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Cannabidiol attenuates cisplatin-induced nephrotoxicity by decreasing oxidative/nitrosative stress, inflammation and cell death

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Abbreviations: BUN, blood urea nitrogen; CBD, Cannabidiol**;** IL-1β, Cisplatin, CP; interleukin-1 beta; iNOS (NOS2), inducible nitric oxide synthase; MDA, malondialdehyde; NT, 3-nitrotyrosine; PARP, poly (ADP-ribose) polymerase; ROS, reactive oxygen species; RNS, reactive nitrogen species; TUNEL, terminal deoxynucleotidyl transferase-mediated uridine triphosphate (dUTP) nick-end labelling ; (TNF)-α, tumor necrosis factor alpha.

ABSTRACT

The platinum compound cisplatin is one of the most potent chemotherapy agents available to treat various malignancies. Nephrotoxicity is a common complication of cisplatin chemotherapy, which involves increased oxidative and nitrosative stress, limiting its clinical use. In this study we have investigated the effects of a nonpsychoactive cannabinoid cannabidiol, which was reported to exert antioxidant effects and has recently been approved for the treatment of inflammation, pain, and spasticity associated with multiple sclerosis in patients, in a mouse model of cisplatin-induced nephropathy. Cisplatin induced increased expression of superoxide generating enzymes RENOX (NOX4) and NOX1, enhanced ROS generation, iNOS expression, nitrotyrosine formation, apoptosis (caspase 3/7 activity, DNA fragmentation, and TUNEL staining), poly (ADP-ribose) polymerase activity, and inflammation (TNF-α and IL1 β) in the kidneys of mice, associated with marked histopathological damage and impaired renal function (elevated serum BUN and creatinine levels) 72 hours following the administration of the drug. Treatment of mice with cannabidiol markedly attenuated the cisplatin-induced oxidative/nitrosative stress, inflammation and cell death in the kidney, and improved renal function. Thus, our results suggest that cannabidiol may represent a promising new protective strategy against cisplatin-induced nephrotoxicity.

INTRODUCTION

Cisplatin, a platinum compound, is one of the most potent chemotherapy agents available to treat a variety of malignancies, including ovarian, lung, head, and neck cancers, as well as testicular and bladder tumors (Ries and Klastersky, 1986; Wang and Lippard, 2005). Unfortunately, cisplatin induces cumulative and dose-dependent nephrotoxicity, which restricts the use of high doses to maximize the therapeutic efficacy. About one third of patients experience renal dysfunction after treatment with cisplatin (Ries and Klastersky, 1986). Cisplatin is taken up by renal tubular cells after administration, with proximal tubular cells of the inner cortex and outer medulla absorbing the highest concentrations of the drug. As a result, these segments are the major sites of cisplatin-induced renal injury, and the loss of tubular cells by necrosis and apoptosis, is followed by infiltration of inflammatory cells. The cisplatin-induced nephrotoxicity is a complex process (Pabla and Dong, 2008), which has been reported to involve DNA damage, caspase activation, mitochondrial dysfunction (Sugiyama et al., 1989), formation of reactive oxygen (Matsushima et al., 1998; Davis et al., 2001) and nitrogen species (Chirino et al., 2004; Chirino et al., 2008), poly (ADP-ribose) polymerase (PARP) overactivation (Racz et al., 2002), and inflammation (Yamate et al., 2002; Faubel et al., 2007). Multiple lines of recent evidence suggest an important role for inflammatory mechanisms mediating the pathogenesis of cisplatin-induced nephrotoxicity through the recruitment of inflammatory cells, such as macrophages and leukocytes, that contribute to the cisplatin-induced damage (Ramesh and Reeves, 2002; Yamate et al., 2002; Faubel et al., 2007; Zhang et al., 2007). Furthermore, cisplatin induces increased renal expression of a variety of inflammatory chemokines and cytokines, such as tumor necrosis (TNF)-α and interleukin-1β (IL-1β) (Ramesh and Reeves, 2002; Zhang et al., 2007). Reportedly, cisplatin-induced kidney injury largely depends on TNF-α, since TNF-α-deficient mice and

TNF-α antibody-treated wild-type mice display resistance to cisplatin-induced kidney damage (Ramesh and Reeves, 2002; Zhang et al., 2007).

Cannabinoids (components of the Cannabis sativa (marijuana) plant), are known anti-inflammatory, immunomodulatory and analgesic agents, which exert these effects through the activation of CB_1 and CB_2 cannabinoid receptors located in the central nervous system and immune cells (Pacher et al., 2006). However, the limitation of the therapeutic use of the major cannabinoid, Delta 9-tetrahydrocannabinol, is the development of psychoactive effects mediated through CB_1 receptor in the CNS (Pacher et al., 2006). On the contrary, cannabidiol (CBD), one of the most abundant cannabinoids of Cannabis sativa is devoid of psychoactive properties due to a low affinity for the CB_1 and CB_2 receptors (Pacher et al., 2006). CBD is well tolerated without side effects when chronically administered to humans and has been reported to exert antioxidant, anti-inflammatory and immunomodulatory effects (Cunha et al., 1980; Consroe et al., 1991; Mechoulam et al., 2007).

Here we have studied the effects of CBD on cisplatin-induced oxidative/nitrosative stress, inflammation, and tissue injury in the kidney using a well-established mouse model of cisplatin-induced nephropathy. Our results may have important relevance for the prevention of the cisplatin-induced nephrotoxicity.

METHODS

Animals and drug treatment

All animal experiments conformed to National Institutes of Health (NIH) guidelines and were approved by the Institutional Animal Care and Use Committee of the National Institute on Alcohol Abuse and Alcoholism (NIAAA; Bethesda, MD, USA). Six to 8-week-old male C57Bl/6J mice were obtained from The Jackson Laboratory (Bar Harbor, ME, USA). All animals were kept in a temperature-controlled environment with a 12-h light–dark cycle and were allowed free access to food and water at all times, and were cared for in accordance with National Institutes of Health (NIH) guidelines.

Mice were sacrificed 72 hrs following a single injection of cisplatin (cis-Diammineplatinum(II) dichloride 20 mg/kg i.p.; Sigma) administration. Cannabidiol was used at 2.5-10 mg/kg, i.p. every day, starting 1.5 hours before the cisplatin exposure to establish the dose-response relationship (Figure 1), and at 10 mg/kg/day in experiments aiming to characterize its detailed mechanism of action (Figures 2-7). Cannabidiol (CBD) was isolated from hashish as described earlier (Gaoni and Mechoulam, 1971)**.** Sources of all the other reagents used in the experiments are mentioned in the text wherever appropriate.

Renal function monitoring

On the day of the sacrifice, blood was collected immediately and serum levels of creatinine and Blood Urea Nitrogen (BUN) were measured using kits from Drew Scientific using Prochem-V chemistry analyzer (Texas, USA).

Western blot analysis

Anti-iNOS and anti-beta-actin antibodies were obtained from Cell Signaling Technology (Danvers, MA). The kidney protein samples were mixed in Laemmli loading buffer, boiled for 10 min, and then subjected to SDS-PAGE. After electrophoresis, proteins were transferred onto nitrocellulose membranes and blotted against primary antibody (1:1000 dilution) for 16 hrs. Membranes were washed with PBS-T and incubated with a secondary antibody (1:1000 dilution) for 2 hrs. Protein bands were visualized by chemiluminescence reaction using SuperSignal West Pico Substrate (Thermo-Fisher, Pittsburg, PA).

Histological examination

Following fixation of the kidneys with 10% formalin, renal tissues were sectioned and stained with periodic acid-Schiff (PAS) reagents for histological examination. Tubular damage in PAS-stained sections was examined under the microscope (200x magnification) and scored based on the percentage of cortical tubules showing epithelial necrosis: 0 = normal; 1 = <10%; 2 = 10–25%; 3 = 26–75%; 4 = >75%. Tubular necrosis was defined as the loss of the proximal tubular brush border, blebbing of apical membranes, tubular epithelial cell detachment from the basement membrane or intraluminal aggregation of cells and proteins. The morphometric examination was performed in a blinded manner by two independent investigators.

ROS production

Malondialdehyde (MDA) is one of the end products of lipid peroxidation and an indicator of ROS production. MDA was quantified in tissues as previously described, with some minor modifications (Pacher et al., 2003). Briefly, tissues were homogenized (100 mg/mL) in 1.15% KCl buffer, homogenates (200 μL) were then added to a reaction mixture consisting of 1.5 mL

of 0.8% thiobarbituric acid, 200 μL of 8.1% sodium dodecyl sulfate, 1.5 mL of 20% acetic acid (pH 3.5), and 600 μL of distilled H_2O, and heated for 45 min at 90°C. After cooling to room temperature, the samples were centrifuged at 10,000 g for 10 min, and the absorbance of the supernatant at 532 nm was measured with 1,1,3,3-tetramethoxypropane as an external standard. The level of lipid peroxides was expressed as nmol MDA/mg protein.

Detection of apoptosis by TUNEL, renal DNA fragmentation and caspase 3/7 activity assays

Apoptosis was assessed by terminal deoxynucleotidyl transferase-mediated uridine triphosphate (dUTP) nick-end labelling (TUNEL), and the number of apoptotic cells, as defined by chromatin condensation or nuclear fragmentation (apoptotic bodies), was counted. Apoptosis was detected in the specimen using the ApopTag Plus Peroxidase In Situ Apoptosis Detection Kit (Chemicon International, CA, USA) according to the manufacturer's protocol. The morphometric examination was performed by two independent, blinded investigators. The number of apoptotic cells in each section was calculated by counting the number of TUNEL-positive apoptotic cells in 10x400 fields per slide.

For caspase assay of tissue lysate, caspase-3/7 activity of the lysate was measured using Apo-One Homogenous caspase-3/7 Assay Kit (Promega Corp., Madison, WI). An aliquot of caspase reagent was added to each well, mixed on a plate shaker for 1 h at room temperature with light protection, and the fluorescence was measured.

The DNA fragmentation assay is based on measuring the amount of mono- and oligonucleosomes in the cytoplasmic fraction of tissue extracts using the commercially available kit (Roche, GmbH) according to manufacturer's instructions.

Renal poly (ADP-ribose) polymerase (PARP) activity

PARP activity was determined by assay kit according to manufacturer's instructions (Trevigen, Gaithersburg, MD).

Renal nitrotyrosine accumulation

Quantification of nitrotyrosine levels from kidney tissues were performed using the sandwich ELISA kit according to manufacturer's instructions (Hycult Biotechnology, Uden, The Netherlands).

Immunohistochemistry

Paraffin-embedded sections were cut, deparaffinized, and hydrated by soaking in 100% xylene and descending ethanol, followed by microwave antigen retrieval treatment. Next, sections were incubated in 0.3% H_2O_2 in PBS to block endogenous peroxidase activity. The sections were incubated with anti-nitrotyrosine (1:200 dilution) obtained from Cayman Chemical (Ann Arbor, MI) overnight at 4ºC in a moist chamber. Biotinylated secondary antibodies and ABC Reagent were applied. Color development was induced by incubation with a DAB kit (Vector Laboratories, Burlingame, CA) for 3 to 5 min, and specific staining was visualized by light microscopy.

Real-time PCR analyses

Total RNA was isolated from kidney homogenate using Trizol LS reagents (Invitrogen, Carlsbad, CA) according to manufacturer's instruction. The isolated RNA was treated with

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RNase-free DNase (Ambion, Austin, TX) to remove traces of genomic DNA contamination. One μg of total RNA of was reverse-transcribed to cDNA using the Super-Script II (Invitrogen, Carlsbad, CA). The target gene expression was quantified with Power Syber Green PCR Master Mix using ABI 7500 Realtime PCR Instrument. Each amplified sample in all wells was analyzed for homogeneity using dissociation curve analysis. After denaturation at 95 °C for 2 min, 40 cycles were performed at 95 °C for 10 s, 60 °C for 30 s. Relative quantification was calculated using the comparative C_T method ($2^{-\Delta\Delta Ct}$ method : $\Delta\Delta Ct = \Delta C_{t\ sample} - \Delta C_{t\ reference}$). Lower ΔC_T values and lower $\Delta\Delta C_T$ reflect a relatively higher amount of gene transcript. Statistical analyses were carried out for at least 6 to 15 replicate experimental samples in each set.

Primers used:

TNFalpha 5`AAGCCTGTAGCCCACGTCGTA3` and 5`AGGTACAACCCATCGGCTGG3`

IL-1beta 5`AAAAAAGCCTCGTGCTGTCG3` and 5`GTCGTTGCTTGGTTCTCCTTG3`

iNOS 5`ATTCACAGCTCATCCGGTACG3` and 5`GGATCTTGACCATCAGCTTGC3`

NOX1 5'TCGAACGCTACAGAAGAAGCC3' and 5'TGGCAATCACTCCAGTAAGGC3'

RENOX 5' TCATTTGGCTGTCCCTAAACG3' and 5' AAGGATGAGGCTGCAGTTGAG3'

Actin 5`TGCACCACCAACTGCTTAG3` and 5`GGATGCAGGGATGATGTTC3`.

Statistical analysis

Results are reported as mean±SEM. Statistical significance between 2 measurements was determined by the 2-tailed unpaired Student's *t* test (and among groups it was determined by ANOVA followed by post-hoc Student-Newman-Keuls) by using GraphPad Prism 4.3 software (San Diego, CA). Probability values of $P<0.05$ were considered significant.

RESULTS

CBD attenuates the cisplatin-induced renal dysfunction in mice

To investigate the effect of CBD on cisplatin(CP)-induced renal dysfunction, levels of BUN and creatinine were measured at 72 h after cisplatin administration in the serum of both CBD-treated and untreated mice. As shown in Figure 1 and 2A, cisplatin administration resulted in severe renal injury, which was dose-dependently attenuated by CBD treatment (n=6/each group, $P<0.01$). Remarkably, CBD at 10 mg/kg/day i.p. was able to attenuate renal injury not only starting from 1.5 h before CP administration (Figure 1 and 2A), but even when it was administered 12 h following the CP exposure (n=6, $P<0.01$). CBD alone had no effects on BUN and creatinine levels as compared with the vehicle-treated group (n=5, Figure 2A).

CBD attenuates the cisplatin-induced tubular necrosis and apoptosis

Histological examination revealed necrosis, protein cast, vacuolation and desquamation of epithelial cells in the renal tubules of the cisplatin-treated control group. Treatment with CBD (10 mg/kg/day i.p. starting from 1.5 h before the CP exposure) dramatically improved the cisplatin-induced renal tubular damage (Figure 2B, n=6, $P<0.01$). Apoptosis of renal tubular epithelial cells was evaluated by TUNEL, and caspase 3/7 activity, and DNA fragmentation assays. As shown in Figures 3A and 4A, the caspase 3/7 activity and DNA fragmentation in kidney homogenates were markedly increased following cisplatin administration, and significantly attenuated by CBD treatment (n=6, $P<0.01$). TUNEL-positive apoptotic cell numbers were also increased in cisplatin-treated mice, and attenuated by CBD treatment (Figure 3B, n=6, $P<0.01$). CBD also attenuated the cisplatin-induced increased PARP activity in the

kidneys (Figure 4B, n=6, P<0.01). CBD alone had no effects on the above mentioned variables (n=5).

CBD attenuates the cisplatin-induced inflammation

Cisplatin markedly increased the mRNA expression of TNF-α and IL1β indicating enhanced inflammatory response, which was attenuated by CBD treatment (Figure 4C and D, n=6, P<0.01). CBD alone had no effects on the inflammatory markers (n=5).

CBD attenuates the cisplatin-induced increased ROS formation and enhanced expression of superoxide generating enzymes RENOX (NOX4) and NOX1

The mRNAs for subunits of RENOX (NOX4) and phagocyte NADPH oxidase (NOX1) were increased in the kidneys of cisplatin-treated mice. Such increases were attenuated by CBD treatment (Figure 5A,B, n=6, P<0.01 and P<0.05, respectively). CBD alone had no effects on the mRNA expression of NOX4 and NOX1 (n=5).

Cisplatin induced marked elevation of MDA levels, one of the end products of lipid peroxidation and an indicator of ROS production, which was attenuated by CBD treatment (Figure 5C, n=6, P<0.01). CBD alone had no effects on MDA (n=5).

CBD attenuates the cisplatin-induced increased iNOS mRNA and protein expression

Cisplatin markedly increased both the mRNA and protein expression of iNOS, which were attenuated by CBD treatment (Figure 6A,B, n=6, P<0.01). CBD alone had no effects on the iNOS expression (n=5).

CBD attenuates the cisplatin-induced increased 3-nitrotyrosine (NT) formation

Cisplatin markedly increases the NT formation as revealed by immunohistochemistry staining and quantitative ELISA from kidney homogenates, which were attenuated by CBD treatment (Figure 7A,B, n=6, $P<0.01$). CBD alone had no effects on NT generation (n=6).

DISCUSSION

In the present study, we have assessed the effects of CBD, a nonpsychoactive component of marijuana, on cisplatin-induced renal oxidative/nitrosative stress, cell death and consequent kidney dysfunction. We demonstrate that CBD attenuates cisplatin-induced increased expression of superoxide generating enzymes RENOX (NOX4) and phagocyte NOX1, ROS generation, iNOS expression, nitrotyrosine formation, inflammation, and apoptosis/necrosis in the kidney of mice, associated with marked improvement of compromised renal function.

CBD has been demonstrated to exert antioxidant and anti-inflammatory effects in numerous preclinical models of inflammatory and degenerative diseases known to be associated with increased ROS and RNS generation, as well as in *in vitr*o systems, independent from classical CB_1 and CB_2 receptors (Hampson et al., 1998; Chen and Buck, 2000; Malfait et al., 2000; Costa et al., 2004; Hayakawa et al., 2004; Iuvone et al., 2004; Sacerdote et al., 2005; El-Remessy et al., 2006; Esposito et al., 2006; Weiss et al., 2006; Durst et al., 2007; Rajesh et al., 2007; Weiss et al., 2008). CBD is devoid of psychoactive effects due to a low affinity for the central nervous system CB_1 receptors (Thomas et al., 1998; Pacher et al., 2006), and is well tolerated when chronically administered to humans (Cunha et al., 1980; Consroe et al., 1991). CBD has been approved for the treatment of inflammation, pain and spasticity associated with multiple sclerosis in humans since 2005 (Barnes, 2006; Pacher et al., 2006; Mechoulam et al., 2007).

Cisplatin is one of the most potent chemotherapy agents available to treat various malignancies. However, the major limitation of cisplatin chemotherapy is the dose-dependent nephrotoxicity. Unfortunately, efficient pharmacotherapies to decrease this devastating complication of chemotherapy are not available.

Increased oxidative (Matsushima et al., 1998; Davis et al., 2001) and nitrosative (Chirino et al., 2004; Chirino et al., 2008) stress and inflammation (Yamate et al., 2002; Faubel et al., 2007), and the activation of downstream effector cell death pathways (e.g. PARP(Racz et al., 2002)) play a critical role in the pathophysiology of cisplatin-induced cell death culminating in renal dysfunction. The cellular sources of increased superoxide production are multiple and may include NADH/NADPH and xanthine oxidases, the mitochondrial respiratory chain, just to name a few. In our study we found marked overexpression of NOX4 (RENOX; NAD(P)H oxidase isoform considered to be the main source of ROS in the kidney (Geiszt et al., 2000)) and to a lesser extent phagocyte NAD(P)H oxidase (NOX1), accompanied by marked increase in ROS generation, in kidneys of cisplatin-treated mice. Cisplatin also induced marked upregulation of TNF-α and IL1β mRNA in the kidney, consistent with the important role of inflammatory component, particularly cytokine TNF-α (Ramesh and Reeves, 2002; Zhang et al., 2007), in the drug-induced nephrotoxicity. Cisplatin-induced superoxide generation might also favor increased expression of iNOS through the activation of NF-κB, which increases the generation of nitric oxide (NO). Indeed we found marked iNOS overexpression in the kidneys of cisplatin-treated mice. The pathophysiological role of iNOS derived NO in this model is also supported by recent findings demonstrating that selective iNOS inhibition reduces renal damage induced by cisplatin (Chirino et al., 2008). Superoxide anion interacts with nitric oxide, forming the potent cytotoxin peroxynitrite, which attacks various biomolecules, leading to organ dysfunction via multiple mechanisms (Pacher et al., 2007). Indeed, the pathogenetic role of nitrosative stress and peroxynitrite, and downstream mechanisms such as PARP have recently been implicated in the development of cisplatin-induced cell death and consequent nephropathy (Racz et al., 2002; Chirino et al., 2004; Chirino et al., 2008).

CBD treatment largely attenuated the cisplatin-induced increased expression of ROS generating enzymes NOX4 and NOX1 and consequent renal oxidative stress. In addition, CBD also decreased the cisplatin-induced inflammatory response (TNF-α and IL1β levels), iNOS overexpression and nitrotyrosine formation (the marker of peroxynitrite generation and more broadly nitrosative stress (Pacher et al., 2007) in the kidneys, and consequent cell death (both apoptotic and necrotic) and renal dysfunction.

Although the exact mechanism of the anticancer activity of the cisplatin is not completely understood, it is widely held that it binds to DNA leading to the formation of inter- and intrastrand cross-links, resulting in defective DNA templates and arrest of DNA synthesis and replication, particularly in rapidly dividing cancer cells (Wang and Lippard, 2005; Pabla and Dong, 2008). While numerous other signaling mechanisms have also been implicated in the antitumor activity of the compound, the oxidative/nitrosative stress does not appear to play a major role (Wang and Lippard, 2005). This is also analogous to other potent chemotherapeutic agent doxorubicin, the major limitation of which is the cardiotoxicity, which also involves increased oxidative/nitrosative stress (Pacher et al., 2003; Pacher et al., 2007). Potent antioxidant approaches, which decrease the cardiotoxicity of doxorubicin do not interfere with its antitumor activity (Pacher et al., 2003). In fact, the clinically approved agent for prevention of doxorubicin-induced heart failure, the iron-chelating agent dexrazoxane, is a potent antioxidant. Therefore, it is not likely, that the antioxidant effect of the CBD would interfere with its chemotherapeutic efficacy. In addition, CBD by itself and its derivative Hu-331 have also been demonstrated to exert various antitumor properties (e.g. inhibition of growth and migration of various cancer cell lines, inhibition of angiogenesis, and attenuation of the growth of xenograft tumors in mice (Vaccani et al., 2005; Kogan et al., 2006; Ligresti et al., 2006; McAllister et al., 2007)), which

rather predict additive and/or synergestic anticancer effect(s) of CBD in combination with various chemotherapeutic agents, undoubtedly deserving further exploration in upcoming studies.

In summary, our results suggest that the non-psychoactive cannabinoid CBD may be of significant therapeutic benefits against the renal complications of cisplatin chemotherapy by attenuating oxidative/nitrosative stress and cell death. This is particularly encouraging in light of the excellent safety and tolerability profile of CBD in humans and reported anticancer and antiangiogenic effect of the compound and its derivatives (Mechoulam et al., 2007).

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Legends for Figures

Figure 1. Cannabidiol dose-dependently attenuates the cisplatin-induced renal dysfunction. Cisplatin (CP) induced profound renal dysfunction 72 h after the administration to mice evidenced by increased serum levels of blood urea nitrogen (BUN) and creatinine, which were dose-dependently attenuated by CBD treatment. CBD (10 mg/kg/day i.p.) even given 12 h following the CP exposure was able to attenuate the renal dysfunction. Results are mean±S.E.M. of 6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 2. Cannabidiol attenuates the cisplatin-induced renal dysfunction and histopathological damage. Cisplatin induced profound renal dysfunction and injury 72 h after the administration to mice evidenced by increased serum levels of blood urea nitrogen (BUN) and creatinine (panel A) and histopathological damage evaluated by PAS staining (panel B), which were attenuated by CBD treatment (10 mg/kg/day i.p. starting from 1.5 h before CP exposure). Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 3. Cannabidiol attenuates the cisplatin-induced renal caspase 3/7(panel A) activity and TUNEL staining (panel B). Cisplatin induced marked increases in caspase 3/7 activity (panel A) and TUNEL staining (panel B) in the kidneys of treated mice 72 h following the administration to mice, which were attenuated by CBD treatment (10 mg/kg/day i.p. starting from 1.5 h before CP exposure). Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 4. Cannabidiol attenuates the cisplatin-induced renal DNA fragmentation (panel A), PARP activity (panel B) and inflammation (panels C and D). Cisplatin induced marked increases in DNA fragmentation (panel A), PARP activity (panel B), and mRNA expression of TNF-α (panel C) and IL1β (panel D) in the kidneys 72 h following the administration to mice, which were attenuated by CBD treatment (10 mg/kg/day i.p. starting from 1.5 h before CP exposure). Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 5. Cannabidiol attenuates the cisplatin-induced renal overexpression of superoxide generating enzymes NOX4(RENOX) and NOX1 (panels A and B) and MDA formation. Cisplatin induced marked increases in mRNA expression of NOX4 and NOX1 (panels A and B) and increased lipid peroxidation (panel C) in the kidneys 72 h following the administration to mice, which were attenuated by CBD (10 mg/kg/day i.p. starting from 1.5 h before CP exposure) treatment. Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 6. Cannabidiol attenuates the cisplatin-induced renal overexpression of iNOS. Cisplatin induced marked increases in protein (panel A) and mRNA (panel B) expression of iNOS in the kidneys 72 h following the administration to mice, which were attenuated by CBD treatment (10 mg/kg/day i.p. starting from 1.5 h before CP exposure). Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

Figure 7. Cannabidiol attenuates the cisplatin-induced renal 3-nitrotyrosine (NT) formation. Cisplatin induced marked increases in NT staining in the kidneys (panel A, representative sections) and in nitrated proteins evaluated by quantitative ELISA (panel B) in the kidneys 72 h following the administration to mice, which were attenuated by CBD (10 mg/kg/day i.p. starting from 1.5 h before CP exposure) treatment. Results are mean±S.E.M. of 5-6 experiments in each group *P<0.05 vs. vehicle; †P<0.05 vs. cisplatin.

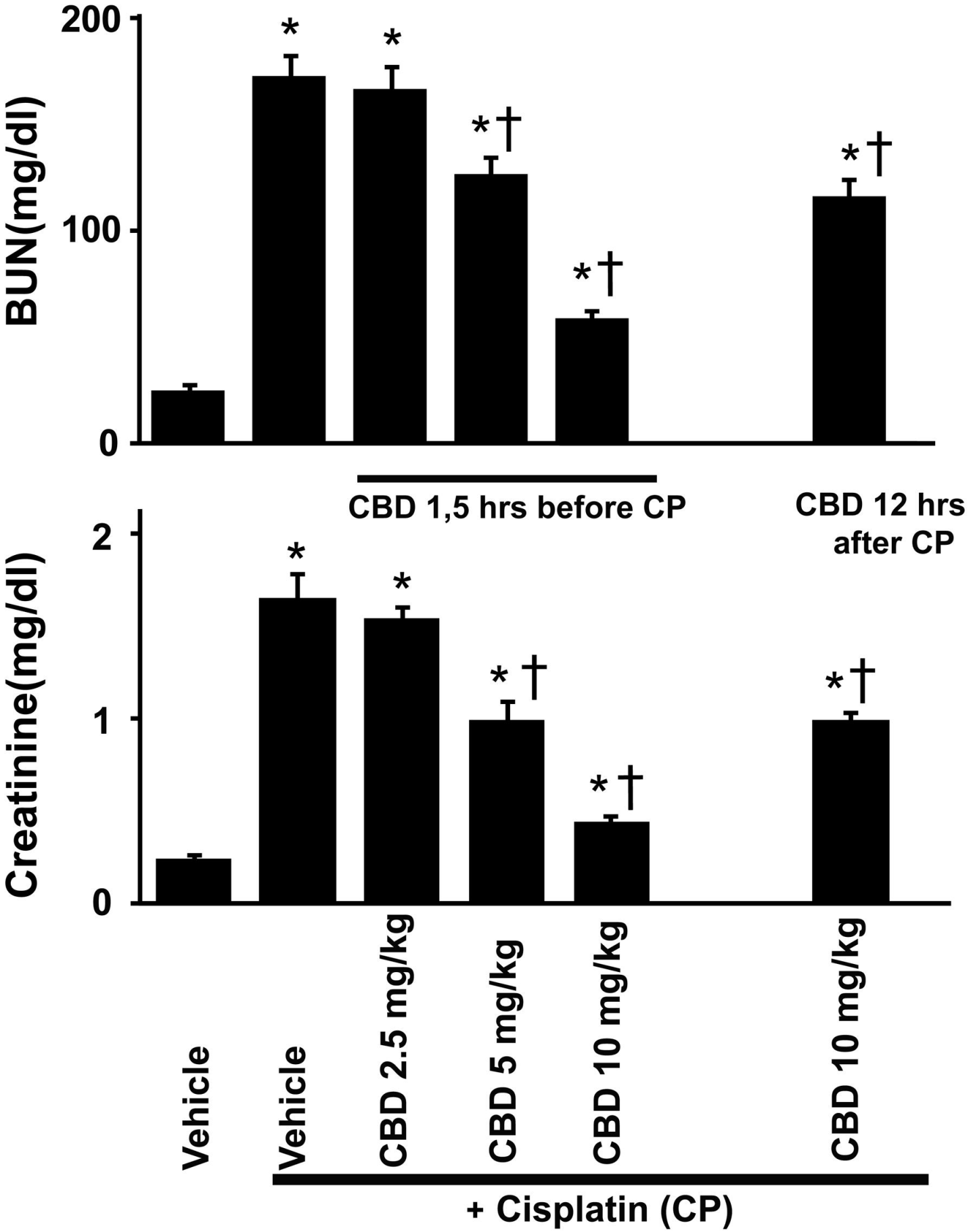

BUN(mg/dl)
200
100
0
*
*
*†
*†
*†
CBD 1,5 hrs before CP
CBD 12 hrs after CP
Creatinine(mg/dl)
2
1
0
*
*
*†
*†
*†
Vehicle
Vehicle
CBD 2.5 mg/kg
CBD 5 mg/kg
CBD 10 mg/kg
CBD 10 mg/kg
+ Cisplatin (CP)

Figure 1

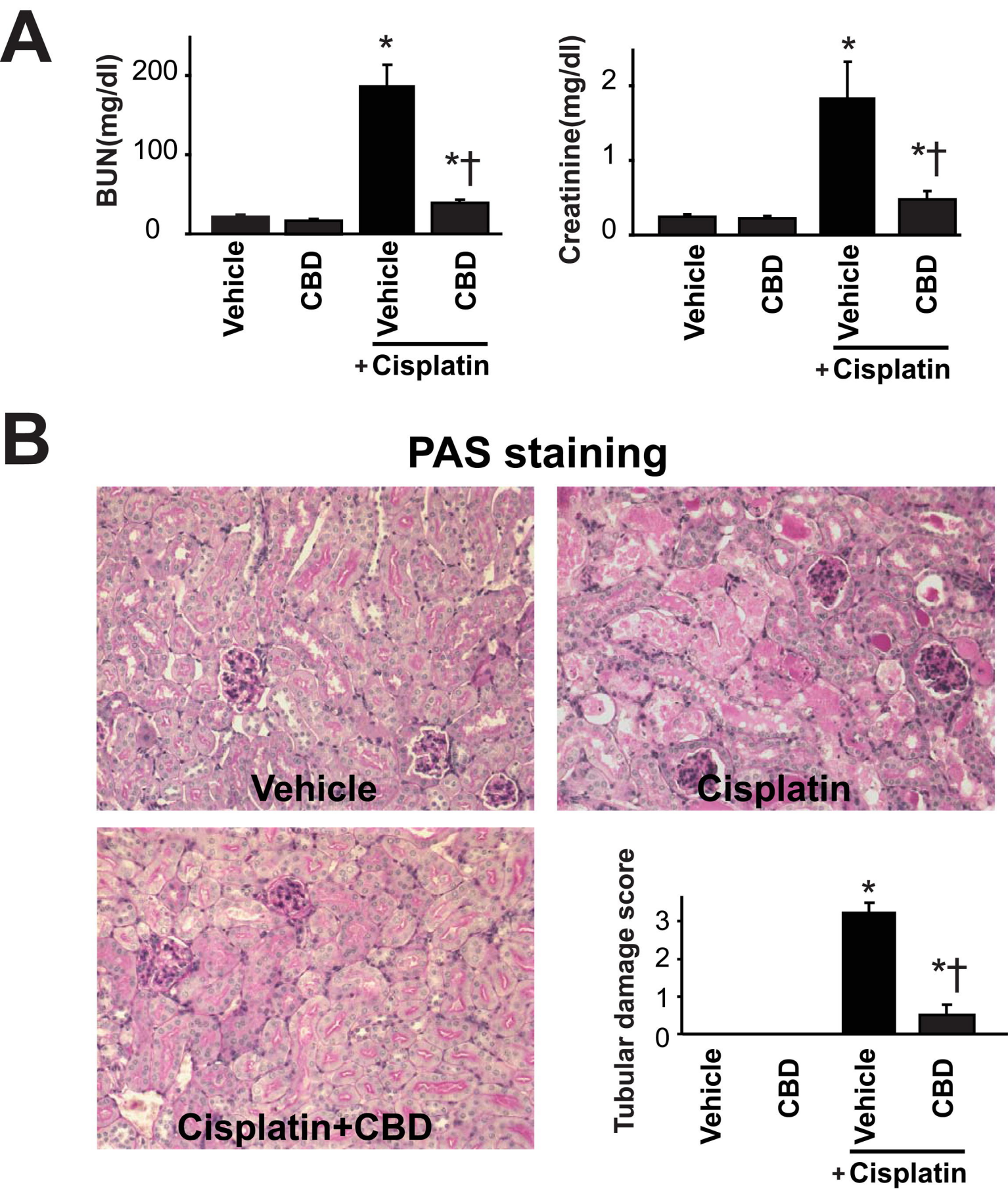
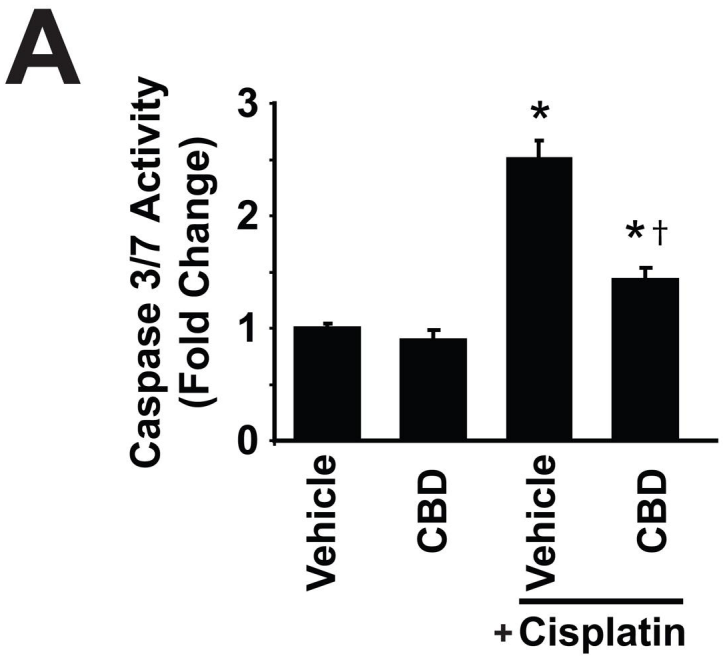

A
BUN(mg/dl)
200
100
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
Creatinine(mg/dl)
2
1
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
B
PAS staining
Vehicle
Cisplatin
Cisplatin+CBD
Tubular damage score
3
2
1
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 2


A
Caspase 3/7 Activity
(Fold Change)
3
2
1
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

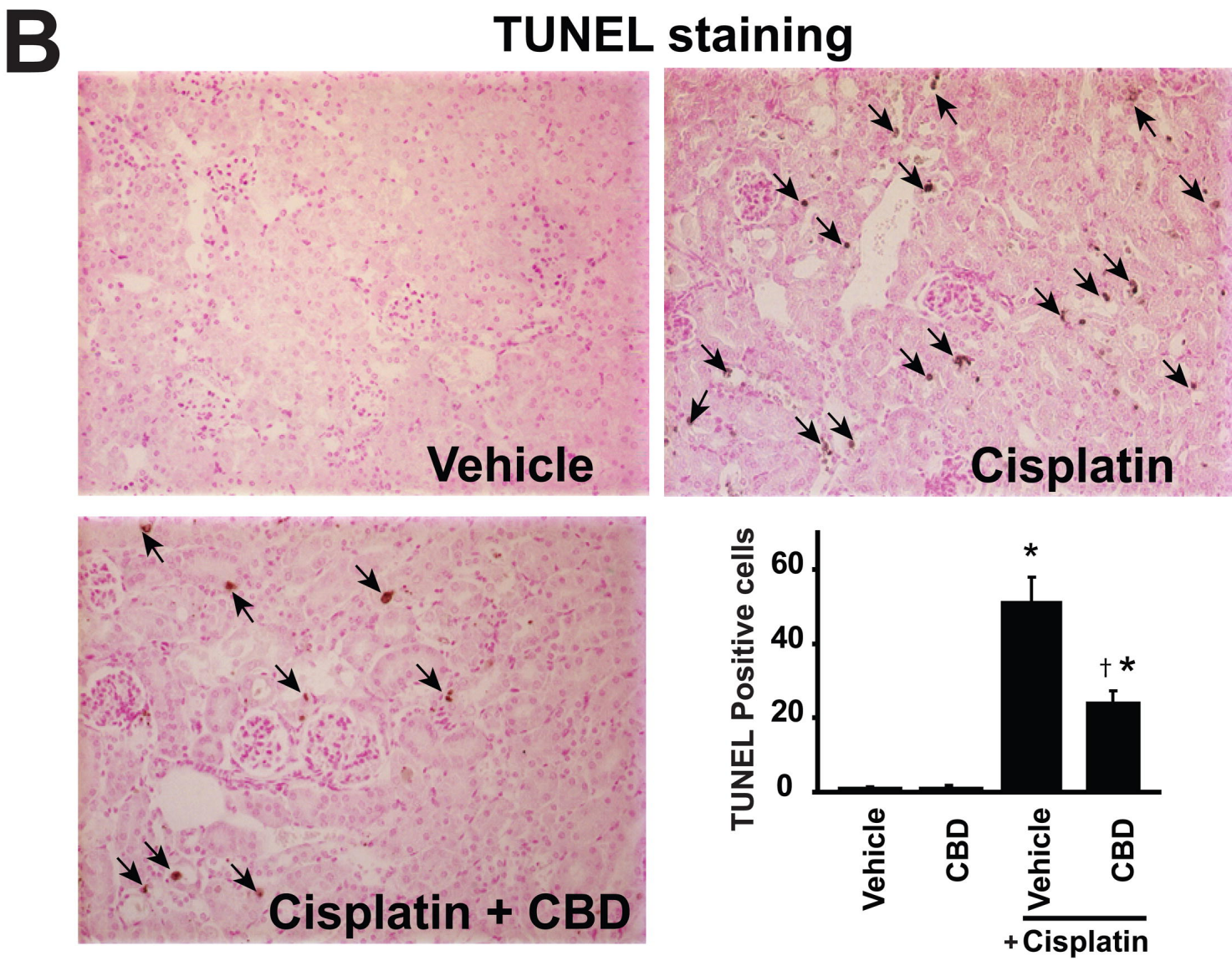

B
TUNEL staining
Vehicle
Cisplatin
Cisplatin + CBD
TUNEL Positive cells
60
40
20
0
*
†*
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 3

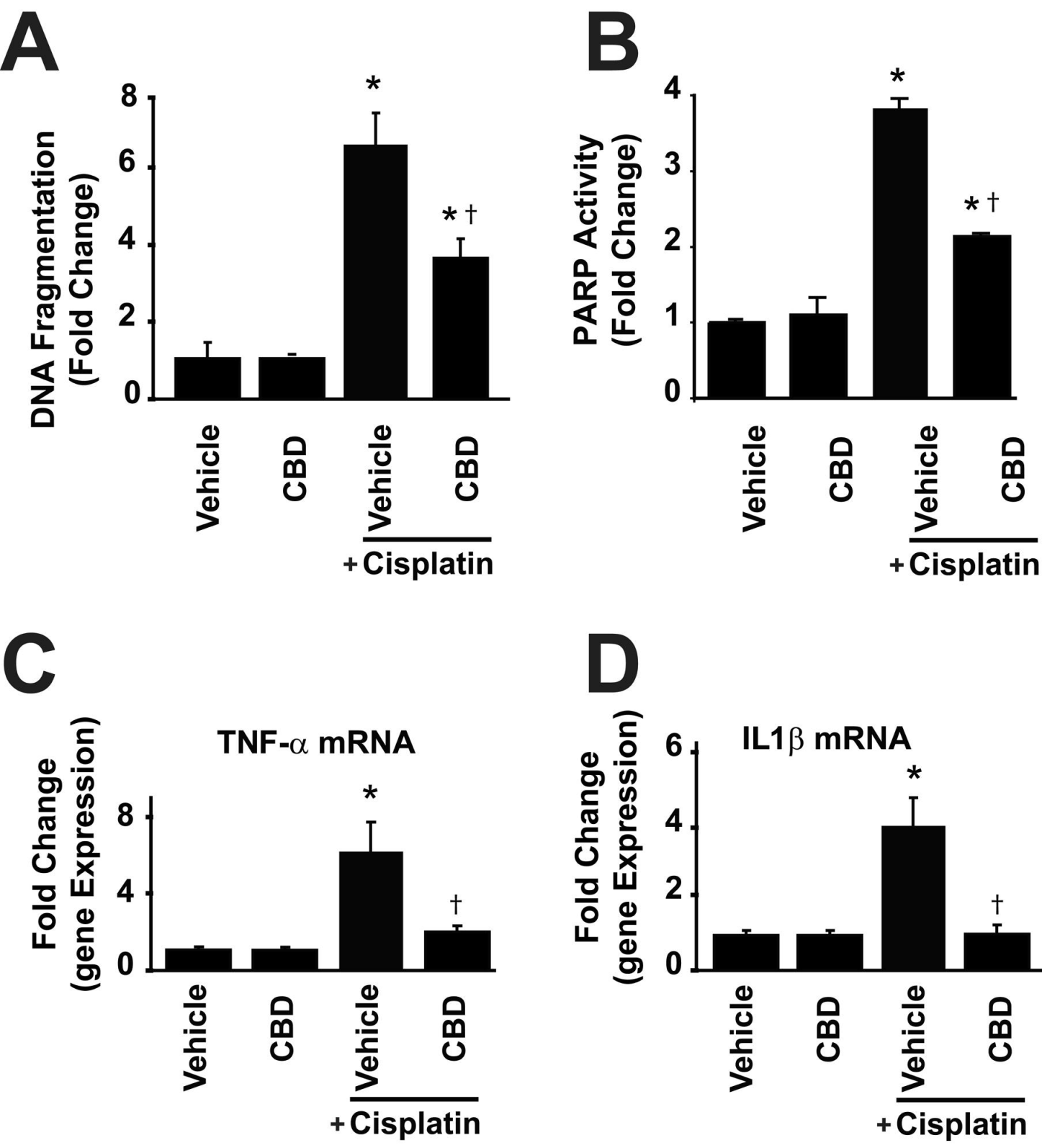

A
DNA Fragmentation
(Fold Change)
8
6
4
2
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
B
PARP Activity
(Fold Change)
4
3
2
1
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
C
TNF-α mRNA
Fold Change
(gene Expression)
8
4
0
*
†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
D
IL1β mRNA
Fold Change
(gene Expression)
6
4
2
0
*
†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 4

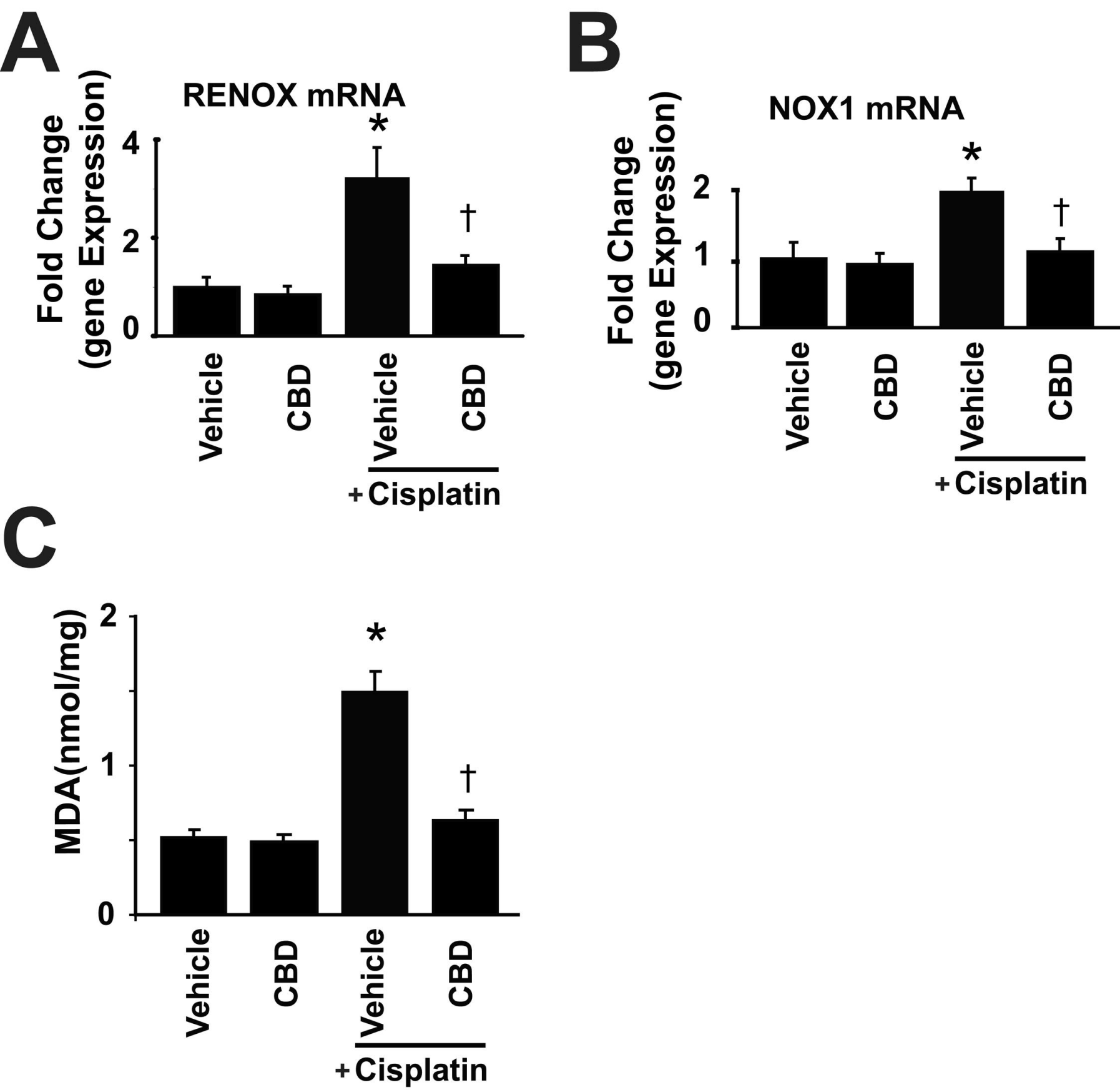

A
RENOX mRNA
Fold Change
(gene Expression)
4
2
0
*
†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
B
NOX1 mRNA
Fold Change
(gene Expression)
2
1
0
*
†
Vehicle
CBD
Vehicle
CBD
+Cisplatin
C
MDA(nmol/mg)
2
1
0
*
†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 5

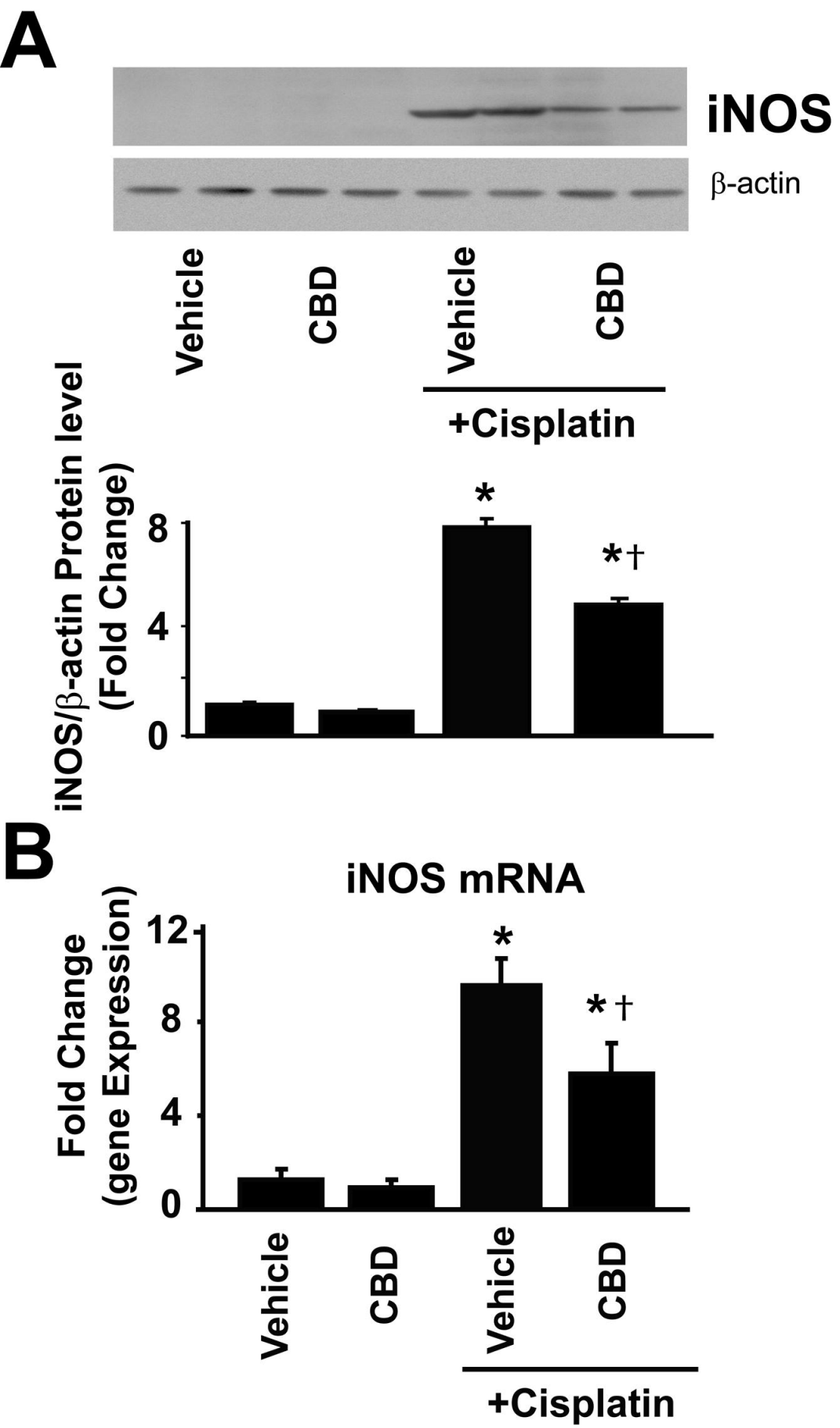

A
iNOS
β-actin
Vehicle
CBD
Vehicle
CBD
+Cisplatin
iNOS/β-actin Protein level
(Fold Change)
0
4
8
*
*†
B
iNOS mRNA
Fold Change
(gene Expression)
0
4
8
12
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 6

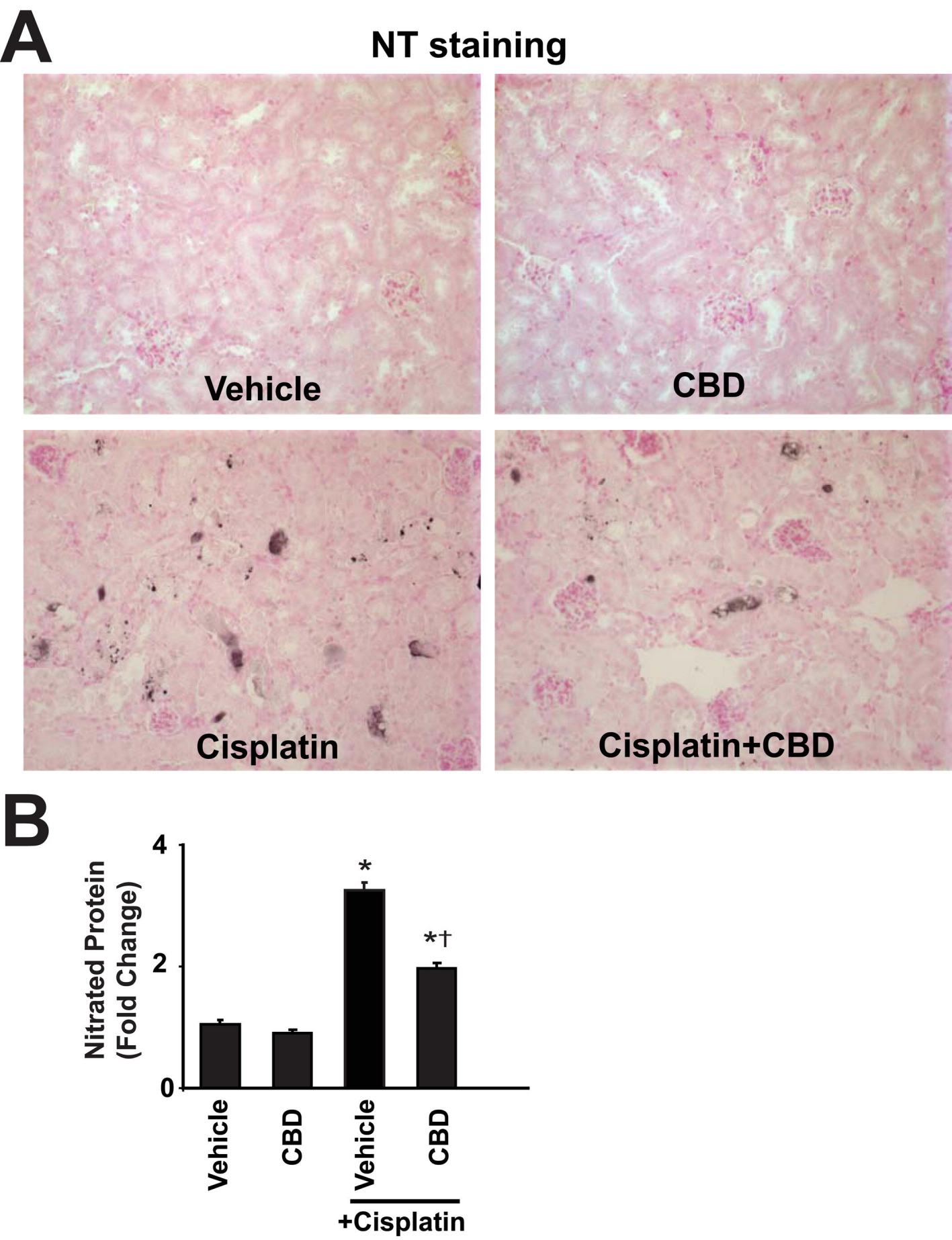

A
NT staining
Vehicle
CBD
Cisplatin
Cisplatin+CBD
B
Nitrated Protein
(Fold Change)
4
2
0
*
*†
Vehicle
CBD
Vehicle
CBD
+Cisplatin

Figure 7