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Captopril suppresses inflammation in endotoxin-induced uveitis in

rats

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ABSTRACT

Captopril is an inhibitor of angiotensin-converting enzyme (ACE) that is largely used in the treatment of cardiovascular diseases. Several previous studies have demonstrated that captopril exhibits a wide variety of biological activities, including an anti-inflammatory action, on which we focused our attention. The aim of the present study was to investigate the efficacy of captopril on endotoxin induced uveitis (EIU) in rats. We investigated its effect upon cellular infiltration and protein leakage, as well as on the concentration of tumor necrosis factor- α (TNF- α), nitric oxide (NO), prostaglandin E2 (PGE2), monocyte chemoattractant protein-1 (MCP-1) in the anterior chamber. In addition, we checked its effect on activation of nuclear factor kappa B (NF- κ B) in iris and ciliary body (ICB) cells in vivo.

EIU was induced in male Lewis rats by a footpad injection of lipopolysaccharide (LPS). One hour after the LPS inoculation, either 1 mg/kg, 10 mg/kg or 100 mg/kg captopril were injected intravenously. 24 hours later, the aqueous humor was collected from both eyes, and the number of infiltrating cells and protein concentration in the aqueous humor were determined. Levels of TNF- α , PGE2, NO and MCP-1 were

determined by enzyme-linked immunosorbent assay. On some eyes, after enucleation, immunohistochemical staining with a monoclonal antibody against activated NF- κ B was performed.

Captopril treatment significantly decreased the inflammatory cells infiltration, the level of protein, concentrations of TNF- α , PGE₂, NO and MCP-1 in the aqueous humor. The number of activated NF- κ B-positive cells was lower in ICB of the rats treated with captopril 3 hours after the LPS injection.

The present results indicate that captopril suppresses the inflammation in EIU by inhibiting the NF- κ B-dependent pathway and the subsequent production of pro-inflammatory mediators.

Introduction

Captopril([S]-1-[3-mercapto-2-methyl-1-oxo-propyl]-L-proline) is the first marketed orally active angiotensin-converting enzyme (ACE) inhibitor designed to treat hypertension by blocking the conversion of angiotensin I (Ang I) into angiotensin II (Ang II) (Cushman et al., 1977; Ondetti et al., 1977;

Cushman and Ondetti, 1999). It is widely used in the treatment of cardiovascular diseases, including high blood pressure, heart failure, coronary artery diseases, renal failure. Recently in the light of quickly emerging data on the variety of properties that local rennin-angiotensin system (RAS) and mainly Ang II exert in peripheral tissues, an interest in finding new therapeutic effects of the ACE inhibitors beyond the regulation of homeostasis arose. Captopril has been clearly shown to express immune regulating and anti-inflammatory properties. ACE inhibitors including captopril have proven to be beneficial in experimental autoimmune encephalomyelitis (Constantinescu et al., 1995), myocarditis (Godsel et al., 2003), adriamycin-induced myocardial and hematological toxicities (O. Al-Shabanah et al., 1998), Freund's adjuvant arthritis (Agha and Mansour, 2000) and experimental rats' colitis (Jahovic et al., 2005). The ability of captopril to act as a reactive oxygen species (ROS) scavenger (Mira et al., 1993) was found to be of major importance in its protection against ischemia-reperfusion-induced arrhythmias (Birincioglu et al., 1997) and liver injury in rats (Gulluoglu et al., 1996). An anti-tumor, antifibrotic

and cytoprotective effects of captopril have also been demonstrated (Williams et al., 2005; Regan et al., 1996; Murley et al., 2004).

The circulating RAS through its main effector Ang II plays a well-known role in the control of blood pressure, renal haemodynamics and homeostasis. Ang II is an octapeptide that has also been shown to play a key role in inflammation, cell growth, fibrosis in different tissues and cell lines including heart, vessels and kidney. It regulates the inflammatory response by production of pro-inflammatory mediators like cytokines, chemokines (Luft et al., 1999), adhesion molecules (Pueyo et al., 2000) and reactive oxygen species (Harrison et al., 2003, Bataller et al., 2003) and is thus considered to be a true cytokine (Ruiz-Ortega et al., 2001). Ang II can directly activate immune cells and regulate their functions inducing chemotaxis, proliferation, differentiation and phagocytosis (Mattana et al., 1995; Ruiz-Ortega et al., 2001; Suzuki et al., 2002; Ruiz-Ortega and Ortiz, 2005). Immune cells express all the components of RAS and can produce angiotensinogen (Gomez et al., 1993; Okamura et al., 1999). RAS components have been identified in human ciliary body and

aqueous humor (Cullinane et al., 2002) and involvement of RAS in ocular inflammation has been suggested by Nagai et al (Nagai et al., 2005), who proved the suppression of endotoxin-induced uveitis (EIU) by an angiotensin II type 1 receptor (AT1-R) inhibition.

Among the intracellular signals involved in Ang II-induced inflammatory response, the activation of nuclear factor kappa B (NF- κ B) is of special interest (Ruiz-Ortega et al., 2001). NF- κ B is a ubiquitous transcription factor with high reactivity potential that is most extensively exploited by immune cells (Baurel and Henkel, 1994). As a primary transcription factor NF- κ B responds directly to numerous extracellular stimuli (including lipopolysaccharide (LPS), reactive oxygen species (ROS) and AngII), rapidly transferring the external information via cytoplasmic/nuclear signaling to DNA where it positively regulates the expression of genes involved in the inflammatory and immune responses, including expression of tumor necrosis factor- α (TNF- α) (Collart et al, 1990; Shakhov et al., 1990; Baurel and Henkel, 1994), monocyte chemoattractant protein -1 (MCP-1), nitric oxide synthase

(NOS), cyclooxygenase-2 and angiotensinogen (Barnes, Karin, 1997; Guijarro, Egido, 2001). Interference in NF- κ B activation is proved to have beneficial effect in suppressing acute inflammatory processes. A significant upregulation of activated NF- κ B in the iris and ciliary body (ICB) during EIU has been demonstrated (Ohta et al., 2002). Inhibition of NF- κ B signaling pathway by astaxanthin, a carotenoid with antioxidant effects, leads to suppression of EIU in rats (Suzuki et al., 2005).

The EIU, which serves as an animal model for acute anterior ocular inflammation in humans, is induced by a systemic injection of a sublethal dose of LPS - an outer membrane component of Gram- negative bacteria and a potent activator of monocytes and macrophages (Rosenbaum et al, 1980). EIU is characterized by percolation of proteins from the serum and by infiltration of macrophages and neutrophils into the eye (Li et al, 1995). In Lewis rats with EIU, acute inflammation develops mainly in the anterior chamber (iridocyclitis) and inflammatory cells may also infiltrate the vitreous and retina (Tuailon et al., 2002). In general, EIU peaks 24 hours after LPS injection and subsides within

the next 96 hours.

LPS triggers the secretion of a variety of inflammatory mediators, such as TNF- α (Tracey and Cerami, 1994), prostaglandin E2 (PGE2) (Bellot et al, 1996); Murakami et al, 2000), MCP-1 (Tuailon et al, 2002), as well as the generation of ROS and excessive amounts of nitric oxide (NO) (Nathan and Xie, 1994), which all contribute to the pathophysiology of septic shock. The transcription of a significant number of these inflammatory mediators is triggered by the intracellular activation of NF- κ B.

In the present study we focused our attention on captopril's anti-inflammatory action and we investigated its effect on several well-described inflammatory markers in EIU.

Materials and Methods

Animal groups and EIU

Six-week-old male Lewis rats were used. The rats weighed 220 – 250 g. EIU was

induced by footpad injections of 200 µg of LPS (100 µg each footpad) from *Salmonella typhimurium* (Sigma, MO, USA) that had been diluted in 0.1 ml of phosphate buffered saline (pH7.4, PBS).

Rats were injected intravenously with 1 mg/kg, 10 mg/kg or 100 mg/kg of captopril (Calbiochem, CA, USA), diluted in 0.1 ml of PBS containing 0.1% dimethyl sulfoxide (DMSO, Sigma, MO, USA). The intravenous injection was administered 60 minutes after the LPS stimulation. For the LPS group and the control group, only PBS containing 0.1% DMSO was administered intravenously using the same schedule as for the captopril administered groups.

24 hours after the LPS injection, the rats were sacrificed and the aqueous humor (15-20 µl/rat) was collected from both eyes by an anterior chamber paracentesis using a 30 gauge needle.

Number of anterior chamber cells and protein concentration

For cell counting, the aqueous humor sample was suspended in an equal amount of Türk stain solution, and the cells were counted using a hemocytometer under a light

microscope; the number of cells per field (an equivalent of 0.01 ml) was manually counted, and the number of cells per microliter was obtained by averaging the results of four fields from each sample.

The total protein concentration in the aqueous humor was determined by BCA protein assay reagent kit (Pierce, Rockford, IL, USA).

The levels of TNF- α , PGE2 and MCP-1

The levels of TNF- α , PGE2 and MCP-1 concentration in aqueous humor were measured by ELISA (R&D systems, MN, USA) according to the manufacturer's instruction. The ELISA assays were carried out in duplicate.

Determination of nitrite concentration in the aqueous humor

NO was measured as its end product, nitrite, by using Griess reagent as described elsewhere (Sigma, MO, USA). The culture supernatant (100 μ l) was mixed with 100 μ l of Griess reagent for 10 min, and the absorbance at 550 nm was measured in a microplate reader. The concentration of nitrite in the samples was determined with

reference to a sodium nitrite standard curve. The data represent the mean of 8 rats \pm SD.

Immunohistochemical studies for NF- κ B

Three hours after the LPS injection, rats were anesthetized with pentobarbital sodium (30 mg/kg) and the eyes were fixed by an intracardiac perfusion of 4% paraformaldehyde in 0.1 M PBS. The eyes were enucleated and immersed in the same fixative for 12 hours. After dehydration and paraffin embedment of the eyes, 5 μ m sagittal sections near the optic nerve head were obtained, slices were rinsed twice in PBS and incubated with normal goat serum, followed by p65 antibody (Santa Cruz, c-20, CA, USA). Binding of the primary antisera was localized using Cy-3 conjugated goat anti-rabbit IgG (Jackson ImmunoResearch Laboratories, Inc, West Grove, PA, USA). Nuclei were then stained with PBS containing YO-PRO-1 (Molecular Probes, Eugene, OR, USA) for 5 min. The sections were examined by laser scanning confocal microscopy (MRC-1024: Bio-Rad, Richmond, CA, USA; and LSM 510: Carl Zeiss, Oberkochen, Germany). Within each ICB sample, two areas were randomly photographed and the number of activated NF- κ B positive cells (NF- κ B having entered

the nuclei resulted in changing green nuclei color into orange) was counted by a masked researcher. The results were averaged for each sample and in each group. This analysis was performed in the six eyes of three rats in each group.

Statistical Analysis

The results were expressed as mean \pm S.D. All data were analyzed by analysis of variance (ANOVA), followed by Scheffe`s test for multiple comparing. A p value lower than 0.05 was considered statistically significant.

Results

Number of inflammatory cells and protein concentration in aqueous humor

In the LPS group, the number of inflammatory cells in aqueous humor 24 hours after LPS treatment was $102.9 \pm 15.1 \times 10^5$ cells/ml (mean \pm SD, n = 8) and the protein concentration was 49.1 ± 8.7 mg/ml. The groups treated with captopril showed very significantly reduced numbers of inflammatory cells (captopril 1 mg/kg: $3.1 \pm 3.6 \times 10^5$ cells/ml; captopril 10 mg/kg: $0.8 \pm 0.6 \times 10^5$ cells/ml; captopril 100 mg/kg: $0.8 \pm 0.6 \times$

10^5 cells/ml) compared to the LPS group ($p < 0.01$, Fig. 1a) and protein concentration (1 mg/kg: 17.2 ± 4.4 mg/ml, $p < 0.01$; 10 mg/kg: 13 ± 3.7 mg/ml; 100 mg/kg: 8.6 ± 1.9 mg/ml; Fig.1b). No infiltrating cells were detected in aqueous humor of non-LPS treated rats (control group) and the level of protein detectable was 2.9 ± 1.5 mg/ml (n=8).

TNF- α , PGE2 and nitrite concentrations in aqueous humor

In the aqueous humor of the control group of rats TNF- α was not detected. In the LPS group its concentration reached 1.2 ± 0.5 ng/ml, while captopril groups showed a significant reduction in the TNF- α levels (1 mg/kg captopril: 0.1 ± 0.1 ng/ml ($p < 0.01$), in the 10 mg/kg captopril and 100 mg/kg captopril treated groups TNF- α was not detectable (Fig. 2a). The concentration of PGE2 in the control group was 0.4 ± 0.1 ng/ml and in the LPS group it was increased to 9.6 ± 4.4 ng/ml. PGE2 levels were also significantly reduced by captopril: 1 mg/kg captopril: 0.4 ± 0.2 ng/ml ($p < 0.01$); 10 mg/kg captopril: 0.4 ± 0.2 ng/ml; 100 mg/kg captopril: 0.3 ± 0.1 ng/ml, (Fig.2b). The content of nitrite in the aqueous humor of control rats was 7.8 ± 3.4 μ M and it rose about 20 fold

in the LPS group ($156.6 \pm 25.4 \mu\text{M}$, $p < 0.01$). Nitrite levels in the aqueous humor 24 hours after captopril treatment were: 1 mg/kg captopril: $90.7 \pm 15.8 \mu\text{M}$, $p < 0.01$; 10 mg/kg captopril : $77.8 \pm 35.9 \mu\text{M}$; 100 mg/kg captopril: $34.8 \pm 24.4 \mu\text{M}$ (Fig.2c).

MCP-1 in aqueous humor

No MCP-1 was detected in the control group of rats while in the LPS group the MCP-1 level was $13.4 \pm 1.2 \text{ pg/ml}$ (Fig.3). Captopril groups had significantly ($p < 0.01$) reduced levels of MCP-1 (1 mg/kg captopril: $6.1 \pm 1.3 \text{ pg/ml}$; 10 mg/kg captopril: $1.0 \pm 0.5 \text{ pg/ml}$; 100 mg/kg captopril: $0.5 \pm 0.1 \text{ pg/ml}$).

Suppression of NF- κ B activation in ICB

No activated NF- κ B-positive nuclei were found in the ICB of normal controls (Fig. 4 Aa, 4B). Three hours after injection of LPS activated NF- κ B p65 was strongly expressed in the ICB of the LPS group ($42.7 \pm 3.2\%$, Fig. 4Ab, 4B). In contrast, the percentage of activated NF- κ B-positive cells was significantly lower in the ICB of rats treated with 100mg/kg captopril ($13.1 \pm 5.4\%$ ($p < 0.01$), (Fig. 4Ac, 4B). The groups treated with lower doses of captopril showed reduction of NF- κ B-positive cells

percentage (1mg/kg: $31.1 \pm 6.4\%$; 10mg/kg: $29.8 \pm 11.3\%$), which was not significant (Fig. 4B).

Discussion

The results of this study suggest that the ACE-inhibitor captopril has a strong anti-ocular inflammatory effect in EIU. We demonstrated for the first time that captopril suppressed the NF- κ B activation in iris and ciliary body cells and it also drastically lowered leucocyte infiltration, protein leakage and certain other inflammatory markers (TNF- α , PGE-2, MCP-1, NO) in aqueous humor in a dose-dependant manner.

The exact mechanism by which captopril suppresses EIU is yet to be established, but our results support the findings that it acts via interfering with NF- κ B pathway activation most probably by blocking the local Ang II production. The specific down-regulation of ACE by captopril has been demonstrated in human dendritic cells and its inhibitory properties have been attributed to its structure containing thiol groups that provide specific binding to ACE as well as to indirect suppression of expression of gene encoding ACE (Lapteva et al., 2002). Ang II rapidly activates NF- κ B (Kranzhofer

et al., 1999) through angiotensin II type 1 (AT-1) and angiotensin II type 2 (AT-2) receptors (De Gasparo et al., 2000; Murphy et al., 1991). Ang II stimulation upregulates PYRIN mRNA (the family member of PYRIN- containing Apaf-1-like proteins) that participates in inflammatory cell signaling by regulating the activation of NF- κ B and cytokine processing (Steinman, 1988; Wang et al, 2002). Reactive oxygen species are regarded as second messengers in NF- κ B activation and cytokine expression (Schreck et al., 1991; Satriano et al., 1993). Ang II stimulates ROS production thus activating different nuclear responses (Puri et al., 1995; Griending and Ushio-Fukai, 2000; Saito and Berk, 2002). A possible mechanism of protecting the NF- κ B activation and inflammatory cascade generation by captopril is the scavenging of ROS.

NF- κ B is comprised of a family of proteins that bind as homo- or heterodimers to κ B-enhancing elements in promotor regions of selected genes. These include RelA (p65), RelB, c-Rel, p52, p50. Under normal conditions in most cells NF- κ B is found in an inactive form in the cytoplasm, bound to the inhibitory I κ B protein. Upon stimulation by a wide variety of signals including LPS and Ang II, NF- κ B moves into the nucleus where it triggers the various pro-inflammatory genes`

transcription. Our immunohistochemical experiment demonstrated that LPS induced p65 nuclear translocation was significantly prevented in the ICB by the high dose captopril. It also showed a tendency towards reduction in the lower-concentration treated groups, but the results did not differ significantly from the LPS group.

TNF- α is a 185 amino acid glycoprotein cytokine that plays a leading role in activation and sustaining inflammatory responses. It is shown to stimulate inflammatory cells recruitment, synthesis of cytokines, eicosanoids and NO. It has recently been reported that symptoms of Behcet's disease uveitis had remarkably been ameliorated by administration of anti-TNF- α antibody (Ohta et al., 2004). The transcription of TNF- α is under NF- κ B control and there is a positive loop, amplifying the cytokine cascade during inflammation as TNF- α is also found to activate NF- κ B (Baurele and Henkel, 1994; Baldwin, 1996; Barnes and Karin, 1997). It has previously been established that ACE inhibitors suppress TNF- α synthesis in vivo and in vitro (Fukuzawa et al., 1997) and in this study captopril successfully down-regulated TNF- α in the aqueous humor, most probably by interfering in the generation of the positive loop between TNF- α and NF- κ B, confirming its anti-inflammatory properties in the eye also.

We investigated the concentration of PGE2 and NO in aqueous humor, which were also significantly down-regulated by captopril treatment. Both PGE2 and NO have a profound effect on local inflammatory processes mainly by vascular permeability regulation and they have been shown to contribute to the breakdown of blood-aqueous barrier in uveitis (Smith et al., 1998, Tilton et al., 1994). The expression of the inducible enzymes, responsible for their synthesis (COX-2 and iNOS respectively), is also controlled by NF- κ B. Bellot et al (Bellot et al., 1996) reported that PGE2 and NO have an additive effect in EIU in rabbits and that inhibition of both pathways would improve the therapeutic management of uveitis. Therefore our data suggest that the suppressed ocular inflammation can be attributed in part to the down-regulation of these mediators by captopril.

Similarly, another inflammation marker, which we measured, MCP-1, is also under NF- κ B control. MCP-1 is an important mediator of monocyte infiltration (Gu et al., 1999) and is shown to be over-expressed in human eyes during acute anterior uveitis (Verma et al., 1997) as well as in the rat EIU model (de Vos et al., 1994). The results of this study show that captopril successfully down-regulates MCP-1 levels in anterior

chamber, thus showing its anti-inflammatory properties also by affecting monocyte recruitment in EIU.

The present study shows that captopril is capable of suppressing EIU in rats.

There has been a continuous search for new anti-ocular inflammatory drugs as the most effective and widely exploited corticosteroids show numerous adverse effects in their prolonged clinical usage in treating inflammatory conditions. Our data suggest that captopril can be addressed as a promising agent for the treatment of ocular inflammation. Further investigations on captopril as well as on other ACE inhibitors in acute (EIU) and chronic uveitis models (experimental autoimmune uveitis) are appealing to us.

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FIGURE LEGENDS

Figure 1. Effect of captopril on LPS induced inflammatory cellular infiltration (a) and protein concentration (b) in the aqueous humor. 24 hours after LPS treatment. Each value represents the mean \pm SD (n=8).

**Significantly different from LPS group, (p<0.01).

Figure 2. Effect of captopril on LPS induced TNF- α (a), PGE2 (b) and Nitrite concentration ((c), as a NO measure) in the aqueous humor 24 hours after LPS treatment. Each value represents the mean \pm SD (n=8).

**Significantly different from LPS group, (p<0.01).

Figure 3. Effect of captopril on LPS induced MCP-1 concentration in the aqueous humor 24 hours after LPS treatment. Each value represents the mean \pm SD (n=8).

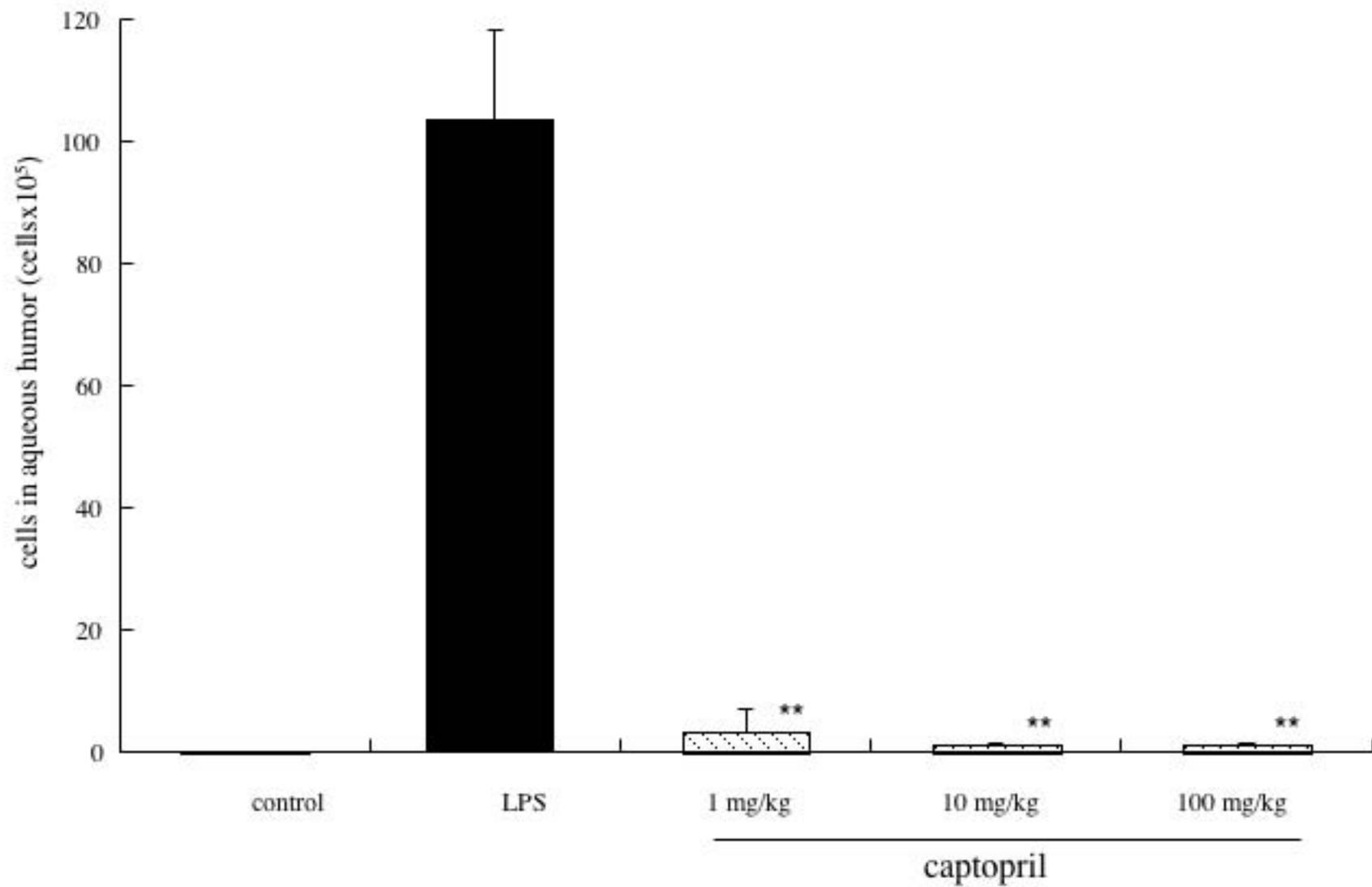
**Significantly different from LPS group, (p<0.01).

Figure 4. Effect of captopril on NF- κ B p-65 activation in the ICB 3 hours after LPS

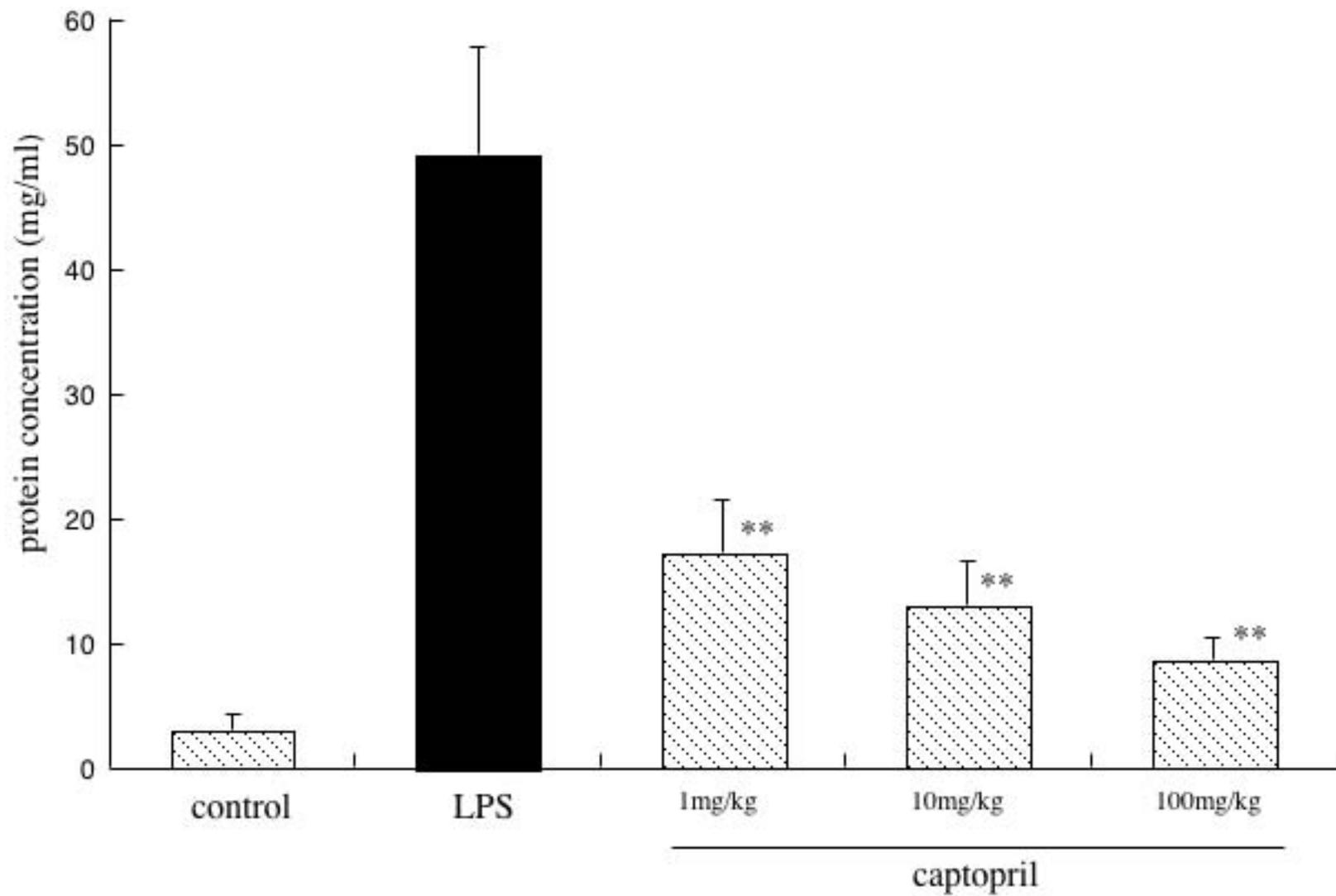
injection. A: Immunohistochemistry of NF- κ B p-65 (red) in the ICB. Dual immunofluorescence labeling showed the colocalisation (yellow) in nuclei (green). (a) control group - no LPS treatment. (b) LPS group – rats injected with LPS and 1 hour later with 0.1 ml PBS. (c) captopril-treated group – rats injected with LPS and 1 hour later with 0.1 ml captopril, diluted in PBS (100mg/kg captopril). Magnification: x400.

Arrows: activated (NF- κ B-positive) cells. B: Quantitative analysis of the percentage of NF- κ B-positive cells in ICB. Each value represents the mean \pm SD (n=3).

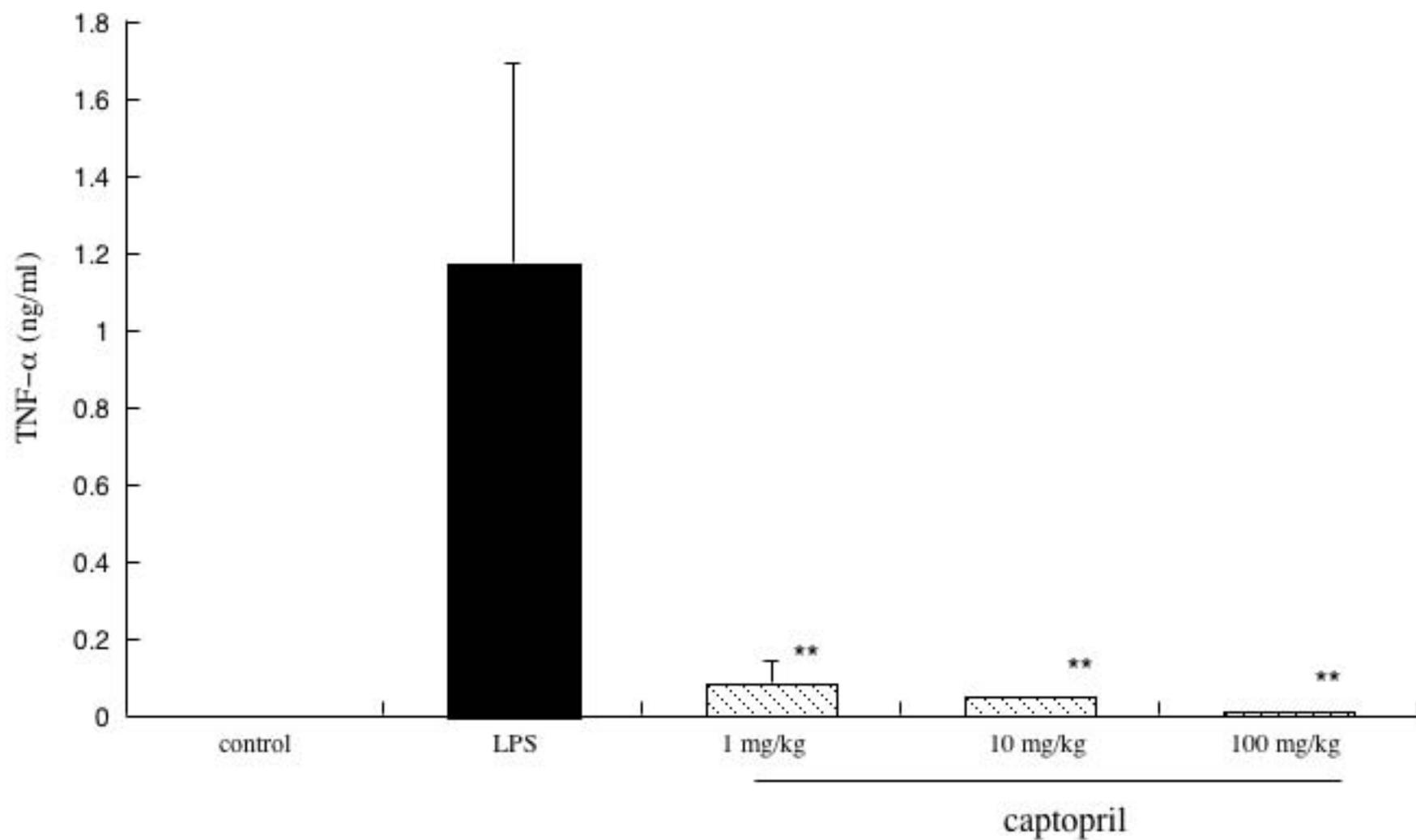
**Significantly different from LPS group, (p<0.01).



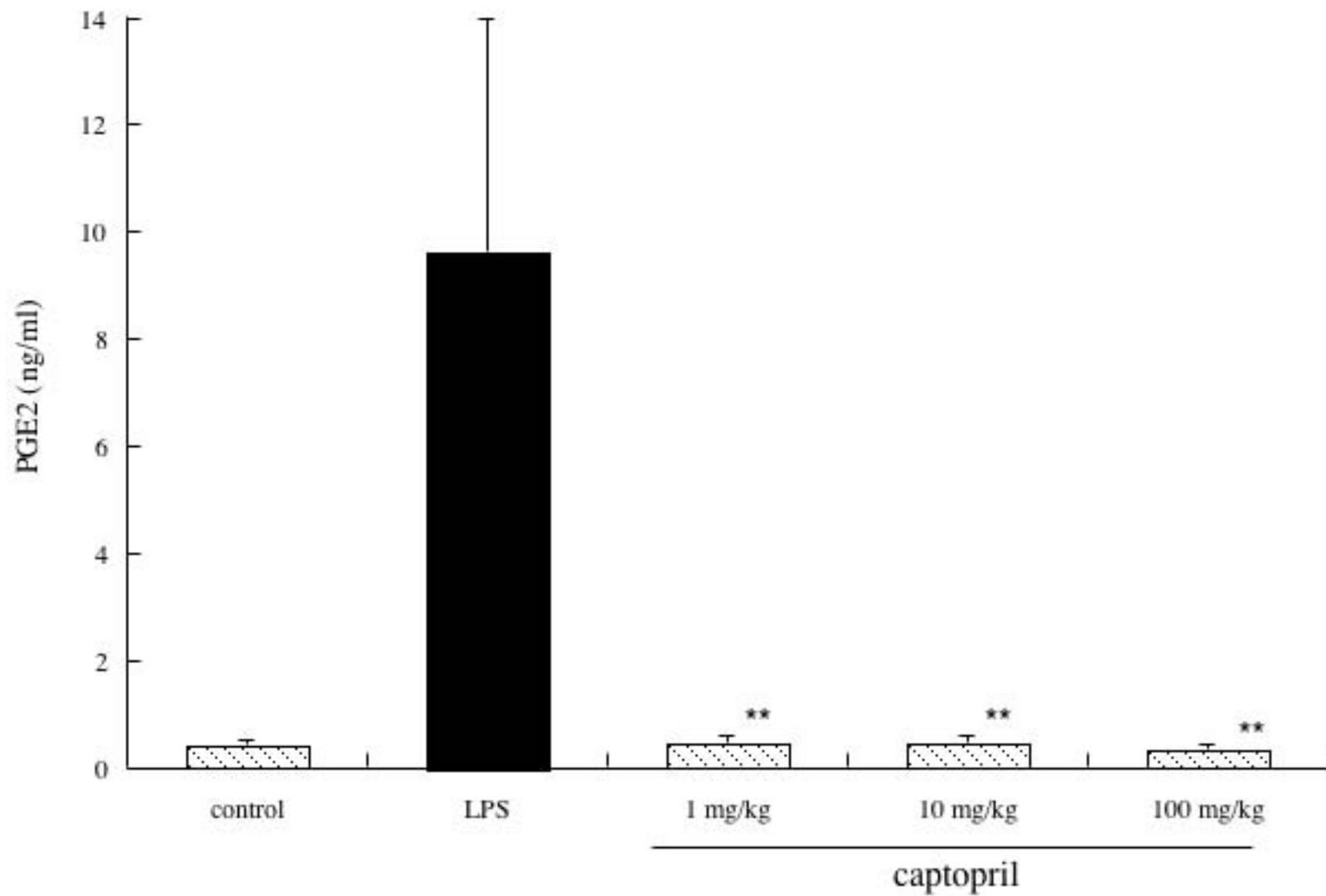
[Fig. 1a Ilieva et al]



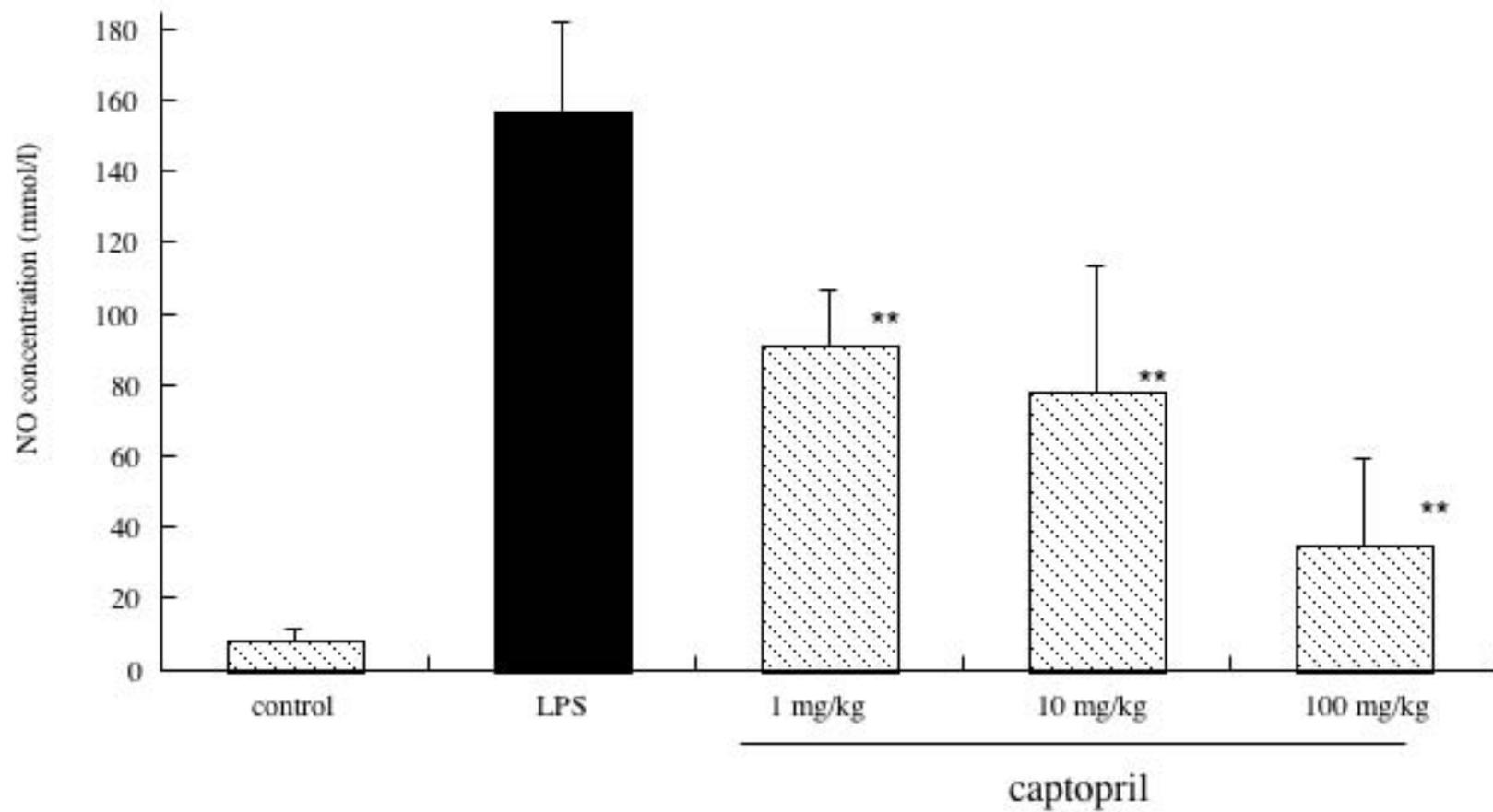
[Fig. 1b Ilieva et al]



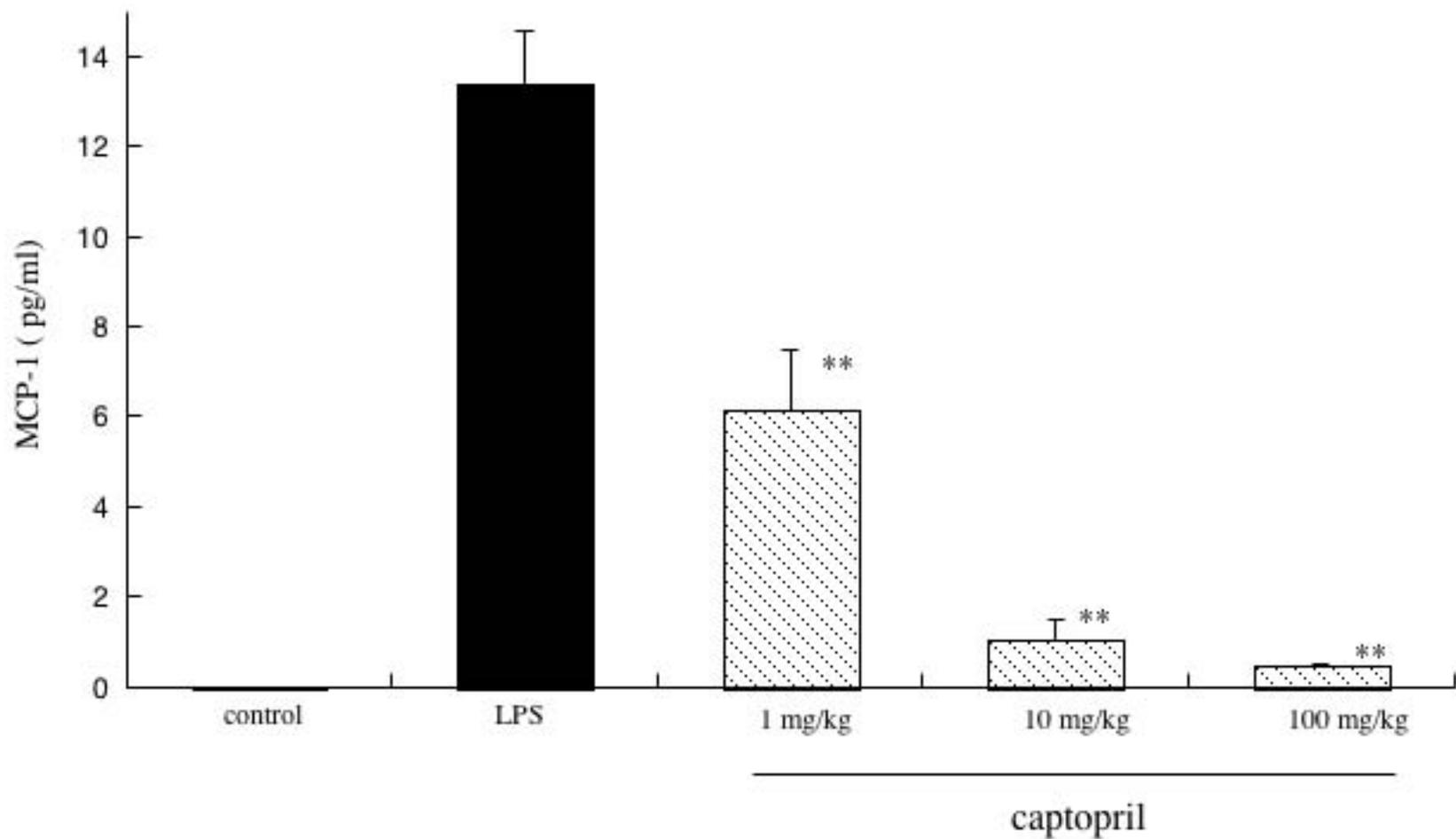
[Fig. 2a Ilieva et al]



[Fig. 2b Ilieva et al]

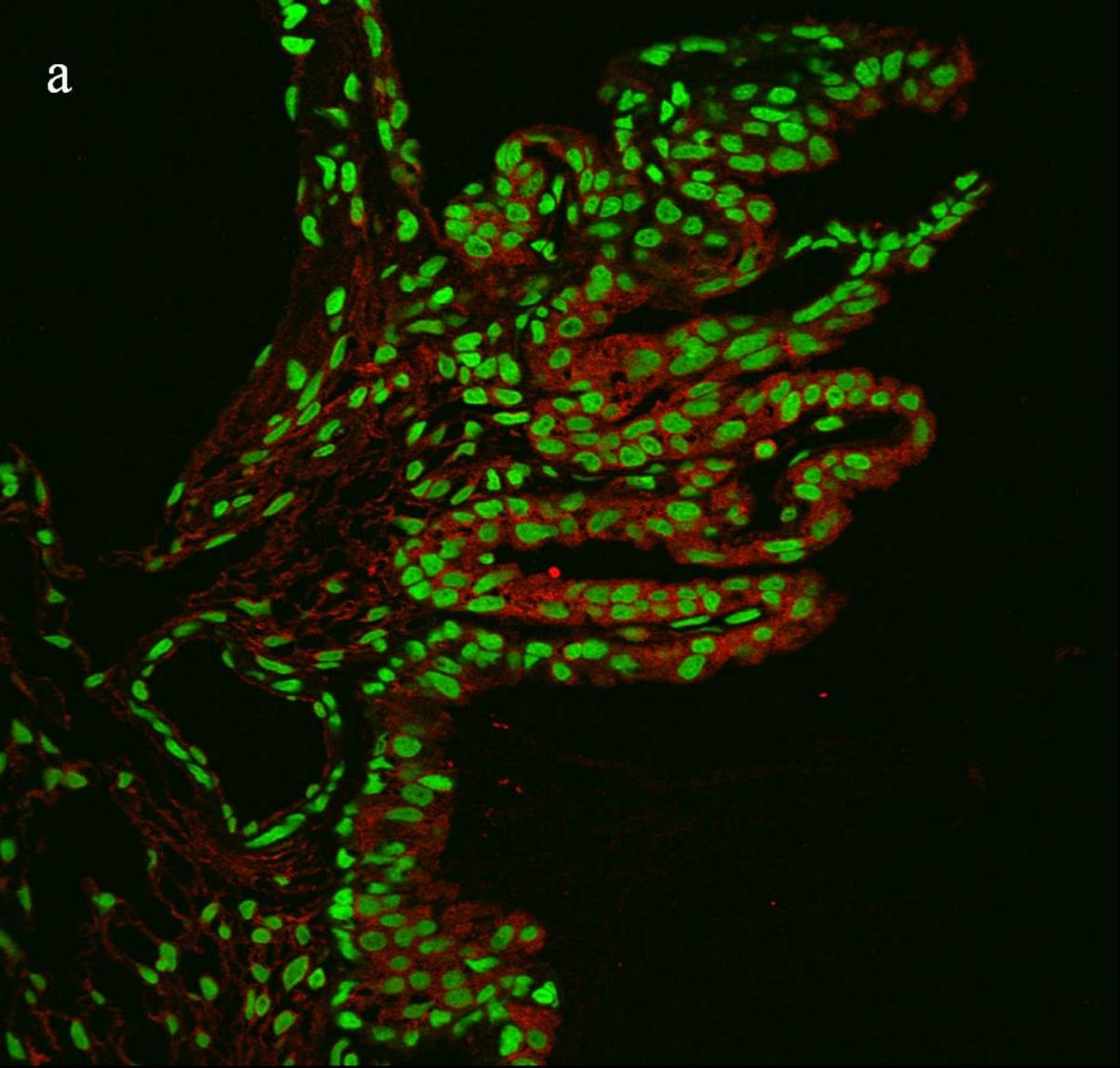


[Fig. 2c Ilieva et al]

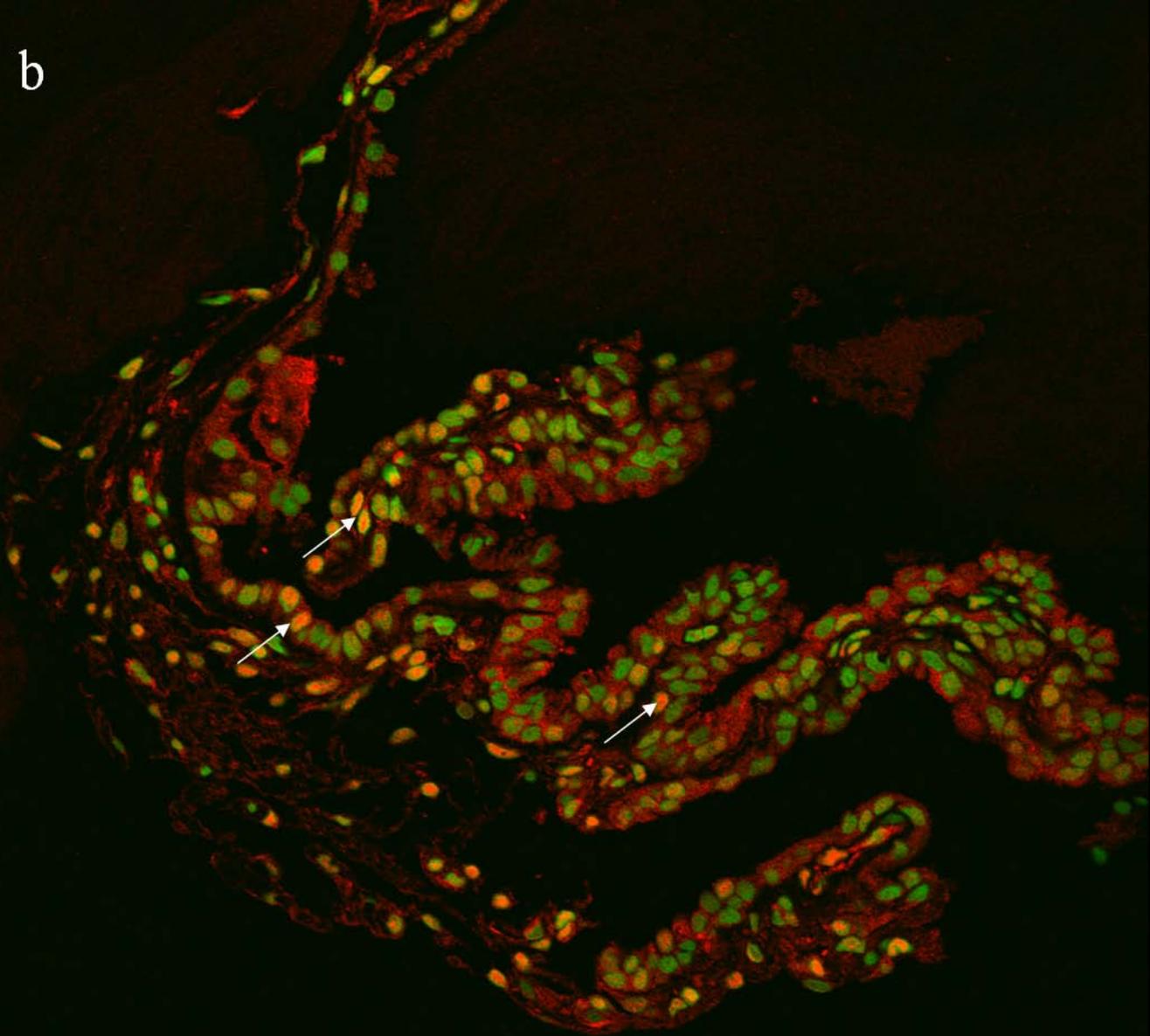


[Fig.3 Ilieva et al]

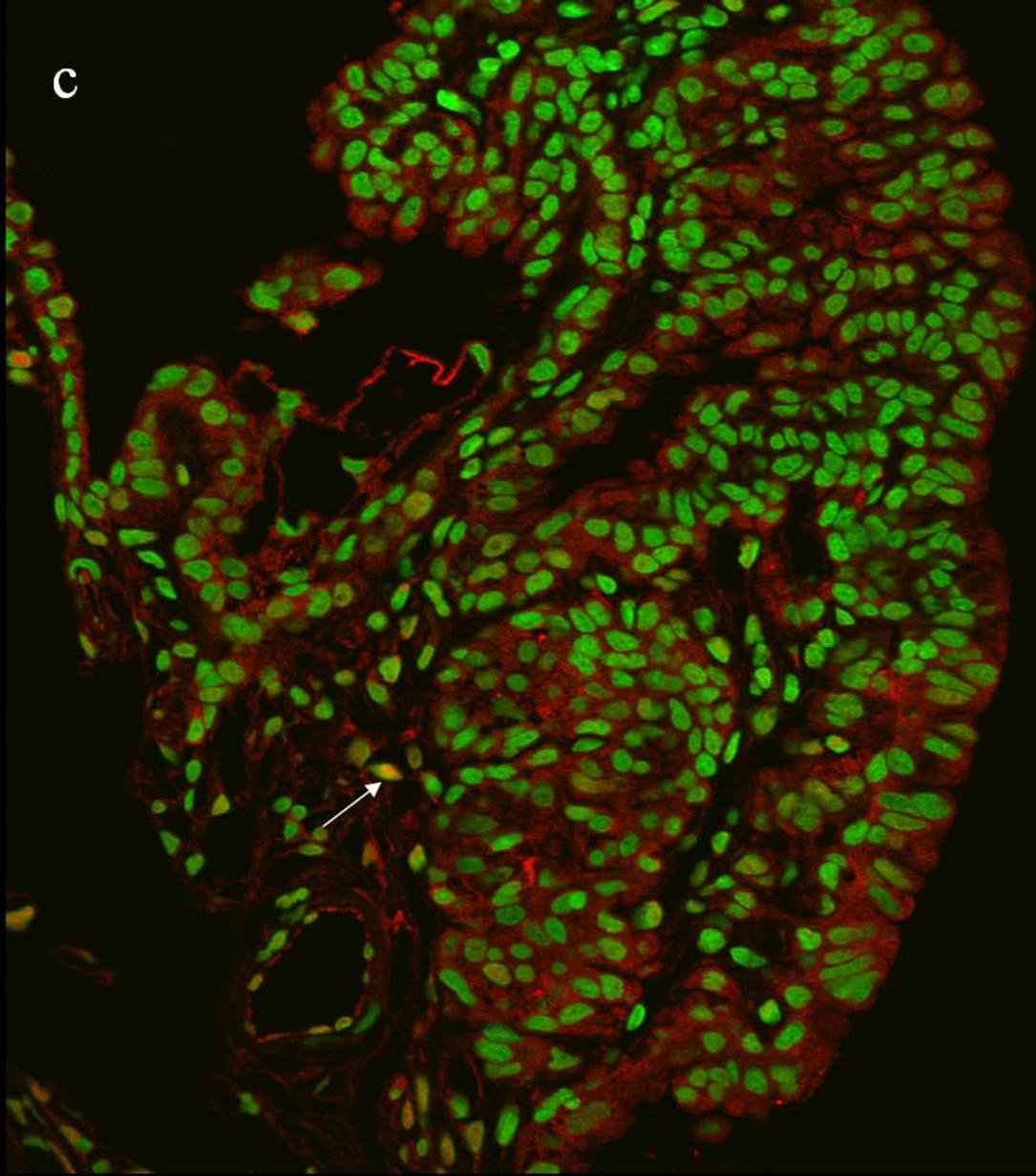
a

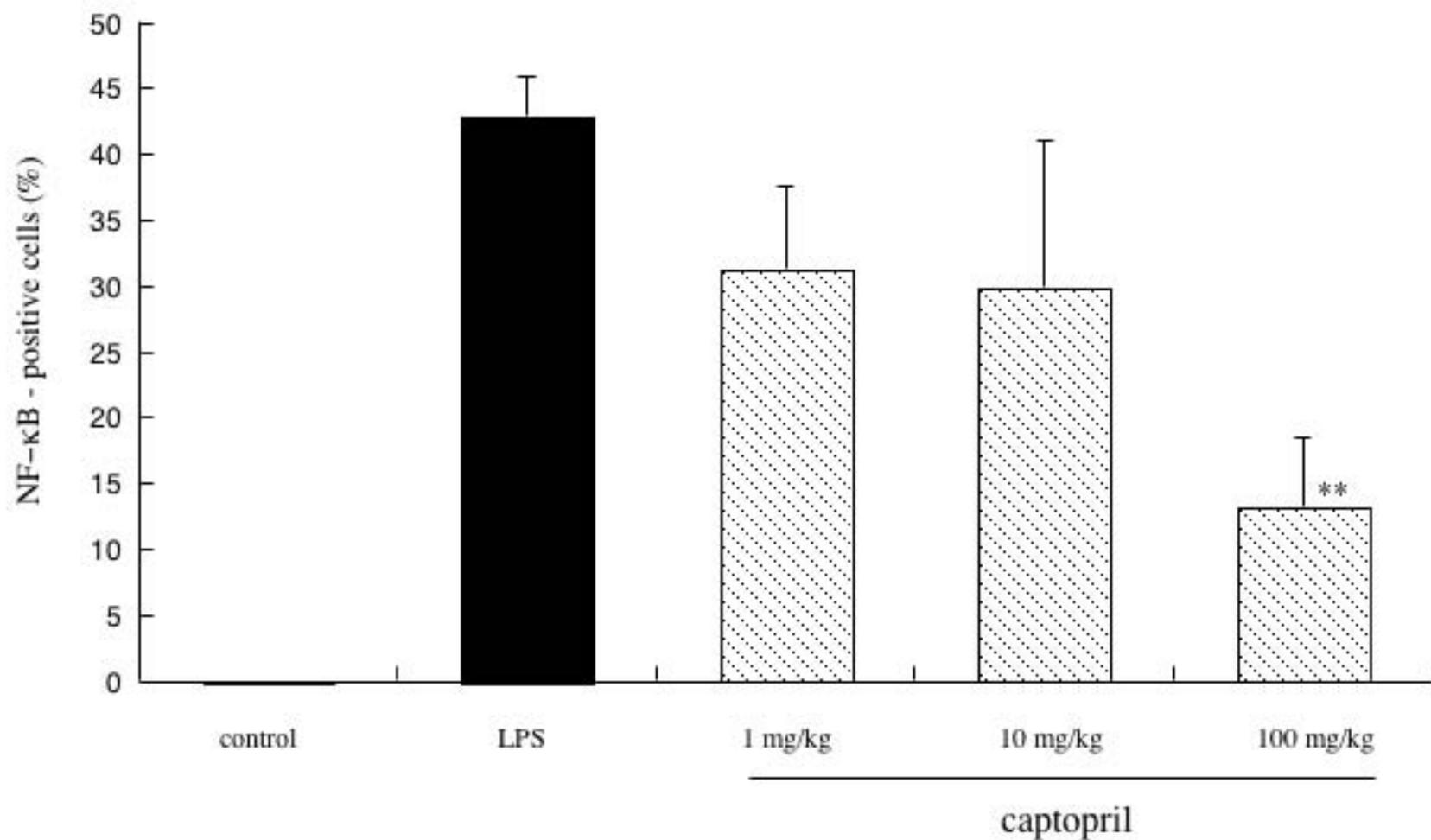


b



C





[Fig. 4B Ilieva et al]