

## Entacapone potentiates the long-duration response but does not normalize levodopa-induced molecular changes

C. Marin<sup>a,d,\*</sup>, E. Aguilar<sup>a</sup>, G. Mengod<sup>b,d</sup>, R. Cortés<sup>b,d</sup>, M.C. Rodríguez-Oroz<sup>c,d</sup>, J.A. Obeso<sup>c,d</sup>

<sup>a</sup> Laboratori de Neurologia Experimental, Àrea de Neurociències, Institut d'Investigacions Biomèdiques August Pi i Sunyer (IDIBAPS), Barcelona, Spain

<sup>b</sup> Departament de Neuroquímica i Neurofarmacologia, Institut d'Investigacions Biomèdiques de Barcelona, CSIC-IDIBAPS, Barcelona, Spain

<sup>c</sup> Department of Neurology and Neurosurgery, Neuroscience Center, Clínica Universitaria and Medical School, University of Navarra and CIMA, Pamplona, Spain

<sup>d</sup> Centro de Investigación en Redes sobre Enfermedades Neurodegenerativas (CIBERNED), Spain

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### ABSTRACT

Coadministration of entacapone with levodopa attenuates motor complications in experimental models of Parkinson's disease. The mechanisms underlying entacapone effects are unknown. We investigated the effect of entacapone, on: long-duration response (LDR) to levodopa, levodopa-induced postsynaptic pharmacodynamic mechanisms and molecular changes in hemiparkinsonian rats. 6-Hydroxydopamine-unilaterally lesioned rats were treated with levodopa (25 mg/kg)+vehicle; levodopa+entacapone (30 mg/kg) or saline, twice daily for 22 days. The LDR and the apomorphine-induced rotations were measured. In situ hybridization was performed measuring the expression of striatal preproenkephalin, preprodynorphin and dopamine D-3 receptor mRNAs, subthalamic cytochrome oxidase mRNA and nigral glutamic acid decarboxylase mRNA. Entacapone potentiated the LDR but did not modify either the apomorphine-induced rotational behavior or the molecular changes. Our results suggest that the effects of entacapone on levodopa-induced motor response are not mediated by postsynaptic mechanisms and that administration of entacapone is not able to normalize the molecular alterations induced by levodopa in the basal ganglia.

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### Introduction

Under physiological circumstances, extra-synaptic striatal dopamine (DA) levels are relatively constant and DA receptors are stimulated in a relatively continuous manner (Abercrombie et al. 1990; Floresco et al. 2003; Venton et al. 2003). In Parkinson's disease (PD), there is a loss of dopaminergic neurons and terminals and striatal DA levels are increasingly dependent on the peripheral availability of levodopa (Abercrombie et al. 1990; Miller and Abercrombie 1999; De la Fuente-Fernández et al. 2004). Therefore, in advanced PD the fluctuations in plasma levels of short-acting dopaminergic agents, such as levodopa, lead to alternating high and low levels of activation of striatal DA receptors. This "pulsatile" pattern of receptor stimulation is a function of both, disease severity (Bédard et al. 1986; Pearce et al. 1998, 2001; Jenner 2000) and the short half-life of the dopaminergic agent employed (Bédard et al. 1986; Nutt 1990; Pearce et al. 1998; Olanow and Obeso 2000; Olanow et al. 2006). Sustained evidence has been accumulated indicating that levodopa-related motor complications in PD are associated with non-physiological, intermittent or pulsatile stimulation of striatal DA receptors (Chase et al. 1989, 1994;

Juncos et al. 1989; Blanchet et al. 1995; Grondin et al. 1996; Stocchi and Olanow 2004; Olanow et al. 2006; Fabbri et al. 2007).

This concept suggests that a more continuous stimulation of DA receptors may ameliorate or even reduce the development of motor complications. The former has been shown in PD (Quinn et al. 1984; Obeso et al. 1986; Mouradian et al. 1990; Nutt 1990; Olanow et al. 2006; Nyholm 2007) and the latter in experimental parkinsonism (Bédard et al. 1986; Blanchet et al. 1995; Grondin et al. 1996; Pearce et al. 1998; Maratos et al. 2001; Jenner 2004; Smith et al. 2005; Nyholm 2007). The concept of continuous dopaminergic stimulation (CDS) is supported by a wealth of experimental data showing that the dopaminergic system exerts a dual (tonic and phasic) effect on the striatum (Grace 1991; Floresco et al. 2003). In patients with PD, clinical pharmacological studies also support the therapeutic concept of CDS (Chase et al. 1989, Obeso et al. 1994, 2000; Olanow and Obeso 2000; Olanow et al., 2006).

There is evidence suggesting that pulsatile striatal stimulation induces postsynaptic pharmacodynamic mechanisms which result in altered regulation of striatal genes and proteins, which ultimately leads to abnormal neuronal firing patterns in the striatopallidal circuitries (Herrero et al. 1995; Jolkkonen et al. 1995; Morissette et al. 1997, 1999; Olanow and Obeso 2000; Aubert et al. 2005; Gardoni et al. 2006; Bychkov et al. 2007). In more detail, chronic levodopa or dopamine agonist treatment elevates the expression of the striatal enkephalin precursor preproenkephalin (PPE), the opioid peptide expressed in the striatal neurons that project to the pars externa of the

\* Corresponding author. Laboratori de Neurologia, Servei de Neurologia, Hospital Clínic, Villarroel 170, 08036 Barcelona, Spain. Fax: +34 93 2275783.

E-mail address: [cmarin@clinic.ub.es](mailto:cmarin@clinic.ub.es) (C. Marin).

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globus pallidus (GPe), above the levels reached after DA denervation alone (Gerfen et al. 1990; Herrero et al. 1995; Henry et al. 1999; Ravenscroft et al. 2004; Chen et al. 2005). Moreover, a significant correlation has been found between levodopa-induced complications and increased striatal levels of preprodynorphin (PDyn) mRNA, the opioid peptide expressed in the striatal neurons that project directly to the output structures of the basal ganglia, in a rodent model of PD (Cenci et al. 1998; Andersson et al. 1999; Carta et al. 2002; Winkler et al. 2002; Ravenscroft et al. 2004). Levodopa-induced changes in striatal gene expression are believed to result from abnormal, intermittent stimulation of supersensitive receptors on DA-denervated striatum because PPE and PDyn mRNA changes can be normalized with long-acting DA agonists that do not induce dyskinesia (Henry et al. 1999; Calon et al. 2000) and when the same short-acting DA agonists are continuously administered (Morissette et al. 1997).

Entacapone is a potent, selective and reversible peripherally acting inhibitor of catechol-O-methyl transferase (COMT), the enzyme that provides the main breakdown pathway for levodopa in the blood after dopa decarboxylase. Inhibition of COMT by entacapone prolongs the half-life of levodopa (Nutt et al. 1994; Ruottinen and Rinne 1996) and this is associated with improved clinical efficacy in PD patients (Kaakkola and Wurtman 1993; Nutt et al. 1994; Ruottinen and Rinne 1996; Parkinson Study Group 1997; Rinne 1998; Poewe et al., 2002; Stocchi et al. 2004; Grandas et al. 2007; Deuschl et al. 2007; Müller et al. 2007) and in experimental models of parkinsonism (Smith et al. 2003; 2005; Marin et al. 2005, 2006). By extending the half-life of levodopa with entacapone, it is possible to deliver the drug in a way that is less pulsatile, thereby allowing the benefit of levodopa with a reduced risk for motor complications. In detail, the administration of entacapone attenuates and prevents the development of levodopa-induced motor fluctuations (Marin et al. 2005) and dyskinesias in 6-OHDA-lesioned rats (Marin et al. 2006) and in MPTP-treated monkeys (Smith et al. 2003, 2005). However, it is still unknown whether the administration of entacapone modifies the molecular changes induced by levodopa in the basal ganglia nuclei.

The motor response to levodopa is comprised of two components: the long-duration response (LDR) and the short duration response (SDR) (Muentner and Tyce 1971). The SDR is characterized by a short-lasting motor improvement typically lasting 3–4 h following a single dose of levodopa. The SDR is the basis for the clinical phenomenon of the motor fluctuation known as “wearing-off”. However, the LDR is a sustained motor improvement that takes days to build up and lasts for many hours to days after levodopa discontinuation (Nutt et al. 1995; Quattrone et al. 1995; Zappia et al. 1997). A study in the *novo* patients (the ELLDOPA trial) has shown that the LDR may actually last for several weeks after cessation of levodopa treatment (Parkinson Study Group 2004). An experimental model of the LDR to levodopa has been recently described in 6-OHDA-lesioned rats (Marin et al. 2007). An improvement in forelimb akinesia that lasted for at least 2 days after levodopa discontinuation resembling the LDR to levodopa in patients, has been observed (Marin et al., 2007). The effect of entacapone on the LDR to levodopa is still unknown.

Based in the hypothesis that entacapone may provide a greater bioavailability of levodopa in the brain and thus, a more continuous stimulation of dopaminergic receptors, we investigated if entacapone administration normalizes the molecular alterations induced by levodopa treatment. We tried to define in more detail the mechanism of action by which levodopa plus entacapone administration reduces motor complications in the 6-OHDA rat model by assessing the effect of entacapone on: (i) the LDR to levodopa, (ii) the postsynaptic pharmacodynamic mechanisms induced by levodopa, and (iii) the levodopa-induced molecular changes in the basal ganglia nuclei. A better definition of putative postsynaptic mechanisms mediating the entacapone effect may be clinically relevant as they may be involved in the development or maintenance of levodopa-induced motor complications and thus, might be avoided with future treatment strategies.

## Materials and methods

### 6-OHDA lesions

Forty-four male Sprague–Dawley rats weighing 220–240 g were housed on a 12-hour light/dark cycle with free access to food and water. Under sodium pentobarbital anaesthesia (50 mg/kg, intraperitoneal, i.p.), rats were placed in a stereotactic frame with the incisor bar positioned 4.5 mm below the interaural line. Each animal received a 6-OHDA (Sigma, Spain) injection (8 µg in 4 µl of saline with 0.02% ascorbate over 8 min) into the left medial forebrain bundle by means of a Harvard infusion pump. Stereotactic injections were placed 4.0 mm anterior to the interaural line, 1.3 mm lateral to the midline and 8.4 mm ventral to the surface of the skull, according to the atlas of Paxinos and Watson (1986). Adequate measures were taken to minimize pain or discomfort. All animal experiments were carried out in accordance with the National Institutes of Health guide for care and use of laboratory animals and approved by the Local Government.

### Protocol of treatments

Animals were distributed in three groups and treated with (1) levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) (Sigma, Spain) plus vehicle ( $n=16$ ) twice a day; (2) levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.,  $n=18$ ) twice a day, or vehicle ( $n=10$ ) for 22 consecutive days.

### Experimental design

Three sets of experiments were performed in order to investigate the effect of chronic entacapone administration on: i) levodopa-induced LDR ii) levodopa-induced postsynaptic pharmacodynamic alterations and, iii) levodopa-induced molecular changes in the basal ganglia nuclei.

In the first set, the effect of chronic entacapone on levodopa-induced LDR was evaluated. The effect of entacapone on the use of the parkinsonian limb induced by levodopa was investigated by performing the cylinder test. LDR was investigated before and after a dose test of levodopa (6 mg/kg) in 6-OHDA-lesioned rats during and until 7 days after levodopa or levodopa plus entacapone chronic treatment (Marin et al. 2007).

In the second set of experiments, we evaluated whether postsynaptic pharmacodynamic mechanisms were involved in the entacapone effect on levodopa-induced motor response. The rotational response to apomorphine (0.5 mg/kg, sc) (Sigma, Spain) was evaluated 3 days after the last treatment day in both, levodopa plus vehicle and levodopa plus entacapone, treated animals.

And finally, to investigate the effects of entacapone on levodopa-induced molecular changes in the basal ganglia nuclei, groups of animals treated following the same protocol than for the behavioral studies, were sacrificed after 3 days of washout and the *in situ* hybridization studies were performed.

### Rotational screening

For the measurement of rotational behavior, rats were placed in circular cages and tethered to an automated rotometer. The number of complete (360°) turns made during each 5-minute period was automatically recorded by a computerized system. Rats were allowed 15 min to habituate to the rotometer before drug administration. Following a three-week recovery period, rats exhibiting a vigorous rotational response (>100 total turns) to apomorphine (0.05 mg/kg, subcutaneous (sc)) were selected for further study. It has been previously demonstrated that rats meeting this criterion have a greater than 95% depletion of striatal dopamine (Papa et al. 1994). Apomorphine-induced rotations (0.5 mg/kg, sc) were measured to evaluate the involvement of postsynaptic mechanisms in entacapone effects.

### Forelimb akinesia-cylinder test

To assess forelimb akinesia the cylinder test was used as previously described (Schallert et al. 2000; Marin et al. 2007). Rats were placed individually in a circular cylinder and the number of supporting well contacts that were carried out with each of the right (parkinsonian) and left forelimb was counted for a period of 5 min prior and 45 min after the administration of a test dose of levodopa (6 mg/kg). No habituation to the cylinder prior to testing was allowed. Forelimb akinesia was evaluated before and after 6-OHDA lesion, 3 days after and then weekly during levodopa or levodopa plus entacapone treatment, followed by evaluations at 4 h, 2, 5 and 7 days after levodopa or levodopa plus entacapone withdrawal.

### Tissue collection

Three days after the last levodopa, levodopa plus entacapone or saline administration rats were sacrificed under an overdose of pentobarbital anaesthesia. Brains were quickly removed from the skull and then frozen on dry ice and kept at  $-80^{\circ}\text{C}$  until cut on a cryostat. Coronal 14  $\mu\text{m}$  thick sections were collected through the striatum onto APTS (3-amino-propyltriethoxysilane) coated slides, and kept at  $-40^{\circ}\text{C}$  until used.

### Dopamine transporter (DAT) immunohistochemistry

Striatal sections were thawed and dried at room temperature and fixed with acetone for 10 min at  $4^{\circ}\text{C}$ . The sections were rinsed in PBS (phosphate-buffered saline, pH 7.4) twice, 5 min each, and immersed in 0.3% hydrogen peroxide in PBS for 10 min to block the endogenous peroxidase. At this point, sections were rinsed again in PBS and incubated with horse serum with 0.1% Triton X-100 for 20 min. Sections were incubated overnight at  $4^{\circ}\text{C}$  with mouse anti-DAT monoclonal antibody (SantaCruz Biotechnology, Spain) at a dilution 1:500 in PBS. Sections were rinsed twice in PBS, 5 min each, and ImmunoPure Ultra-Sensitive ABC Peroxidase staining kit (Pearce, Spain) was used to carry out the ABC staining method. By so doing, sections were incubated with biotinylated horse anti-mouse Ig-G for 30 min, followed by two rinses in PBS, and then incubated with avidin-biotinylated peroxidase complex for 30 min more. Finally, sections were rinsed in PBS and incubated with 3-3'-diaminobenzidine and 0.01% hydrogen peroxide for 15 min. Slides were washed with PBS, dehydrated in ascending alcohol concentrations, cleared in xylene and coverslipped in DPX-EXLI mounting medium.

### In situ hybridization histochemistry

The oligonucleotides used were complementary to the following base sequences (GeneBank accession number in brackets): preprodynorphin, bases 607–654 [NM\_019374]; preproenkephalin, bases 513–542 [K02807]; cytochrome oxidase subunit I, bases 644–688 [S79304]; glutamic acid decarboxylase 67 (GAD67), bases 191–235 and 1600–1653 [NM\_017000]; dopamine D3 receptors, bases 85–132, 1144–1191 and 1381–1426 [NM\_017140]. They were synthesized and HPLC purified by Amersham Pharmacia Biotech (UK) and by Isogen Bioscience BV (Maarsden, The Netherlands). The oligonucleotides were labelled at their 3'-end by using [ $^{32}\text{P}$ ]dATP (3000 Ci/mmol, New England Nuclear, Boston, MA, USA) and terminal deoxynucleotidyl-transferase (TdT, Oncogene Research Products, San Diego, CA, USA), and purified using QIAquick Nucleotide Removal Kit (QIAGEN GmbH, Hilden, Germany).

For in situ hybridization, frozen tissue striatal sections were brought to room temperature, air-dried, and fixed for 20 min in 4% paraformaldehyde in phosphate-buffered saline ( $1\times\text{PBS}$ : 2.6 mM KCl, 1.4 mM  $\text{KH}_2\text{PO}_4$ , 136 mM NaCl, and 8 mM  $\text{Na}_2\text{HPO}_4$ ), washed once in  $3\times\text{PBS}$ , twice in  $1\times\text{PBS}$ , 5 min each, and incubated in a freshly prepared solution of predigested pronase at a final concentration of

24 U/ml in 50 mM Tris-HCl pH 7.5, 5 mM EDTA. The enzymatic activity was stopped by immersion for 30 s in 2 mg/ml glycine in  $1\times\text{PBS}$ . Tissues were finally rinsed in  $1\times\text{PBS}$  and dehydrated through a graded series of ethanol. For hybridization, radioactively-labelled probes were diluted to a final concentration of  $10^7$  cpm/ml in a solution containing 50% formamide,  $4\times\text{SSC}$  ( $1\times\text{SSC}$ : 150 mM NaCl, and 15 mM sodium citrate),  $1\times\text{Denhardt's}$  solution (0.02% Ficoll, 0.02% polyvinylpyrrolidone, 0.02% bovine serum albumin), 10% dextran sulfate, 1% sarkosyl, 20 mM phosphate buffer pH 7.0, 250  $\mu\text{g/ml}$  yeast tRNA and 500  $\mu\text{g/ml}$  salmon sperm DNA. Tissues were covered with 100  $\mu\text{l}$  of the hybridization solution and overlaid with Nescofilm (Bando Chemical, Kobe, Japan) coverslips to prevent evaporation. Sections were incubated in humid boxes overnight at  $42^{\circ}\text{C}$  and then washed 4 times (45 min each) in 600 mM NaCl, 20 mM Tris-HCl, pH 7.5, 1 mM EDTA at  $60^{\circ}\text{C}$ . Hybridized sections were exposed to BIOMAX-MR film (Kodak) for 1 day to five days depending on the probe used at  $-70^{\circ}\text{C}$  with intensifying screens.

The specificity of the nucleotide hybridization signals was assessed as follows. For a given oligonucleotide probe the presence of a 50-fold excess of the same unlabelled oligonucleotide in the hybridization buffer resulted in the abolishment of the specific hybridization signal (data not shown). The thermal stability of the hybrids was examined by washing a series of consecutive hybridized sections at increasing temperatures. Specific hybridization signals were still present in sections washed at  $70^{\circ}\text{C}$  but they were completely absent from sections washed at  $80^{\circ}\text{C}$ . No such decrease was observed in the background levels of the signal (data not shown).

The average densities of the mRNAs in different brain regions were evaluated semi-quantitatively on film autoradiograms with the aid of an image analysis system (MCID M4, Imaging Research, St Catherines, Ontario, Canada).

Hybridized tissue section images from film autoradiograms were photographed with a digital camera (DXM1200 F, Nikon) and ACT-1 Nikon Software using a Wild makroscope M-420. Figures were prepared for publication using Adobe Photoshop software (Adobe Software, San Jose, CA, USA). Contrast and brightness of images were the only variables we adjusted digitally. For anatomical reference, sections close to those used were stained with Cresyl violet.

### Statistics

Data were analyzed by analysis of variance (ANOVA) followed by Dunnett's *t*-test for multiple comparisons or paired Student *t*-test when required. The level of statistical significance was set at  $p<0.05$  for all analyses.

## Results

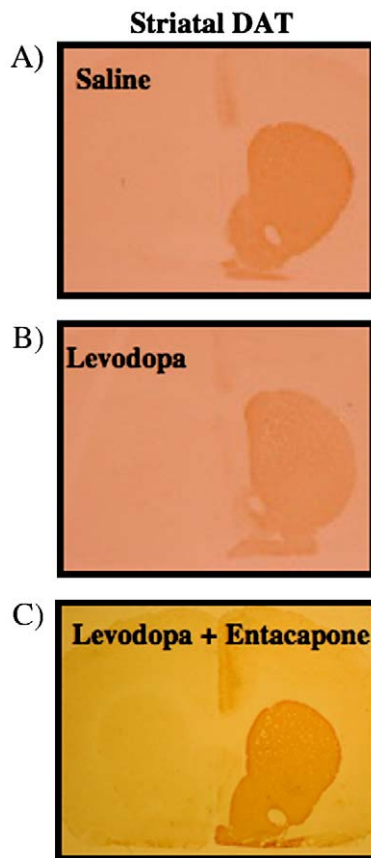
### Characterization of the unilateral 6-OHDA lesion

Rats with a complete 6-OHDA lesion exhibited a rotational response to apomorphine injection ( $>100$  rotations). A quantitative analysis showed an absence of dopamine transporter (DAT)-immunoreactivity in the ipsilateral striatum (Fig. 1). No significant differences in the degree of dopaminergic denervation were observed among the groups of rats that received levodopa, levodopa plus entacapone or saline administration (Fig. 1).

### Effects of chronic administration of levodopa plus entacapone on forelimb akinesia

Prior to 6-OHDA lesion, the proportion of wall contacts performed with the right paw amounted to 55% and 52% of total in levodopa and levodopa plus entacapone-treated animals, respectively. This percentage of wall contacts with the right (parkinsonian) paw was minimal 3 weeks after 6-OHDA lesion in all animals ( $p<0.01$ ) (Fig. 2).



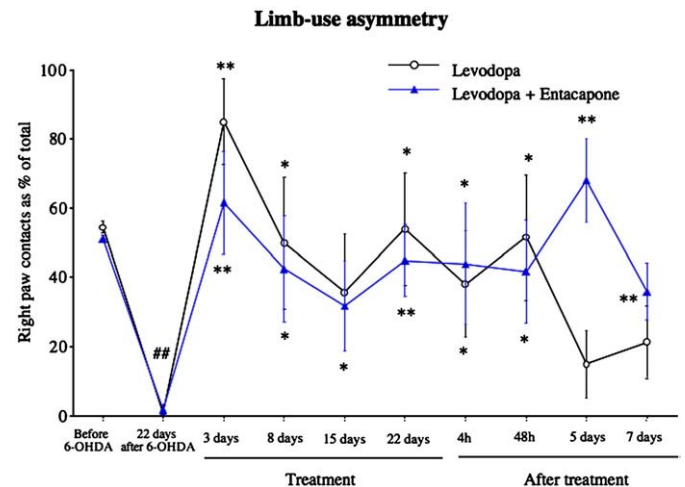


**Fig. 1.** Representative DAT immunohistochemistry from 14  $\mu$ m coronal sections of the rostral striatum. Sections are from rats receiving 6-OHDA injection in the left forebrain bundle, and then treated for 22 days with (A) saline ( $n=10$ ), (B) levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle ( $n=16$ ) twice a day, and (C) levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.,  $n=18$ ) twice a day. Note the significant absence of DAT immunoreactivity in the lesioned side regardless of the drug treatment.

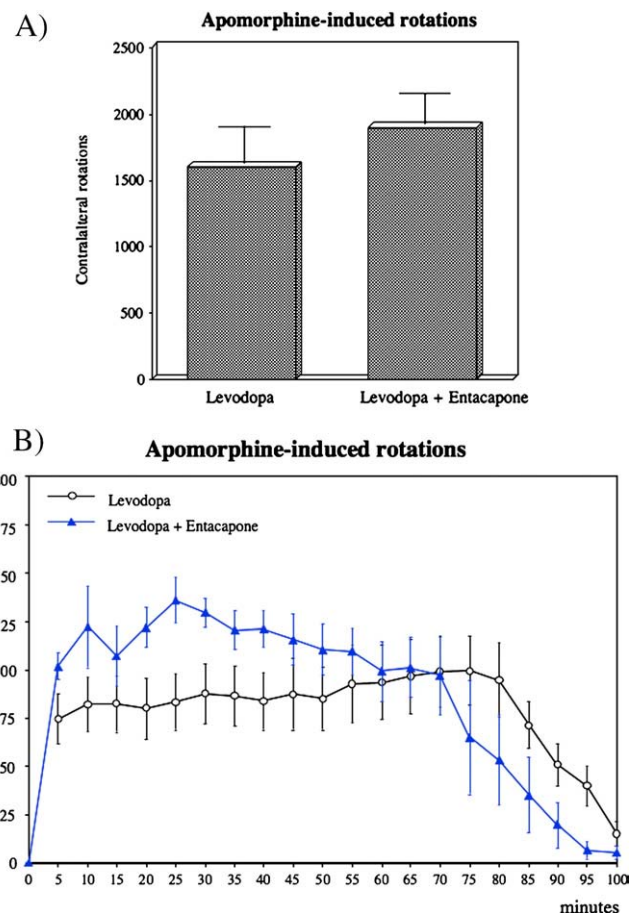
During levodopa (25 mg/kg with 6.25 mg/kg benserazide) or levodopa plus entacapone (30 mg/kg) treatment, the limb asymmetry was measured 45 min after a test dose of levodopa (6 mg/kg), (Fig. 2). Forelimb akinesia was evaluated before and after 6-OHDA lesion, 3 days after and then weekly during levodopa or levodopa plus entacapone treatment, followed by evaluations at 4 h, 2, 5 and 7 days after levodopa or levodopa plus entacapone withdrawal. A similar significant improvement in limb use asymmetry was observed in both group of animals chronically treated with levodopa or levodopa plus entacapone. This effect reached similar percentages of wall contacts than the ones achieved by the same limb prior to 6-OHDA lesion. The benefit lasted for several days. The increased limb activity in the levodopa-treated group was significant up to 48 h after levodopa treatment withdrawal, as previously reported (Marin et al. 2007) (Fig. 2). In the group treated with levodopa plus entacapone the benefit lasted for 7 days after treatment withdrawal.

#### Effects of chronic administration of levodopa plus entacapone on apomorphine-induced rotational behavior

No differences were observed in the total number of contralateral rotations induced by apomorphine between both levodopa and levodopa plus entacapone treated groups (Fig. 3a). The administration of entacapone did not decrease the maximal peak of rotation induced by apomorphine and the duration of the rotational behavior was not significantly modified (Fig. 3b).



**Fig. 2.** Long-duration response to levodopa: forelimb akinesia evaluated 45 min after a levodopa dose test (6 mg/kg, i.p.) in unilateral 6-OHDA-lesioned rats chronically treated for 22 days with levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day, and levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p., twice a day). Values are expressed as mean  $\pm$  SEM. ## $p<0.01$  vs before 6-OHDA; \* $p<0.05$ , \*\* $p<0.01$  vs 22 days after 6-OHDA.



**Fig. 3.** Effect of entacapone on the postsynaptic mechanisms evaluated by means of apomorphine-induced rotational behavior. The coadministration of entacapone (30 mg/kg, i.p., twice a day) did not modify the effect of levodopa on apomorphine-induced rotations; (A) total number of rotations; (B) time-course curve. Values are expressed as mean  $\pm$  SEM.

### Effects of chronic administration of levodopa plus entacapone on molecular markers in basal ganglia

#### Striatal PPE mRNA expression

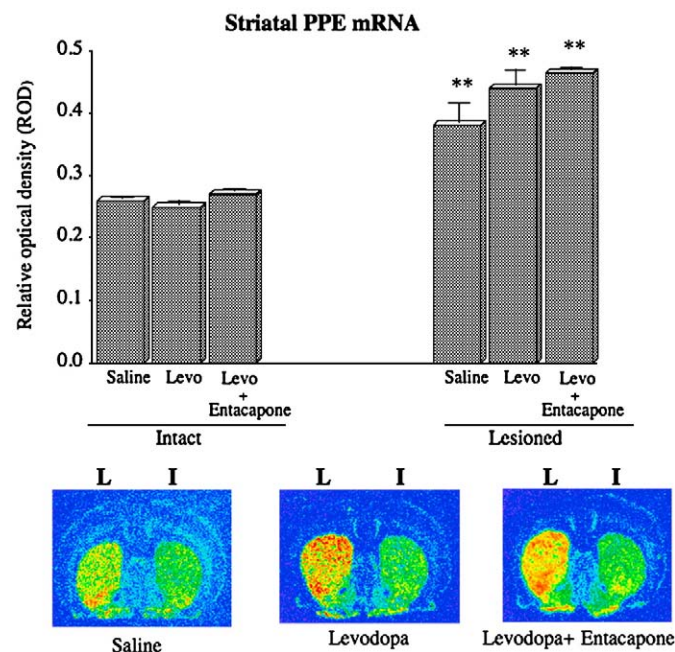
As expected, a significant increase in PPE mRNA levels in the lesioned striatum was observed after 6-OHDA lesion in the saline-treated animals compared with the intact striatum ( $p < 0.01$ ) (Fig. 4). Levodopa treatment maintained the increase in striatal PPE levels ( $F_{2,11}$ : 3.04). In the group of animals treated with levodopa plus entacapone, the PPE mRNA levels did not differ from the ones achieved by levodopa treatment (Fig. 4). PPE mRNA expression levels were not modified in the intact striatum of any group.

#### Striatal PDyn mRNA expression

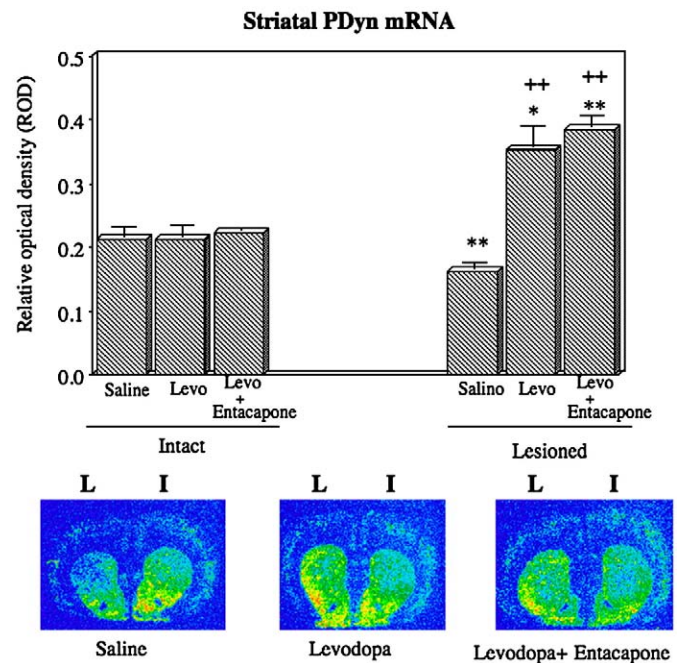
Striatal PDyn mRNA levels were significantly reduced in the 6-OHDA-lesioned striatum ( $p < 0.01$ ) in the saline-treated animals compared with the intact striatum, as expected (Fig. 5). Levodopa treatment induced a significant increase in PDyn mRNA in the lesioned striatum in comparison with saline-treated rats ( $p < 0.01$ ) ( $F_{2,13}$ : 27.53) and with intact side ( $p < 0.05$ ). In the group of animals treated with levodopa plus entacapone, the PDyn mRNA levels did not differ from the ones achieved by levodopa treatment (Fig. 5). There were no significant changes in PDyn mRNA expression levels in the intact side in any group.

#### Striatal dopamine D-3 receptor mRNA expression

Dopamine D-3 receptor mRNA expression was not modified by the 6-OHDA lesion compared with the intact striatum (Fig. 6). Rats that received chronic intermittent treatment with levodopa showed a significant increase in DA D-3 mRNA in the lesioned striatum in comparison with the intact side ( $p < 0.01$ ) ( $F_{2,12}$ : 2.83). In the group of animals treated with levodopa plus entacapone, the D-3 mRNA levels did not differ from the ones achieved by levodopa treatment (Fig. 6). There were no significant changes in DA D-3 mRNA expression levels in the intact side in any group.



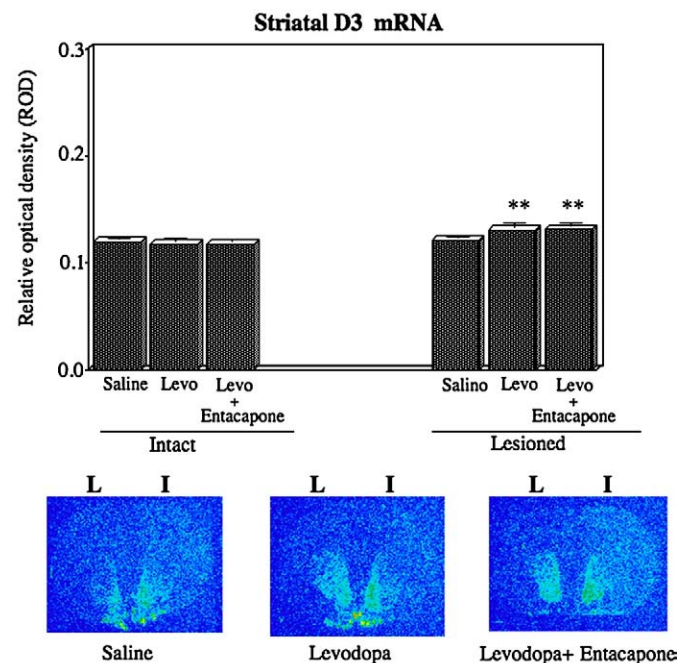
**Fig. 4.** Striatal PPE mRNA expression in 6-OHDA-lesioned rats chronically treated for 22 days with: levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day; levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.) twice a day or saline. Upper: Values are expressed as mean  $\pm$  SEM. \*\* $p < 0.01$  vs the corresponding intact side. Bottom: Representative film autoradiograms of coronal brain sections (14  $\mu$ m) showing striatal PPE mRNA labelling in all treatment groups.



**Fig. 5.** Striatal PDyn mRNA expression in 6-OHDA-lesioned rats chronically treated for 22 days with: levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day; levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.) twice a day or saline. Upper: Values are expressed as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$  vs the corresponding intact side; ++ $p < 0.01$  vs saline-treated animals. Bottom: Representative film autoradiograms of coronal brain sections (14  $\mu$ m) showing striatal PDyn mRNA labelling in all treatment groups.

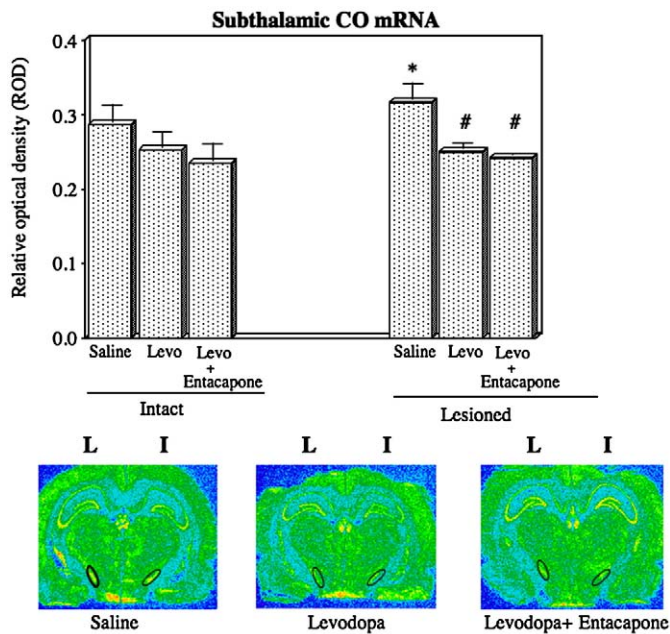
#### Subthalamic cytochrome oxidase (CO) mRNA expression

Unilateral 6-OHDA lesion induced a significant increase in CO mRNA expression in the ipsilateral subthalamic nucleus ( $p < 0.05$ ) (Fig. 7). Rats



**Fig. 6.** Striatal dopamine D-3 mRNA expression in 6-OHDA-lesioned rats chronically treated for 22 days with: levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day; levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.) twice a day or saline. Upper: Values are expressed as mean  $\pm$  SEM. \*\* $p < 0.01$  vs the corresponding intact side. Bottom: Representative film autoradiograms of coronal brain sections (14  $\mu$ m) showing striatal D-3 mRNA labelling in all treatment groups.





**Fig. 7.** Subthalamic CO mRNA expression in 6-OHDA-lesioned rats chronically treated for 22 days with: levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day; levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.) twice a day or saline. Upper: Values are expressed as mean  $\pm$  SEM. \* $p < 0.05$  vs the corresponding intact side; # $p < 0.05$  vs saline-treated animals. Bottom: Representative film autoradiograms of coronal brain sections (14  $\mu$ m) showing subthalamic CO mRNA labelling in all treatment groups.

that received chronic intermittent treatment with levodopa showed a significant decrease in CO mRNA in the STN in comparison with saline-treated rats ( $p < 0.05$ ) ( $F_{2,13}$ : 4.28). This effect was noticeable as the levels were normalized in comparison with the intact side in the same group. In the group of animals treated with levodopa plus entacapone, the subthalamic CO mRNA levels did not differ from the ones achieved by levodopa treatment (Fig. 7). There were no significant changes in CO mRNA expression levels in the STN contralateral to the lesion.

#### Nigral GAD mRNA expression

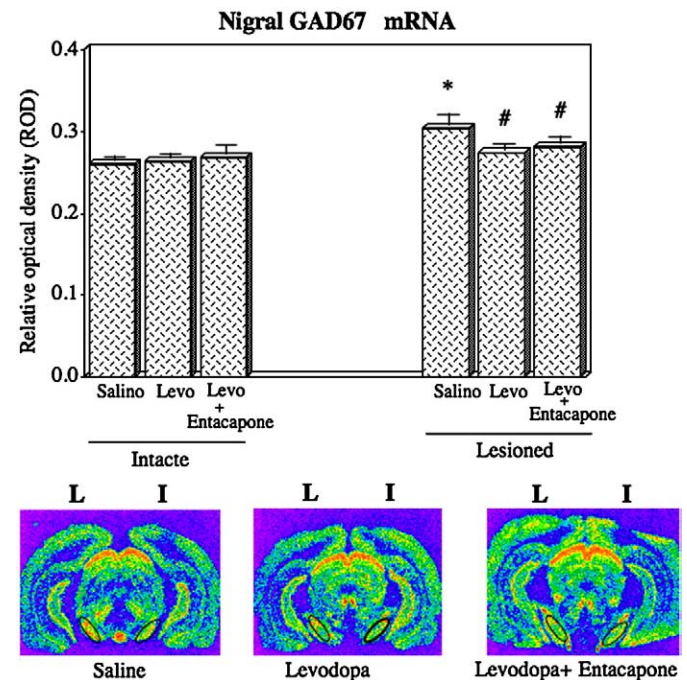
Unilateral 6-OHDA lesion induced a significant increase in GAD<sub>67</sub> mRNA expression in the ipsilateral pars reticulata of the substantia nigra ( $p < 0.05$ ) (Fig. 8). Rats that received chronic intermittent treatment with levodopa showed a significant decrease in GAD<sub>67</sub> mRNA in the ipsilateral SNr in comparison with saline-treated rats ( $p < 0.05$ ) ( $F_{2,13}$ : 3.22). In the group of animals treated with levodopa plus entacapone, the nigral GAD<sub>67</sub> mRNA levels did not differ from the ones achieved by levodopa treatment (Fig. 8). There were no significant changes in GAD<sub>67</sub> mRNA expression levels in the SNr contralateral to the lesion.

#### Discussion

Our present results show that the administration of entacapone increased the LDR induced by levodopa since in the 6-OHDA-lesioned rats treated with levodopa plus entacapone the beneficial motoric effect lasted for, at least, 7 days after treatment discontinuation. In the present study, we used a sub-threshold dose of levodopa as a test to evaluate the LDR to levodopa in animals chronically treated with a higher dose of levodopa, as previously described (Marin et al. 2007). Using such paradigm, we have observed an improvement in forelimb akinesia that lasted for, at least, 2 days after levodopa discontinuation (Marin et al. 2007). The phenomenology of this improvement and its further decay when levodopa is stopped resembles the LDR to levodopa. The potentiation of the LDR to levodopa by entacapone

administration agrees with previous observations showing that entacapone attenuates and prevents levodopa-induced motor fluctuations in 6-OHDA-lesioned rats (Marin et al. 2005) and PD patients (Parkinson Study Group 1997; Rinne et al. 1998; Reichmann et al. 2005; Grandas et al. 2007). In addition, a beneficial effect of entacapone administration attenuating levodopa or DA agonist-induced dyskinesias in 6-OHDA-lesioned rats (Marin et al. 2006) and in MPTP-treated monkeys (Smith et al. 2003, 2005; Zubair et al. 2007) has been already shown. Because it has been associated with levodopa, a presynaptic mechanism has been considered as one of the mechanisms involved in the LDR (Quattrone et al. 1995; Nutt and Holford 1996). However, a LDR can be produced in the *novo* patients with the dopamine agonist apomorphine (Nutt and Carter 2000) suggesting the involvement of postsynaptic pharmacodynamic mechanisms.

To address the possible postsynaptic mechanisms involved in the entacapone effect on levodopa-induced motor responses, we have measured the rotations induced by apomorphine 3 days after last treatment administration (Juncos et al. 1989). The action of apomorphine is mediated through postsynaptic D1 and D2 receptors and is not dependent of presynaptic mechanisms as occurs with levodopa. Juncos et al. (1989) found that continuous levodopa administration attenuated the increased rotational behavior response to apomorphine induced after intermittent administration indicating that the postsynaptic mechanisms involved in the motor effects after pulsatile stimulation of DA receptors were attenuated by the continuous administration of levodopa. In the present study, we show that coadministration of entacapone did not modify the rotational response to apomorphine in comparison with the one elicited by levodopa alone. This result suggests that postsynaptic mechanisms might not be involved in the entacapone effects on levodopa-induced motor responses such as LDR.



**Fig. 8.** GAD<sub>67</sub> mRNA expression in the *pars reticulata* of the substantia nigra in 6-OHDA-lesioned rats chronically treated for 22 days with: levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus vehicle twice a day; levodopa methyl ester (25 mg/kg with 6.25 mg/kg benserazide, i.p.) plus entacapone (30 mg/kg, i.p.) twice a day or saline. Upper: Values are expressed as mean  $\pm$  SEM. \* $p < 0.05$  vs the corresponding intact side; # $p < 0.05$  vs saline-treated animals. Bottom: Representative film autoradiograms of coronal brain sections (14  $\mu$ m) showing nigral GAD<sub>67</sub> mRNA labelling in all treatment groups.

Abundant experimental evidence indicates that discontinuous dopaminergic stimulation leads to dysregulation of genes and proteins in the basal ganglia nuclei in PD animal models, that in turn may lead to abnormal neuronal firing patterns that have been associated with dyskinesia in PD (Morissette et al. 1997; Vitek and Giroux 2000; Levy et al. 2001; Aubert et al. 2005; Alonso-Frech et al., 2006). Neither, the gene changes nor the dyskinesia associated with a short-acting dopaminergic drug are reported when the same drug is given by continuous infusion (Morissette et al. 1997). In detail, the enkephalin precursor PPE mRNA is co-expressed with gammaaminobutyric acid (GABA)-striatal D-2 bearing neurons and levels of PPE mRNA are up-regulated after a DA lesion (Gerfen et al. 1990; Jolkkonen et al. 1995; Morissette et al. 1997; Henry et al. 1999; Bezard et al. 2001; Ravenscroft et al. 2004; Marin et al. 2007). In 6-OHDA-lesioned rats, repeated administration of levodopa elicits and enhanced behavioral response that is associated with an increased striatal PPE mRNA expression (Ravenscroft et al. 2004; Chen et al. 2005; Marin et al. 2007). However, following repeated administration of antiparkinsonian agents with longer half-life such as bromocriptine, which does not cause behavioral enhancement, PPE mRNA expression is not increased (Henry et al. 1999). In MPTP monkeys, intermittent levodopa administration induces dyskinesia in association with persistent or even further up-regulation of striatal PPE (Jolkkonen et al. 1995; Morissette et al. 1997, 1999). In contrast, long-acting dopamine agonists do not induce dyskinesia, and PPE levels are down-regulated (Morissette et al. 1999). Moreover, when dyskinesias are induced by intermittent delivery of short-acting DA agonists, PPE levels remain up-regulated whereas when the same agonist is administered continuously, the animals do not experience dyskinesia and PPE levels are down-regulated (Morissette et al. 1997). On the other hand, PDyn mRNA that is expressed in the direct pathway is decreased in 6-OHDA-lesioned rats (Henry et al. 1999; Ravenscroft et al. 2004). Intermittent levodopa administration reverses, or further increases, the decrease in striatal PDyn mRNA (Andersson et al. 1999; Henry et al. 1999; Ravenscroft et al. 2004; Marin et al. 2007). However, long-acting drugs normalize the PDyn mRNA to pre-lesion levels (Henry et al. 1999).

All of the above observations suggest that the motor improvement and the attenuation of motor complications-induced by the CDS are associated with a normalization of levodopa or DA agonist-induced molecular changes in the basal ganglia. From a theoretical point of view, provision of a constant supply of DA or a DA agonist to striatal DA receptors should mimic the state seen during normal tonic firing of dopaminergic receptors, by avoiding fluctuations in DA levels that accompany intermittent levodopa dosing and thus facilitate more normal control of movement (Olanow et al. 2006).

A promising therapeutic strategy for PD focused on the potential of providing CDS to ameliorate or prevent levodopa-related motor complications have been developed using COMT inhibitors such as entacapone (Fenelon et al. 2003; Deuschl et al. 2007; Grandas et al. 2007; Müller et al. 2007). Administration of a single dose of levodopa with a COMT inhibitor increases the levodopa plasma area under the curve and its elimination half-life without augmenting peak plasma levels (Nutt et al. 1994; Heikkinen et al. 2002). According to these pharmacokinetic features, the administration of levodopa with a COMT inhibitor could maintain more stable plasma levels, thus providing an increase in the bioavailability of levodopa and an increase in a longer duration of striatal DA receptor stimulation (Heikkinen et al. 2002; Gerlach et al. 2004; Pajja et al. 2005). Until present, it was unknown whether the COMT inhibitor entacapone normalizes levodopa-induced molecular changes.

Our present results show that the coadministration of entacapone with levodopa was not able to normalize levodopa-induced molecular changes in the basal ganglia nuclei. In detail, entacapone administration did not modify the increase in striatal PPE, PDyn or D-3 mRNAs induced by levodopa. No significant differences were observed in CO

mRNA in the subthalamic nucleus and in the GAD67 mRNA in the SNr between levodopa alone and levodopa plus entacapone groups. Altogether these data indicates that the potentiation of the LDR to levodopa shown in the present study and the attenuation of levodopa-induced motor fluctuations and dyskinesias by entacapone previously reported (Marin et al. 2005, 2006) are not related with a normalization of the molecular changes induced by levodopa in the basal ganglia nuclei. However, these observations do not contradict one to each other. The pharmacokinetics and pharmacodynamics of entacapone need to be taken in account. Microdialysis studies in rats showed that entacapone is able to enhance striatal DA output following administration of levodopa (Kaakola et al. 1993; Törnwall et al. 1994). The increased DA efflux produced by COMT inhibitors is thought to result from the higher brain availability of levodopa consequent to the reduced peripheral conversion of the amino acid into 3-O-methyl-DOPA (3-OMD). It has been shown that central COMT inhibitors in comparison with peripheral inhibitors, such as entacapone, have the additional capacity to further extend the half-life of levodopa being more effective than entacapone in increasing extracellular striatal levels of DA (Napolitano et al. 2003) and, thus, in stimulating the DA receptors in a more continuous manner.

Thus, plasma levels of levodopa and consequent DA striatal concentrations achieved by administering levodopa plus benserazide plus entacapone twice daily are probably insufficient to achieve CDS and therefore, incapable to normalize levodopa-induced molecular changes. Indeed, the half-life of entacapone might also be relevant to the lack of modification of levodopa-induced molecular alterations since it has been shown that is shorter than central COMT inhibitors (Forsberg et al. 2003). Our findings as well as clinical pharmacokinetics studies (Stocchi et al. 2005) indicate that the triple combination of levodopa plus benserazide plus entacapone should be given several times per day (i.e. 4 times) in order to minimize the risks of developing motor complications. This has practical clinical implications in the designs of trials and for routine practice where levodopa plus benserazide plus entacapone is usually administered thrice a day.

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