Pivotal Role of the a2A-Adrenoceptor in Producing Inflammation and Organ Injury in a Rat Model of Sepsis

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Abstract

Background: Norepinephrine (NE) modulates the responsiveness of macrophages to proinflammatory stimuli through the activation of adrenergic receptors (ARs). Being part of the stress response, early increases of NE in sepsis sustain adverse systemic inflammatory responses. The intestine is an important source of NE release in the early stage of cecal ligation and puncture (CLP)-induced sepsis in rats, which then stimulates TNF-α production in Kupffer cells (KCs) through the activation of the α2-AR. It is important to know which of the three α2-AR subtypes (i.e., α2A, α2B or α2C) is responsible for the upregulation of TNF-α production. The aim of this study was to determine the contribution of α2A-AR in this process.

Methodology/Principal Findings: Adult male rats underwent CLP and KCs were isolated 2 h later. Gene expression of α2A-AR was determined. In additional experiments, cultured KCs were incubated with NE with or without BRL-44408 maleate, a specific α2A-AR antagonist, and intraportal infusion of NE for 2 h with or without BRL-4408 maleate was carried out in normal animals. Finally, the impact of α2A-AR activation by NE was investigated under inflammatory conditions (i.e., endotoxia and CLP). Gene expression of the α2A-AR subtype was significantly upregulated after CLP. NE increased the release of TNF-α in cultured KCs, which was specifically inhibited by the α2A-AR antagonist BRL-44408. Equally, intraportal NE infusion increased TNF-α gene expression in KCs and plasma TNF-α which was also abrogated by co-administration of BRL-44408. NE also potentiated LPS-induced TNF-α release via the α2A-AR in vitro and in vivo. This potentiation of TNF-α release by NE was mediated through the α2A-AR coupled Gsα protein and the activation of the p38 MAP kinase. Treatment of septic animals with BRL-44408 suppressed TNF-α, prevented multiple organ injury and significantly improved survival from 45% to 75%.

Conclusions/Significance: Our novel finding is that hyperresponsiveness to α2-AR stimulation observed in sepsis is primarily due to an increase in α2A-AR expression in KCs. This appears to be in part responsible for the increased proinflammatory response and ensuing organ injury in sepsis. These findings provide important feasibility information for further developing the α2A-AR antagonist as a new therapy for sepsis.

Introduction

Sepsis and septic shock are complications and considered to be major causes of morbidity and mortality in patients with severe trauma, burns, or blood loss [1]. Tissue-fixed macrophages such as the hepatic Kupffer cells (KCs) are involved in inflammatory and metabolic responses to sepsis [2,3]. The impairment of hepatocellular function observed in early sepsis appears to be due to upregulation of proinflammatory cytokines such as TNF-α [4,5]. We [6] and Kovarik et al. [7] reported that systemic levels of norepinephrine (NE) increased significantly after the onset of sepsis, induced by cecal ligation and puncture (CLP). Enterectomy prior to the onset of sepsis markedly reduced circulating levels of NE, showing that the gut is a major source of NE in sepsis [8]. The catecholamines NE and epinephrine mediate their physiological responses through a group of adrenergic receptor (AR) subtypes [9]. Studies have suggested that NE at concentrations similar to those found in septic animals (~20 nM) mainly stimulate α2-adrenergic receptors (ARs). In our previous studies, we reported that gut-derived NE upregulates TNF-α production in KCs through the α2-adrenergic pathway [9]. This is a novel finding, since the immunological effect of the sympathetic nerve activity and the adrenal epinephrine was previously considered to be anti-inflammatory through the activation of β-ARs on leukocytes [10]. α2-ARs are G-protein coupled receptors that mediate the central and peripheral actions of the primary sympathetic neurotransmitter, NE, and the adrenal hormone epinephrine through the intracellular suppression of cAMP [11]. However, it remains
unknown which of the three α2-AR subtypes (i.e., α2A, α2B or α2C) is responsible for the upregulation of TNF-α production. The aim of this study was therefore to determine the contribution of α2A-AR in NE-mediated proinflammatory effects in sepsis.

**Materials and Methods**

**Experimental model of sepsis**

Polymicrobial sepsis was induced in adult male rats by cecal ligation and puncture (CLP). Briefly, rats were fasted overnight prior to the induction of sepsis, but allowed water ad libitum. The animals were anesthetized with isoflurane inhalation and a 2-cm ventral midline abdominal incision was made. The incision was closed in layers and the animals were resuscitated with 3 ml/100 g BW normal saline subcutaneously immediately after CLP [12]. This model of sepsis is associated with an early, hyperdynamic phase (i.e., 2–10 h after CLP; characterized by increased cardiac output and tissue perfusion, decreased vascular resistance, and hypoglycemia) [5,13,14]. Sham-operated animals underwent the same surgical procedure except that the incision was neither ligated nor punctured. Studies were then conducted at 2 h (early sepsis) and 20 h (late sepsis) after the induction of sepsis. This project was approved by the Animal Care and Use Committee of the Feinstein Institute for Medical Research and following national guidelines for the use of animals in research.

**Isolation of Kupffer cells**

Kupffer cells were isolated from normal and septic rats as previously described elsewhere with some modifications [12]. Briefly, under isoflurane anesthesia, following a midline incision the inferior vena cava was cannulated and the portal vein was severed. The liver was immediately perfused in situ with ~60 ml of Hanks balanced salt solution without Ca2+ and Mg2+ (Celiorgo, VA) at 37°C at a rate of 15 ml/min. This was followed by perfusion with 120 ml of HBSS containing 0.02% collagenase (Worthington, Lakewood, NJ; Type IV, 180 U/mg) and 100 mM CaCl2 solution at the same perfusion rate. The liver was then removed en bloc, rinsed with ~25 ml of HBSS, minced in a petridish containing HBSS with collagenase, and incubated for 20 min at 37°C to further dissociate the cells. The cell suspension was then passed through a 150-mesh, stainless steel screen into cold Dulbecco modified Eagle medium (DMEM; Gibco Life Technologies, Carlsbad, CA), containing 10% heat-inactivated fetal bovine serum and centrifuged (50 g for 2 min at 4°C) to sediment hepatocytes. The remaining cells in the supernatant were collected by centrifugation (450 g for 10 min at 4°C). The cell pellets resuspended in DMEM. After washing twice, cells were centrifuged on a density cushion of Percoll at 1,000 g for 15 min at 4°C. The buffy coat containing the KCs fraction was collected. The cells were further washed twice. Cell viability as determined by trypan blue exclusion was more than 95%. The yield was at 8–12×10⁶ KCs/liver with a purity of at least 90%. The isolated KCs were then cultured in DMEM, containing 10% heat-inactivated fetal bovine serum, 10 mM HEPES, 100 U/ml penicillin and 100 µg/ml streptomycin at the concentration of 10⁶ cells/ml overnight with 5% CO2 at 37°C. KCs were allowed to adhere to the bottom of a 24-well plate (Costar) overnight and unattached cells were removed by gentle washing.

**Assessment of α2A-AR mRNA**

Gene expression of α2A-AR was assessed by real-time quantitative PCR (Q-PCR). Total RNA was extracted from KCs of CLP and Sham-operated animals as well as from cultured KCs using Tri-reagent (Molecular Research Center, Cincinnati, OH). Q-PCR was carried out on cDNA samples reverse transcribed from 2 μg RNA using murine leukemia virus reverse transcriptase (Applied Biosystems). Using the Quantitect SYBR Green PCR kit (Qiagen, Valencia, CA), reactions were carried out in 24 μl final volume containing 2 pmol of forward and reverse primers, 12 μl Quantitect Master Mix, and 1 μl cDNA. Amplification was performed according to Qiagen’s recommendations with an Applied Biosystems 7300 real-time PCR. Expression amount of rat GAPDH mRNA was used for normalization of each sample, and analysis of each specific mRNA was conducted in duplicate. Relative expression of mRNA was calculated by the ΔΔCt method, and results expressed as fold change with respect to the corresponding experimental control. The following rat primers were used: GAPDH (AF 106860): 5'-ATG ACT GTA CCC ACG GCA AG-3' (forward), 5'-CTG GAA GAT GGT GAT GGG TT-3' (reverse); rat α2A-AR (NM_012739), 5'-CGT GTT CGT GGT GTG TTG GT-3' (forward), 5'-GGA GCC GAC CGC TAT GAG-3' (reverse).

**Binding capacity and affinity of KC α2-adrenoceptors**

Freshly isolated KCs (10⁶) from sham and septic animals at 2 h after CLP were incubated with [³H]-yohimbine (a radioactively labeled α2-AR antagonist; specific activity 79.2 Ci/mmol; Dupont/NEN; final concentration, 2 to 64 nM in a volume of 200 µl) with or without 10 µM of unlabeled yohimbine for 30 min at 37°C in an assay buffer (40 mM Tris-HCl, 10 mM MgCl₂, pH 7.5) [15]. The value of Bₘₐₓ and Kᵢ were determined by Scatchard analysis after logarithmic transformation.

**Stimulation of isolated Kupffer cells with the α2A-AR subtype inhibitor BRL-44408**

KCgs isolated from normal animals were cultured overnight in DMEM medium with 10% heat inactive fetal calf serum, 100 U/ml penicillin/streptomycin, 100 mM HEPES and 100 U/ml L-glutamine at the concentration of 10⁶ cells/ml. KCs were then stimulated with NE (20 nM) with or without α2A-AR specific antagonist BRL-44408 maleate (1 µM, Tocris, UK) for 4 h. The supernatant was then collected and TNF-α levels were measured by enzyme-linked immunosorbent assay (ELISA) kit specific for rat TNF-α (Pharmingen, San Diego, CA). The assay was carried out according to the instructions provided by the manufacturer. For additional p38 MAP kinase pathway studies, KCs were cultured in DMEM for an 1 h (p38 phosphorylation) or 24 h (TNF-α release) with the following treatments: NE (20 nM), LPS (100 ng/ml, E. coli 055:B5; Sigma, St. Louis, MO), and the inhibitors BRL-44408 (1 µM), pertussis toxin (PTX, 100 ng/ml), or SB203580 (10 µM).

**Intraportal administration of NE**

Following anesthesia with isoflurane, a 3-cm midline incision was performed. The small intestine was exposed and a branch of the superior mesenteric vein was cannulated with a PE-10 catheter. It should be noted that this procedure did not cause any apparent gut ischemia. NE (20 µM in normal saline containing 0.1% ascorbic acid to prevent NE oxidation) or vehicle was infused into the portal vein at a rate of 13 µl/min for 2 h using a Harvard pump. Since portal blood flow is ~13 ml/min/liver [16], the above rate of NE infusion would be expected to increase the portal NE level to 20 nM, which is similar to that...
observed during sepsis[6]. A third group also received BRL-44408 maleate (1 mM solution at 13 μl/min), which was first infused into the portal vein for 15 min and then followed by infusion of 20 μM NE in combination with 1 mM BRL-44408 for 2 h at an infusion rate of 13 μl/min. After 2 h blood samples were collected by cardiac puncture and KCs were isolated as described above. In additional groups of NE, NE plus BRL-44408, or vehicle-infused animals, LPS (7.5 mg/kg) was administered through intra-peritoneal injection at 30 min after the onset of 2-h infusion. At the end of the infusion (i.e., 1.5 h after LPS challenge), blood samples were collected for plasma TNF-α measurement.

Determination of TNF-α production
Plasma, supernatant from KC culture, and cellular (5 x 10^6 KCs) TNF-α levels were determined using an ELISA assay kit specific for rat TNF-α (Pharmingen, San Diego, CA). Isolated KCs were also used to determine the TNF-α gene expression by RT-PCR as described previously [17].

Determination of p38 MAP kinase phosphorylation
KC were lysed (10 mM Tris saline, pH 7.5 with 1% Triton-X-100, 1 mM EDTA, 1 mM EGTA, 2 mM Na-orthovanadate, 0.2 mM PMSF, 2 μg/ml leupeptin, 2 μg/ml aprotinin), centrifuged at 16,000 g for 10 min, the supernatant was collected, and the density of the bands was determined through intraperitoneal injection at 30 min after the onset of 2-h infusion. At the end of the infusion (i.e., 1.5 h after LPS challenge), blood samples were collected for plasma TNF-α measurement.

Treatment of septic rats with BRL-44408
Rats underwent CLP as described above, the femoral vein was cannulated and connected to a Harvard pump. BRL-44408 (2.5 mg/kg BW) or vehicle was infused for 30 minutes using a Harvard pump. After 2 h, blood samples were collected by cardiac puncture and KCs were isolated as described above. In additional groups of NE, NE plus BRL-44408, or vehicle-infused animals, LPS (7.5 mg/kg) was administered through intraperitoneal injection at 30 min after the onset of 2-h infusion. At the end of the infusion (i.e., 1.5 h after LPS challenge), blood samples were collected for plasma TNF-α measurement.

Statistical analysis
All data that passed the normality test are expressed as mean±SE and compared by Student’s t-test or analysis of variance (ANOVA) using Student-Newman-Keuls post-hoc analysis. Data that are of percentile based nature or failed the normality test are expressed as mean±95% confidence, and compared with ANOVA on Ranks. The binding capacity and affinity was estimated using the Scatchard analysis and curves compared by two-way ANOVA. The survival study was analyzed using the Kaplan-Meyer log-rank test. Differences in values were considered significant if P<0.05. All statistical analysis was performed using either the SigmaStat® or PRISM® software.

Results

Upregulation of KC α2AR expression in CLP-induced sepsis
Rats were subjected to sepsis by CLP and KCs were isolated 2 h thereafter. As shown in Figure 1, the gene expression of α2A-AR was significantly upregulated by 179% at 2 h post-CLP compared to respective sham-operated animals. In contrast, α2A and α2C-AR expression did not show any changes after CLP (Data not shown). Increased KC α2-AR binding capacity and affinity in sepsis
To investigate whether increased α2-AR expression in sepsis leads to enhanced receptor binding, we incubated KCs isolated from sham-operated or CLP animals with [3H]yohimbine, a radio-labeled α2-specific AR antagonist. As shown in Figure 2A, the binding of KC α2-AR was saturated at approximately 30 nM [3H]yohimbine in both sham-operated and CLP animals. However, maximal binding of the α2-specific ligand was much lower in CLP animals compared to sham-operated controls.
Portal infusion of NE induces $\alpha_{2A}$-AR-dependent TNF-$\alpha$ production in KCs

To elucidate whether the $\alpha_{2A}$-AR is also responsible for TNF-$\alpha$ upregulation in vivo, we administered NE through the portal vein in normal animals for 2 h and isolated KCs for analysis. TNF-$\alpha$ gene expression was upregulated by 4-fold in KCs from animals that were subjected to intraportal infusion of NE as compared to vehicle-treated animals (Fig. 4A). BRL-44408 pretreatment prevented the upregulation of TNF-$\alpha$ gene expression. Similarly, TNF-$\alpha$ protein levels increased after intraportal infusion of NE by 10-fold and co-administration of NE with BRL-44408 maleate reduced cellular TNF-$\alpha$ levels by 47% (Fig. 4B). Serum levels of TNF-$\alpha$ also increased after intraportal infusion of NE from 40.2±0.8 pg/ml to 55.7±5.2 pg/ml (Fig. 4C). BRL-44408 significantly suppressed plasma TNF-$\alpha$ levels by 25% to blood TNF-$\alpha$ concentrations found in sham operated animals (Fig 4C). These results underline the crucial role of the $\alpha_{2A}$-AR in the proinflammatory response of Kupffer cells after NE-stimulation under in vivo conditions.

NE-mediated potentiation of LPS-mediated TNF-$\alpha$ release through the $\alpha_{2A}$-AR

To investigate the role of the $\alpha_{2A}$-AR in NE-mediated potentiation of a proinflammatory response to endotoxin, we studied the response of KCs to NE and LPS in the presence or absence of the $\alpha_{2A}$-specific inhibitor BRL-44408 in vitro (Fig. 5A) and in vivo (Fig. 5B). Cultured KCs were responsive to endotoxin and TNF-$\alpha$ levels increased by over 16-fold after stimulation with NE.$\alpha_{2A}$-AR blockade by BRL-44408 (1 $\mu$M) significantly attenuated TNF-$\alpha$ release by over 60% (Fig. 5A). Concurrent inhibition of the $\alpha_{2A}$-AR using BRL-44408 [1 $\mu$M] significantly suppressed TNF-$\alpha$ release from cultured KC. To verify the crucial role of the $\alpha_{2A}$-AR in the proinflammatory response to NE in endotoxemia, we measured plasma levels of TNF-$\alpha$ after intraperitoneal injection of LPS (7.5 mg/kg) and systemic intravenous administration of NE. LPS alone resulted in a 10-fold increase of TNF-$\alpha$ plasma levels after 4 h (Fig. 5B) and the co-administration of NE resulted a marked enhancement in plasma
TNF-α release by 155-fold (P<0.05; Fig. 5B). Administration of the a2A-AR antagonist BRL-44408 completely blocked the LPS/NE-induced TNF-α release (Fig. 5B). Thus, NE-mediated potentiation of LPS-induced TNF-α release is a2A-AR-dependent even after systemic application of NE.

a2A-AR-dependent activation of p38 MAP kinase

LPS induces the activation of intracellular pathways, including the p38 MAP kinase by its phosphorylation, which plays a crucial role in the proinflammatory response of macrophages [18]. To determine, whether a2A-AR activation affects the p38 pathway, we stimulated cultured KCs with NE (20 nM) and blocked either the a2A-AR with BRL-44408 or its coupled Gαi-protein with pertussis toxin (PTX). Both BRL-44408 (1 μM) and pertussis toxin (PTX, 100 ng/ml) prevented the NE-induced phosphorylation of the p38 MAP kinase (Fig. 6A). This indicates that NE acts through the a2A-AR and Gαi protein to activate the p38 MAP kinase. To verify this effect under inflammatory conditions, we assessed NE-mediated phosphorylation of the p38 MAP kinase in cultured KC at 1 h after stimulation with LPS (100 ng/ml) and with or without BRL-44408 (BRL, 1 μM). Data are presented as mean±SE (n=8) and compared by one-way ANOVA and Student-Newman-Keuls test. *P<0.05 vs. Control; #P<0.05 vs. LPS alone; †P<0.05 vs. NE+LPS.

Figure 4. Portal infusion of NE induces a2A-AR-dependent TNF-α production in KCs. *P<0.05 vs. Control; #P<0.05 vs. NE.

Figure 5. NE-mediated potentiation of LPS-mediated TNF-α release through the a2A-AR. *P<0.05 vs. Control; #P<0.05 vs. LPS alone; †P<0.05 vs. NE+LPS.
(10 μM; a p38 MAP kinase inhibitor) attenuated the NE-mediated increase in TNF-α release by 46% and 55% respectively (Fig. 6C). This study further confirms that NE potentiates LPS-induced TNF-α through the α2A-AR coupled G<sub>ia</sub> protein and the activation of the p38 MAP kinase.

**BRL-44408 is beneficial in experimental sepsis**

Using the above in vitro and in vivo systems, we were able to show that BRL-44408 can attenuate the proinflammatory effect of NE either alone or in conjunction with LPS. To investigate the beneficial effect of BRL-44408 in sepsis, we used an experimental sepsis model of CLP in rats receiving BRL-44408. 20 h later we measured cytokine levels in KCs, plasma and injury parameters for liver (AST & ALT), kidney (creatinine) and general oxygenation (lactate). As expected, TNF-α mRNA levels in KCs as well as plasma levels were increased 20 h after CLP by 6.6-fold and 2.4-fold, respectively (Figs. 7A-B). BRL-44408 treatment completely inhibited TNF-α production and release (Figs. 7A-B). Similarly, CLP-induced increases in surrogate markers for liver and kidney injury (AST, ALT and creatinine by 4.8-, 4.1-, and 2.9-fold, respectively) were completely blocked after treatment with BRL-44408 (Figs. 7C-E). Lactate, a marker for tissue perfusion and oxygenation, that was increased by 3-fold after CLP and was significantly suppressed by 37% after BRL-44408 infusion (Fig. 7F). These above results indicate that BRL-44408 confers an anti-inflammatory effect and protects from organ injury and tissue malperfusion in CLP-induced sepsis in rats. To show that these beneficial effects translate into an improved outcome, we conducted a survival study. As shown in Figure 8, CLP and vehicle treatment resulted in a 55% mortality rate over a 10-day period. Treatment with BRL-44408, however, protected over 55% of animals at risk, resulting in an overall survival rate of 75%.
determine the effect of the α2A-AR blockade on other organ system, we monitored MAP and heart rates during BRL-44408 administration in normal rats. As shown in Figure 9, intravenously infusion of BRL-44408 at the dose of 2.5 mg/kg BW had no measurable effects on MAP and heart rates.

Discussion

Gut-derived NE has been shown to play a critical role in inducing hepatocellular dysfunction in early sepsis, exerting its effect through the non-synaptic, high-affinity α2-AR [19]. Kotanidou et al. have shown that urethane, a general anesthetic with α2-AR blocking properties, protects against LPS partly by reducing TNF-α release [20]. We have previously reported that TNF-α secretion from NE stimulated Kupffer cells can be inhibited by the general α2-AR inhibitor yohimbine, suggesting that α2-ARs on Kupffer cells are particularly responsible for the upregulation of TNF-α release [21]. The presence of α2-ARs on macrophages has been previously confirmed by receptor binding assays and in situ hybridization [22,23]. Studies by other groups have shown that TNF-α upregulation can be mediated by the stimulation of α2-ARs [11,24]. Here we show that it is the α2A-AR that is upregulated in KCs leading to enhanced receptor binding and proinflammatory cytokine release in sepsis.

We have previously shown that TNF-α is significantly increased by incubation with NE (20 nM) for 4 h [21]. Since KCs are a major source of proinflammatory cytokines [25], intraportal infusion of NE appears to have a direct measurable effect on TNF-α release in vivo. Infusion of NE through the femoral vein may reduce active NE levels reaching the liver compared to direct intraportal injection. Hence, one may expect a diminished proinflammatory response of NE after systemic administration. We have shown however, that even after peripheral intravenous administration of NE, the LPS-induced TNF-α increase becomes dramatically potentiated through an α2A-AR-dependent pathway, possibly through the involvement of other tissue macrophages.

Adrenergic receptors are subdivided in to three major subtypes α1, α2, and β, which are then subdivided into α1A, α1B, and α1C, α2A, α2B, and α2C, and β1, β2, and β3. Upon binding of β2-ARs for example, epinephrine and high doses of NE through increasing intracellular cAMP levels [26]. α2-adrenoceptors are Gι- and Gια-protein coupled receptors that decrease intracellular cAMP, open K+ channels, and inhibit voltage gated Ca2+ channels, all of which lead to hyperpolarization of neurons and activation of immune responses.

Figure 7. Beneficial effects of α2A-AR inhibition in sepsis. (A–B) BRL-44408 mediated suppression of TNF-α gene expression in Kupffer cells (A) and plasma concentrations (B) 20 h after CLP. (C–F) BRL-44408 mediated improvement of organ damage parameters. Rats underwent CLP and 20 h later ALT (C), AST (D), creatinine (E) and lactate (F) levels were measured as described in the methods. Values (n = 5/group) are presented as means±SE and compared by one-way ANOVA and Student-Newman-Keul’s method. *P<0.05 vs. Sham; #P<0.05 vs. CLP+Vehicle.

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cells [26]. In the CNS, α₂-adorenoceptors are predominantly presynaptic. They regulate the release of neurotransmitters through a negative feedback. Functional studies of the genetic receptor subtypes have linked the α₂B-adrenoceptor to peripheral vasoconstriction and analgesic effects of N₂O (nitrous oxide) and other anesthetic agents. The α₂A-AR, either alone or with α₂C-AR co-activation, is involved in the central inhibition of sympathetic activities, modulation of neurotransmitter release, sedation, and anti-epileptic effects. As we have shown here, the pro-inflammatory action of NE, mediated by the α₂A-receptor subtype expressed on hepatic macrophages (i.e., KCs) can now be added to this list.

So far, however, we could only come up with only one report regarding the α₂-AR subtypes responsible for TNF-α upregulation in pulmonary inflammation and none in sepsis itself. In their work by Flierl et al., the authors focused on the phagocyte-derived catecholamines that boost inflammatory responses via the α₂B-AR [27]. Although this report indicated similar increases in the α₂A-AR subtype in alveolar macrophages and neutrophils after LPS-stimulation, the role of individual subtypes in the proinflammatory response was not addressed [27]. In our study we have assessed the influence of these subtypes in hepatic macrophages, i.e., KCs. We have shown that the gene expression of α₂A-AR has significantly increased 2 h after CLP, while no significant changes in α₂B and α₂C-AR could be observed. Kupffer cells stimulated with NE in combination with the α₂A-AR inhibitor BRL-44408 maleate reduced TNF-α release, while the α₂B-AR inhibitor imiloxan hydrochloride increased TNF-α levels (data not shown). The difference between those two receptor subtypes may lie in the intracellular signaling pathways. While all α₂-ARs suppress intracellular cAMP levels through its Gαs coupled protein, they also change intracellular calcium and potassium levels to a different degree, which may influence intricate signaling pathways and eventually cellular response. As opposed to in vivo findings that showed no differences, our in vitro results show that α₂B-AR inhibition is able to inhibit TNF-α release from cultured KCs, which is further complicating the role of α₂B-ARs in the inflammatory response. In vivo, intraportal administration of NE significantly increased serum and Kupffer cell levels of TNF-α, and only the α₂A-AR specific antagonist, BRL-44408 could significantly reduce TNF-α plasma levels and activities, modulation of neurotransmitter release, sedation, and anti-epileptic effects. As we have shown here, the pro-inflammatory action of NE, mediated by the α₂A-receptor subtype expressed on hepatic macrophages (i.e., KCs) can now be added to this list.

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In summary, our results suggest that hyperresponsiveness to $\alpha_2$-AR stimulation observed in sepsis is primarily due to an increase in $\alpha_2\text{A-AR}$ expression in KCs. This appears to be in-part responsible for the increased proinflammatory response and ensuing organ injury in sepsis. These findings provide important feasibility information for further developing the $\alpha_2\text{A-AR}$ antagonist as a new therapy for sepsis.

**References**


**Author Contributions**

Conceived and designed the experiments: RW SMG TSR PW. Performed the experiments: PD MZ WD YJ. Analyzed the data: MM PD MZ RW. Wrote the paper: MM PW.