid of specific α-syn reactivity.

**Stereology**

The stereological cell counts also suggested a dose-dependant loss of TH+ neurons (Fig. 6 graph). For reference, normal Göttingen minipigs have an estimated 80,700 neurons in their SNc unilaterally (Nielsen et al. 2009) and this number including SD’s was included in Fig. 6. The TH and the HE stainings were compared, and the specific

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**Fig. 5.** HPLC for DA, DOPAC, 3-MT and HVA in the different MPTP groups and normal animals. The number of observations was limited (1 in the 6 and 24 mg MPTP groups; 2 in the 0, 4 and 12 mg MPTP groups; and 4 in the 18 mg MPTP group). However, the overall trend was that of a dose-dependent decrease in dopamine and related metabolites. The (DOPAC+HVA+3-MT)/Dopamine ratio shown in E is a sensitive marker of dopamine turnover, increasing in the 18 and 24 mg groups.
dopaminergic neuronal loss seen on the TH stained sections corresponded well with the neuronal loss observed in the HE stained sections (data not shown).

**DISCUSSION**

For the first time, this study suggests that continuous intravenous delivery of MPTP for 11 weeks results in chronic and stable PD deficits in the Göttingen minipig. We found 18 mg MPTP/day to be the optimal dose, as the animals in this group displayed moderate to severe and stable parkinsonian behavior, evidence of decreased gait velocity, loss of TH+ neurons evaluated histopathologically and stereologically, and a HPLC-verified decrease in striatal dopamine and metabolites. As this was the first study of its kind in a large animal, we included just 2 animals in each group to target the optimal MPTP dose and doubled the number of animals to 4 once this dose was established. The small n precluded detailed statistical analysis, but provided valuable information for future studies of its kind in animals of this size and weight.


![Fig. 6. (A–D) TH-staining of the SNc in A – normal; B – 12 mg; C – 18 mg; and D – 24 mg MPTP animals at corresponding levels. A dose-dependent decrease in the number of TH+ neurons was visible. Scale bar: 1 mm.](image1)

![Fig. 6. (E–H) TH-staining in the striatum in E – normal; F – 12 mg; G – 18 mg; and H – 24 mg MPTP animals. TH+ terminals were swollen in the 12 mg animals. Likewise, the 18 mg animals showed swollen terminals, reduced in number and with fewer fibers. The 24 mg animals displayed only few terminals and fibers, and the fibers appeared completely disorganized. Terminals were not as swollen as in the 12 and 18 mg groups. Scale bar: 20 µm.](image2)

![Graph: the stereological results. n=4 in the 18 mg group, n=2 in all other groups. Both SNc's in each animal were counted. The results show the average number of neurons unilaterally. The dose-dependent decrease in TH+ neurons seen in Figs 6B–6D was confirmed, pointing towards fewer neurons in the 12, 18 and 24 mg MPTP groups. The dashed horizontal lines indicate the mean and SD's in normal Göttingen minipigs based on Nielsen and others (2009).](image3)
The MPTP model of selective DA neuron damage has been used to investigate the pathogenesis in PD, the pharmacological consequences of the DA loss, the compensatory adaptations, efficacy testing of new symptomatic treatments and the potential of gene therapies and alternate neuroprotective approaches. Promising results of neuroprotection in rodent and primate models with a variety of agents have failed to show convincing effects in subsequent clinical trials. A plausible explanation could be the lack of current animal models for preclinical screening to accurately mimic the slow progressive course of the idiopathic disease (Kieburtz and Ravina 2007, Olanow et al. 2008). Conventionally, acute nigral DA neuron loss has been performed by injecting high MPTP doses hours or days apart but usually within a short time frame, until the animal displayed persistent PD symptoms (Emborg 2004, Przedborski et al. 2001). Attempts to mimic progressive neuron loss by subacute/chronic MPTP intoxication using lower doses over longer periods of time have been performed (Bezard et al. 1997, Gibrat et al. 2009, Meredith et al. 2008). However, it has been argued that this also in essence represents acute intoxication (Jenner 2008). Continuous administration of MPTP exposes the SNc neurons to chronic toxic stress and therefore supposedly models the progressive pathology seen in PD patients. This was performed in mice by osmotic minipumps (Fornai et al. 2005, Gibrat et al. 2009) and may be the closest yet to a true chronic PD toxin model. To date, we have not found evidence of continuous administration of MPTP or other PD-related neurotoxins in a large animal model as performed here. Additionally, our study is the first to administer MPTP continuously for as long as 11 weeks.

The behavioral analysis performed in the minipig resembles those described for primates with obvious exceptions such as evaluation of facial expression, fine hand movements etc. (Bezard et al. 1997, Doudet et al. 2004, Emborg 2004). Behavioral evaluation in an animal model of neuroprotection is very important, and require a standardized scoring system, which would optimally correspond to the Unified Parkinson Disease Rating Scale (UPDRS) assessment in PD patients, as this scale is often used in clinical trials for evaluation of treatment efficacy. Although blind assessment would be preferred, it was impossible in this feasibility study due to the obvious presence of the large implanted pumps. Nevertheless, the subjective behavioral assessment by two investigators with experience in pig behavior was remarkably similar to the data obtained from the objective gait analysis, measuring movement velocity (see below).

Continuous delivery of 18 mg MPTP/day led to stable PD symptoms in 3 out of 4 animals (Fig. 2C). Comparison of the average motor scores and daily or cumulative MPTP doses suggested stability of the behavioral scores in the 12 and 18 mg MPTP/day groups (Fig. 3). These observations also suggested that the 24 mg animals could be regarded as acutely and not chronically intoxicated, as severe symptoms occurred quickly and persisted after slight recovery despite cessation of the MPTP infusion. This behavioral time course was similar to that of acute MPTP intoxication described previously in pigs and non-human primates (Emborg 2007, Mikkelsen et al. 1999). Clinical recovery after acute exposure to MPTP intoxication is thoroughly described in the literature (Boulet et al. 2008, Mikkelsen et al. 1999, Mounayar et al. 2007) in both bilaterally and unilaterally lesioned animals. Additionally, examination of the animals’ individual clinical responses shown in Fig. 2 clearly demonstrated significant variability in the sensitivity of the different animals exposed to the same dose of MPTP. Similar variability is commonly described with toxin exposure in primates, minipigs and MPTP-exposed addicts (Ballard et al. 1985, Emborg 2007, Mikkelsen et al. 1999).

As described previously by our group (Glud et al. 2011), we confirmed that digital gait analysis is possible on properly trained minipigs and offers a sensitive method of motor performance assessment. The trends of decreased...
gait velocity in the 18 mg MPTP group confirmed that this was the optimal dose for animals of this age and weight. The decreasing trend of the gait velocity from 4 to 11 weeks in the 12 and 18 mg groups corresponded with the behavioral signs of stability to possibly slight progression, which however the subjective behavioral analysis was not sensitive enough to register. In addition, digital gait analysis confirmed the behavioral recovery observed in the 24 mg group. The gait analysis equipment was previously used to assess gait parameters in PD patients (Johnsen et al. 2009), emphasizing that the pig may help bridge laboratory and clinical neuroscience. The minipigs were easily trained for the procedure. However, training must be started well before the first data analysis acquisition (baseline) to avoid the effects of learning and habituation (i.e. the animals walking faster and more confidently following the investigator) during the actual experimental part of the study. Such effects could otherwise easily confound the velocity measurements in the preclinical or early phase of the intoxication. Decreases in gait velocity after MPTP can be reliably measured and used as an objective estimate of motor disability. Due to inter-individual variations in the normal gait velocity among animals, although the set-up is time consuming, it is necessary to obtain sufficient baseline, pre-MPTP gait velocity measurements for each individual animal for post-operative gait velocity data comparison, instead of using a population average gait velocity.

The histopathology suggested a dose-dependent loss of TH+ neurons in the SNc, confirmed by stereological cell counting. The number of neurons on HE stains correlated well with the TH stains, confirming that neurons were permanently lost and not just devoid of TH (data not shown). This was also reported previously in acute MPTP intoxication (Seniuk et al. 1990). The 12 mg MPTP group, which showed mild and stable PD symptoms and slightly decreased gait velocity, displayed a neuron loss in the SNc of about 37%. This observation was consistent with previous reports in animal models and in PD patients suggesting the existence of a significant amount of internal compensation early in the disease: indeed, it is widely accepted that at least 50% DA neuronal loss in the SNc is necessary for clearly recognizable clinical symptoms. The 18 mg MPTP group showed greater DA neuron loss (about 60%), accompanied with significantly more severe motor symptoms and decreased DA and metabolites. Interestingly, Fig. 5E showed an increased metabolite/DA ratio in this group, suggesting increased DA turnover. Increased DA turnover has been reported both postmortem and in vivo by PET in non-human primates (Doudet et al. 1998) as well as in early PD patients (Sossi et al. 2002) and is believed to represent one of the early compensatory mechanisms to neuronal loss. Our 4–12 mg animals showed variable loss of DA and metabolites, relatively stable turnovers but little significant motor impairments or decreases in TH+ neurons, confirming the very early existence of internal compensatory biochemical changes. The 24 mg group, however, also showed increased DA turnover, similarly consistent with the behavioral and pathological observations of serious motor impairments and 78% loss of TH+ neurons in the SNc.

The striatal TH staining showed pronounced loss of TH-fibers rostrally, loss becoming more severe and eventually more widespread with increasing dose and exposure to the toxin. In PD, the dorsolateral striatal quadrant is typically the most affected (Bové et al. 2005). This observation supports the validity of the proposed model of continuous infusion. We did not see evidence of sprouting in any of the infused animals as has otherwise been reported previously (Song and Haber 2000).

In contrast to Fornai and others (2005) and Gibrat and colleagues (2009) we did not detect α-syn positive intraneuronal inclusions, which is in accordance with others studies in chronic MPTP models and monkeys examined after 10 years of parkinsonism (Alvarez-Fischer et al. 2008, Halliday et al. 2009, Shimoji et al. 2005). However, the neuronal inclusions described by Fornai and Gibrat were restricted the mice receiving the highest daily doses. It is likely that the doses used in our study were not sufficient to produce similar effect. We did, however, observe a tendency to a more intense α-syn stain with increased continued MPTP doses in contrast to the acutely intoxicated 24 mg animals. This could suggest different pathological mechanisms of the two different administration regimens. Thus, it has been previously shown that acute MPTP intoxication causes necrotic cell death whereas chronic intoxication causes apoptotic neuron loss (Schmidt and Ferger 2001). Double staining of TH and α-syn to confirm the α-syn pathology in dopaminergic neurons under chronic toxic stress as seen in mice is worth performing in future studies in the minipig (Gibrat et al. 2009).

The continuous MPTP intoxication used in this study required large amounts of toxin. Each 18 mg animal received approximately 1200 mg MPTP to produce moderate and stable PD. In comparison, the 24 mg acutely intoxicated animals received 264 mg MPTP, whereas the acutely intoxicated minipigs described by Mikkelsen and others (1999) just received approximately 120 mg. Thus the chronic administration of MPTP appeared to induce a substantial tolerance to the toxin, perhaps as a result of hepatic detoxification (Markey and Schmuff 1986, Yoshihara et al. 2000). Chronic MPTP intoxication seemed to require 10 times as much MPTP as acute intoxication, which may raise economical issues. However, if further studies of this administration route confirm greater similarities to the clinical state of PD than the acute model or even show progression when carried out for longer than 11 weeks, the possibility of valid translational results may by far exceed the economical drawback of the model.
CONCLUSION

The Göttingen minipig model of the chronic PD based on continuous MPTP infusion presented here has been preliminarily characterized behaviorally, chemically, histopathologically and stereologically. Although based on few animals, this model already suggests many resemblances to the clinical state of PD and provides hope for future demonstration of actual disease progression.

The continued lack of accordance between preclinical data of neuroprotective agents and clinical efficacy in PD patients keep emphasizing the need for improved PD animal models. The pig with its large gyrated brain, low cost and easy handling compared with primates along with its genetic and subcortical anatomical resemblance to primates and possibilities of implantation of stem cells, human-sized devices and gene transfer offers a valuable platform for preclinical efficacy and safety experiments. We thus propose that this Göttingen minipig model of PD based on continuous MPTP intoxication may prove valuable in future preclinical neuroprotective studies in PD.

ACKNOWLEDGEMENTS

We greatly acknowledge the expert technical assistance from D. Jensen, LM. Fitting, A. Funder, A. Meier, W. Sloth and the staff at the Paaskehøjgaard Animal Facility, Denmark.

We also greatly acknowledge the financial support from The Novo Nordisk Foundation, The Lundbeck Foundation, The Danish Medical Association Research Fund/Svend Aage Nielsen Wacherhausen’s Grant/Højmosegård Grant, The Helga and Peter Korning Foundation, The Karen Elise Jensen Foundation and the Danish Medical Research Council.

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