Adrenomedullin expression in a rat model of acute lung injury induced by hypoxia and LPS

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Submitted 20 August 2004; accepted in final form 23 November 2004

Agorreta, Jackeline, Javier J. Zulueta, Luis M. Montuenga, and Mercedes Garayoa. Adrenomedullin expression in a rat model of acute lung injury induced by hypoxia and LPS. Am J Physiol Lung Cell Mol Physiol 288: L536–L545, 2005. First published December 3, 2004; doi:10.1152/ajplung.00314.2004.—Adrenomedullin (ADM) is upregulated independently by hypoxia and LPS, two key factors in the pathogenesis of acute lung injury (ALI). This study evaluates the expression of ADM in ALI using experimental models combining both stimuli: an in vivo model of rats treated with LPS and acute normobaric hypoxia (9% O2) and an in vitro model of rat lung cell lines cultured with LPS and exposed to hypoxia (1% O2). ADM expression was analyzed by in situ hybridization, Northern blot, Western blot, and RIA analyses. In the rat lung, combination of hypoxia and LPS treatments overcomes ADM induction occurring after each treatment alone. With in situ techniques, the synergistic effect of both stimuli mainly correlates with ADM expression in inflammatory cells within blood vessels and, to a lesser extent, to cells in the lung parenchyma and bronchiolar epithelial cells. In the in vitro model, hypoxia and hypoxia + LPS treatments caused a similar strong induction of ADM expression and secretion in epithelial and endothelial cell lines. In alveolar macrophages, however, LPS-induced ADM expression and secretion were further increased by the concomitant exposure to hypoxia, thus paralleling the in vivo response. In conclusion, ADM expression is highly induced in a variety of key lung cells types in this rat model of ALI by combination of hypoxia and LPS, suggesting an essential role for this mediator in this syndrome.

acute respiratory distress syndrome; endotoxin; alveolar macrophages; endothelial cells; type II pneumocytes

ACUTE RESPIRATORY DISTRESS SYNDROME (ARDS), the most severe expression of acute lung injury (ALI), is characterized by increased microvascular permeability, severe hypoxemia, and diffuse pulmonary infiltrates (2). Although there are many clinical disorders associated with the development of ARDS, sepsis is the most common cause of this syndrome. ALI/ARDS represent important clinical entities with mortality rates of 40–50% (30). A recent study estimates an incidence for sepsis-associated ARDS of 45–63 cases per 105 persons per year in the USA (10).

Even though LPS treatment induces hypoxemia (via lung injury), classical rodent models of ALI in which large doses of LPS are administered result in higher levels of circulating cytokines than those found in patients with sepsis (14); the animals die from “cytokine storm,” often not accurately reflecting clinical developments in human ALI (32). As noted by a National Heart, Lung, and Blood Institute working group on ALI (25), two-hit animal models might better reflect actual conditions present in patients with ALI. Taking into account that hypoxia and endotoxin are the main factors involved in this syndrome (40), we have developed in vivo and in vitro rat models of ALI combining acute normobaric hypoxia and LPS insult (1).

Several cytokines, such as IL-1, -6, -8, -10, and TNF-α (40), and other mediators, such as nitric oxide (NO) (1), have been found to play a crucial role in the orchestration of the inflammatory response associated with ALI. Adrenomedullin (ADM) is a multifunctional regulatory peptide, and its numerous biological actions support an integrator role in the cellular response to inflammation (7). ADM was originally isolated from a human pheochromocytoma (16) and belongs to the calcitonin family, which includes calcitonin gene-related peptide and amylin. It was initially described for its hypotensive activity and has since been implicated in diverse physiological functions that include bronchodilation, antimicrobial activity, modulation of central brain function, cell growth regulation, survival from apoptosis, and induction of angiogenesis (20). ADM is expressed in a wide variety of organs, including adult and fetal lung, and in several types of cancer also comprising lung cancer (8, 22). Hypoxic conditions, most proinflammatory cytokines, and LPS upregulate ADM basal expression in cultured cells (8, 26) and in many organs such as lung, heart, and liver (12, 34). Furthermore, ADM plasma levels are elevated in patients with lung cancer, asthma, sepsis, chronic obstructive pulmonary disease, and the systemic inflammatory response syndrome (SIRS) (20). Together, these premises suggest that ADM may also play a role in the development of ALI. In an attempt to investigate this hypothesis, as well as to study the effect of hypoxia as an added cofactor to LPS treatment in ALI-reproducing conditions, we have studied the expression of ADM in in vivo and in vitro models of rat ALI. ADM expression has been analyzed by Northern blot, RT-PCR, in situ hybridization (ISH), Western blot, and RIA techniques.

MATERIAL AND METHODS

Animals and Treatments

The protocol followed was similar to that applied previously (1). Female 7-wk-old Fischer Harlan rats, weighing 125–200 g, were intraperitoneally injected with saline (200 μl) or LPS (0.1 mg/kg Escherichia coli O111:B4, phenol extract; Sigma, St. Louis, MO) and immediately exposed to normoxia (room air, 21.8°C, and relative humidity of 40%); both parameters monitored by datalogger device Tinytag Ultra; Meaco Europa, IJzendoorn, Netherlands) or normobaric hypoxia (9% O2); rats were placed in a 300 × 350 × 600-mm

L536 1040-0605/05 $8.00 Copyright © 2005 the American Physiological Society http://www.ajplung.org
Plexiglas chamber specially designed for this project (Martínez Íñigo, Pamplona, Spain) at 22.1°C, relative humidity of 50.2%, and gassed with a mixture of 9% O₂-91% N₂ at a constant flow throughout the experiment. Oxygen concentration in the chamber was continuously monitored with a microPac oxygen sensor (Drager Sicherheitstechnik). Four groups resulted from these experimental conditions: 1) normoxia group (control): rats subjected to normoxia + saline, 2) hypoxia group: hypoxia + saline, 3) LPS group: normoxia + LPS, and 4) hypoxia + LPS group. Rats were killed by cervical dislocation after 3, 6, 12, or 24 h of treatment. At each time point, four rats were examined in each group (n = 64). In the hypoxia + LPS group, all rats survived after 3 or 6 h of exposure; however, the survival rate after 12 h was 80%, and the treatment was 100% lethal after 24 h. The study protocol was approved by the University of Navarra Animal Care and Use Committee (no. 00299) and conforms to National Institutes of Health guidelines. The lungs were excised, and the left lobes were fixed in buffered formalin for 24 h, dehydrated, and embedded in paraffin. The correspondent right lobes were divided into two portions and frozen in liquid nitrogen for subsequent protein or RNA analyses.

Vascular Permeability to Protein

Extravasation of intravascular protein was measured with FITC-labeled BSA as an estimate parameter of vascular permeability (35). In brief, four animals per group (n = 16) were injected with 7 mg/kg of FITC-BSA in 0.1 M phosphate buffer (PB), pH 7.6, in one of the caudal veins before exposure to each treatment for 6 h. Animals were deeply anesthetized with an intraperitoneally injected mixture of ketamine (80 mg/kg) and xylazine (15 mg/kg), the thoracic cavity was opened, and 1 ml of blood was obtained by cardiac puncture and adequately reserved for subsequent serum extraction (centrifugation at 1,430 g at 4°C for 30 min). After perfusion of the pulmonary circulation with PB rinsing solution, the lungs were harvested. The accessory lobe was fixed in 4% buffered formalin for 24 h, dehydrated, and embedded in paraffin; the rest of the lung was weighed, encased in aluminum foil, and frozen in liquid nitrogen. Immunohistochemical techniques for FITC were applied on 4-μm-thick paraffin sections of lung tissue. After dewaxing, endogenous peroxidase was inactivated by treatment with 3% hydrogen peroxide for 15 min, nonspecific background was blocked with normal goat serum (1:20) inactivated by treatment with 3% hydrogen peroxide for 15 min, nonspecific background was blocked with normal goat serum (1:20) inactivated by treatment with 3% hydrogen peroxide for 15 min. The sections of formalin-fixed rat lung were deparaffinized, rehydrated, and mounted in histologic plasticizer xilene mountant.

Northern Blot

Northern blot was performed as previously described (8) with slight modifications. Samples of 15 μg of total RNA were separated in 1% agarose gels containing 2.2 M formaldehyde. RNA was then transferred by capillarity to nitrocellulose membranes (Schleicher & Schuell, Keene, NH), and blots were subjected to UV crosslinking at 120 J/cm². The rat ADM cDNA probe used in this study was kindly donated by Dr. Alfredo Martínez (23). cDNA templates were labeled with [α-32P]dCTP (3,000 Ci/μmol; Amersham Pharmacia Biotech, Buckinghamshire, UK) by random priming, and unincorporated nucleotides were removed using Probe-Quant G-50 Micro columns (Amersham Pharmacia Biotech). Hybridization was carried out overnight at 42°C in a hybridization buffer containing 40% formamide. Autoradiographic signal was detected using XAR Film (Kodak, Rochester, NY). Densitometric analysis of ADM mRNA expression was expressed as the ratio of ADM to ribosomal protein S9 mRNA values.

ISH for Rat ADM

The protocol followed was similar to that applied previously (1). Sections of formalin-fixed rat lung were deparaffinized, dehydrated, and permeabilized in 0.2% Triton-PBS for 15 min. After a proteinase K (60 μg/ml in 0.1 M Tris-50 mM EDTA, pH 8) digestion at 37°C for 30 min, the process was stopped in 0.1 M glycine-PBS. Tissue was subsequently acetylated with 0.25% acetic anhydride in 0.1 M triethanolamine, pH 8, washed in diethyl pyrocarbonate-treated H₂O, and
These data were analyzed by a two-way ANOVA, if the hypotheses of
overnight at 4°C with a primary rabbit antiserum directed to the
membranes was accomplished at 30 V for 1 h. Membranes were
then electophoretically separated in a gradient NuPage 4–12% Bis-
agarose gel (Invitrogen). After prestaining and electrophoresis, the
blots were blocked with 5% nonfat dry milk in Tris-buffered saline
(TBS) and washed with TBS-Tween 20 (TBST). The nitrocellulose
membranes were probed with rat ADM antiserum at 1:1,000 (Santa
Cruz Biotechnology, Santa Cruz, CA) and developed with Western
blotting Luminol Reagent kit (Santa Cruz Biotechnology, Santa Cruz,
CA). β-Actin antibody (Sigma) diluted 1:5,000. Characterization
of this antibody was performed using the β-actin cDNA sequence
from rat lung as a probe (5′-TTTTCCTCGCTAGGTTTTGGA-3′ sense,
and 5′-TTTTCCTCGCTAGGTTTTGGA-3′ antisense, bp 1,003–1,022) was
blunted into the pCR-II vector (Invitrogen). After plasmid linear-
ization, digoxigenin-labeled riboprobes were synthesized with T7 or
SP6 RNA polymerases with a digoxigenin RNA labeling kit (Roche
Diagnostics, Mannheim, Germany). Hybridization with the antisense
probe (50 ng/µl) was performed overnight at 43°C in a moist chamber;
hybridization with the sense probe (50 ng/µl) in the same
conditions was used as a negative control. After increasingly stringent
washes, the slides were treated with RNase A (20 µg/ml) at 37°C for
15 min. Sections were incubated for 2 h with 1:300 antidigoxigenin
antibody labeled with alkaline phosphatase (AP) (Roche Diagnostics).
Nitroblue tetrazolium chloride and 5-bromo-4-chloro-3-indolyl phos-
phate (Roche Diagnostics) were used to visualize AP activity. Slides
were mounted in 1:1 glycerol-PBS.

RIA for Rat ADM

Cells were seeded in triplicate and subjected to normoxia, hypoxia,
LPS, or hypoxia + LPS treatments for 12, 24, or 48 h. The condi-
tioned media were collected and stored at −20°C with 5 mM EDTA
and a protease inhibitor cocktail. Cellular protein concentration per
plate was determined to verify similar cell protein content so that
ADM in the media could be compared. The concentration of ADM
was measured by RIA analysis according to manufacturer’s instruc-
tions in a commercially available RIA kit for rat ADM (Phoenix
Pharmaceuticals, Belmont, CA). In brief, 0.1 ml of conditioned
medium (or appropriate dilution of standard ADM) was preincubated
for 18 h at 4°C with 0.1 ml of primary antibody against rat ADM.
After that, 0.1 ml of 125I-ADM was added (10,000 cpm), and the
mixtures were incubated at 4°C for 18 h. Bound tracer was separated
by precipitation with goat anti-rabbit serum and normal rabbit serum. The
supernatant was aspirated, and the radioactivity in the pellet was
determined by a gamma counter.

In Vivo Model

Assessment of lung permeability to protein after different
treatments. To determine which treatments of hypoxia, LPS, or hypoxia + LPS induced pulmonary vascular injury, extravasation of intravascular protein was measured with
FITC-labeled BSA. Compared with the control group, the
permeability index was found to increase significantly only
after the hypoxia + LPS treatment (3.75 ± 0.31, n = 4 vs.5.57 ± 1.2, n = 4, respectively; P = 0.0034). Immunohisto-
chemical detection of FITC in lung sections revealed weak
positivity in rat lungs treated with hypoxia or LPS alone (Fig.
1, B and C). However, FITC immunostaining was greatly
increased in the perivascular space and in alveolar macroph-
eges of lungs from animals treated with hypoxia + LPS (Fig.
1, D–F). Therefore, in contrast to the other experimental
conditions, only the hypoxia + LPS treatment seems to induce
pulmonary vascular injury as determined by extravasation of
albumin results.

ADM mRNA levels in rat lungs. Northern analysis for ADM
expression in rat lung demonstrated a consistent increase in its
mRNA induced by hypoxia, LPS, and hypoxia + LPS treatments (Fig.
2). A synergistic effect in the upregulation of ADM mRNA could be observed between hypoxia and LPS, with a
significant increase in the expression of ADM mRNA in lungs
of rats exposed to the combined treatment compared with the
expression after each treatment alone (Fig. 2A). This interac-
tion (synergism) in the combined treatment was found to be
statistically significant at 6 (P = 0.003) and 12 (P < 0.001) h of
treatment.

ISH on lung sections from control animals showed expres-
sion of ADM mRNA in some epithelial cells of bronchioles,
the endothelium of blood vessels, some cells of the lung
parenchyma, and in alveolar macrophages (Fig. 3, A–C). After
hypoxic exposure alone, there was an increase in the number of
positive bronchiolar cells and cells of the lung parenchyma,
and endothelial cells showed a more intense staining (Fig.
3, D–F). In LPS-treated rat lungs (Fig. 3, G–I), ADM mRNA
expression was found only in inflammatory cells adhering to
vascular endothelial cells (Fig. 3I). The combined treatment
with hypoxia + LPS (Fig. 3, J–L) caused the highest expres-
sion of ADM mRNA, which was localized in bronchiolar
epithelial cells, inflammatory-like cells present in blood ves-
sels, and in most cells of the lung parenchyma (Fig. 3K).
Absence of staining using the sense riboprobe demonstrated
the specificity of the technique (Figs. 4, A and B).

ADM protein expression. Western blot analysis of rat lung
extracts revealed five immunoreactive bands for ADM and its
precursor species with approximate molecular masses of 22,
18, 15, 13, and 6 kDa (Fig. 4C), as described previously (15).
Only the 6-kDa band, corresponding to the fully processed ADM, changed its intensity along with the different treatments, while the area and intensity of the rest of the immunoreactive bands remained constant. Therefore, we focused our analysis on the changes observed for the fully processed ADM peptide. Adsorption controls of the antiserum against ADM with the amidated ADM22-52 peptide showed no immunoreactive bands (Fig. 4C).

Hypoxia and LPS treatments alone elicited an increase in ADM expression compared with the signal in the control group (Fig. 5). In accordance with the Northern blot results, the combined treatment of hypoxia and LPS further increased ADM production compared with either treatment alone, suggesting a synergistic interaction of both treatments (Fig. 5). In fact, a significant interaction between LPS and oxygen concentration was found at 3 (P < 0.001), 6 (P = 0.009), and 12 (P = 0.036) h of treatment.

In Vitro Model

ADM expression in cell lines. Rat lung type II epithelial cells (CCL-149), RPMVEC, and rat alveolar macrophages (CRL-2192) were exposed to normoxia or hypoxia for 0.5, 1, 3, 6, 12, or 24 h (Northern blot analysis) or 12, 24, or 48 h (RIA of the conditioned medium) and concomitantly treated with or without LPS. The study of ADM mRNA expression (Northern blot) and secreted peptide (RIA) revealed different responses according to cell type. Treatment with LPS in normoxic conditions in these two cell types did not significantly modify ADM expression and secretion compared with the control group (Figs. 6 and 7). However, hypoxia and hypoxia + LPS treatments resulted in an equivalent and strong induction of ADM gene expression and secretion into the conditioned media in both cell types.

Fig. 1. Permeability to albumin was assessed by immunolocalization of FITC. In control lungs (A), no detectable immunostaining for FITC is found. In rat lungs treated with hypoxia (B) or LPS (C), slight immunoreactivity is observed in the perivascular space (arrows). After the hypoxia + LPS treatment (D–F), FITC-albumin is highly accumulated in the perivascular space (D) and phagocyted by alveolar macrophages (E and F). Bars: 30 μm (A–E), 6 μm (F).

Fig. 2. Northern blot analysis of adrenomedullin (ADM) in rat lungs. A: representative Northern blot analysis of ADM and S9 mRNA from lung extracts of rats exposed to normoxia (20% O2) or hypoxia (9% O2) and injected with saline or LPS (0.1 mg/kg) for 3, 6, 12, and 24 h. Combined treatment of hypoxia and LPS was lethal at 24 h of exposure. Fifteen micrograms of total RNA were loaded per lane. B: quantitation of ADM mRNA levels normalized to the signal for S9 mRNA. To standardize between experiments, we assigned an arbitrary density of 1 to the band obtained from lungs of rats exposed to normoxia. Values are expressed as means ± SD (bars) (n = 4 for each group at each time point). **P < 0.01 compared with the control group; †P < 0.05, ††P < 0.01 compared with the hypoxia + LPS group.
In the rat alveolar macrophage cell line, ADM mRNA signal was barely detectable in cells exposed to normoxia or hypoxia (Fig. 8A). However, treatment with LPS resulted in a significant induction of ADM gene expression, which was further increased with the combined treatment of hypoxia + LPS (Fig. 8A and B). Nevertheless, very low levels of secreted ADM in the culture media were found by RIA analyses, with no significant differences between groups (Fig. 8C). To explore possible causes for the low ADM secretion levels in this cell line, we performed experiments based on the addition of exogenous ADM to the conditioned media with or without protease inhibitors (5 mM EDTA and 0.5 mM 1,10 phenanthroline). Data in Fig. 8D suggest that ADM is being degraded in the conditioned media of macrophages exposed to the four experimental groups. Compared with the control group, the degradation rate of ADM was greater in the hypoxia, LPS, and hypoxia + LPS groups and was prevented by the addition of EDTA or 1,10 phenanthroline (Fig. 8D). Although direct addition of 1,10 phenanthroline to the macrophages at the beginning of the experimental treatments considerably affected cell viability (cell death 40 ± 5%), secreted ADM was detectable in all the conditioned media, with the hypoxia + LPS treatment showing a significant increase compared with the control group (Fig. 8E).

**DISCUSSION**

The pathological features used to characterize ALI and ARDS are increased permeability of the alveolar capillary membrane, accumulation of edema, and severe hypoxemia (2). This pathological process is typically described through three overlapping phases (40). The acute (inflammatory) phase (usually develops the first week after the onset of the disorder) is characterized by a rise in permeability of the alveolar-capillary barrier and the influx of protein-rich edema. There is also an increase in margination of pulmonary leukocytes, which together with alveolar macrophages, secrete numerous pro- and anti-inflammatory mediators. The acute phase is followed by the proliferative stage, which is essentially characterized sequentially by organization of exudates and fibrosis of the alveolar spaces. Finally, in the fibrotic phase there is progression of the fibrotic lung injury, which involves the reduction of lung compliance and impaired gas exchange. As previously described (1), histological examination of the present rat model showed a considerable rise in the number of inflammatory cells (monocytes, neutrophils, and lymphocytes) migrating to the lung in LPS-treated rats compared with rats treated with normoxia or hypoxia. The number of inflammatory cells was further increased when treatment with LPS was combined with
the concomitant exposure to hypoxia. In addition, the combination of hypoxia and LPS treatments was also characterized by a significant increase in wet-to-dry lung weight ratio compared with the other experimental conditions, which is consistent with the pulmonary vascular injury observed in clinical ALI (1). The present data on extravasation of FITC-albumin shown both by permeability index determination and by immunocytochemical localization of FITC add further evidence to support the relevance of the hypoxia/LPS treatment as a good experimental model that seems to mimic the acute (inflammatory) phase of ALI.

Various studies have demonstrated elevated plasma levels of ADM in animal models of ALI and in patients with SIRS (20). In these studies, plasma ADM levels positively correlated with the severity of ARDS (39). The increased production and release of ADM in ARDS and other stress-associated pathologies have been considered as having a protective role during the inflammatory response (7). In relation to this, Shindo et al. (34), using transgenic mice overexpressing ADM in their vasculature, have demonstrated the protective role of ADM against circulatory collapse, organ damage, and mortality characteristic of endotoxic shock. Furthermore, the combined administration of ADM and the complement component factor H, an ADM binding protein, attenuated tissue injury and reduced the mortality rate in the cecal ligation and puncture rat model of sepsis (42). Specifically, in experimental ALI/ARDS conditions, elevated plasma and lung levels of ADM have been proposed to perform its beneficial role mainly by two complementary mechanisms: firstly, reducing endothelial hyperpermeability by cAMP-dependent relaxation of the endothelial microfilament system and thus reducing edema formation (11), and secondly, ensuring myocardial performance through its vasodilatory effects counteracting those of endothelin-1 from the lung (36).

ADM has been found to be upregulated by hypoxia and LPS, two key factors involved in ALI, both in vivo (12) and in vitro (26). In the present work we have analyzed the expression of ADM by a variety of biochemical and molecular techniques in a rat experimental model of ALI that combines hypoxia and LPS stimuli. In parallel, we have performed in situ techniques to identify which cell types in the lung are involved in the synthesis and release of ADM. Our results show that acute hypoxia and LPS treatments alone induce ADM expression (mRNA and protein) in rat lung as reported previously (12, 24). ISH techniques in the lungs of rats exposed to hypoxia showed that, apart from endothelial cells (41), upregulation of ADM mRNA is further localized in epithelial cells of bronchioles and cells in the parenchyma. In the LPS-treated group, besides endothelial cells (24), a large number of inflammatory cells within blood vessels are the main source of ADM mRNA overexpression. Interestingly, when hypoxia and LPS stimuli
are combined, ADM expression (mRNA and protein) is synergistically induced in rat lungs. As demonstrated by ISH in the combined treatment, the cells mostly responsible for this increase in ADM mRNA expression in the lungs are numerous inflammatory cells within blood vessels; to a lesser extent, also cells and in the lung parenchyma and epithelial cells in bronchioles and alveoli account for the upregulated ADM synthesis. Our results demonstrate that ADM is greatly overexpressed in this experimental model of the inflammatory phase of ALI, suggesting that this peptide may play a relevant role in this syndrome, although more studies are needed to describe the precise role of ADM in ALI. Moreover, our data point to the lungs as a likely contributing source of the elevated ADM plasma levels occurring in ALI patients.

ADM biology is closely related to nitric oxide synthase-2 (NOS2) and the NO cascade. NO has been shown to stimulate ADM production in endothelial and smooth muscle cell lines (6, 13). Furthermore, in transgenic mice overexpressing ADM in their vasculature, NO production is highly augmented (34). Both ADM and NO share diverse physiological functions that...
include vasodilation, bronchodilation, and antimicrobial activity. A previous study from our laboratory reported an increase in the expression of NOS2 in the present model of ALI and the involvement of inflammatory cells in this event (1). In this animal model of ALI, ADM and NO appear to be upregulated in a coordinated fashion that may possibly be related to a cooperative role in the control of the inflammatory response.

In accordance with the animal model, a differential regulation of ADM expression in the three rat lung cell types studied (endothelial, type II epithelial cells, and alveolar macrophages) was found in our in vitro studies. Endothelial and epithelial cells showed basal detectable levels of ADM (mRNA and protein) in normoxic conditions. In the same way, ADM expression had been observed previously in endothelial cells from different species and types of blood vessels (26, 37). Also, ADM and its receptor L1 have been found in human type II pneumocytes (21) and have been correlated with increased secretion of phosphatidylcholine, the predominant component of pulmonary surfactant (31). After LPS treatment, ADM expression in epithelial and endothelial cells was similar to that in the control group. In the type II epithelial cell line (CCL-149), this finding was not surprising since we did not find expression of Toll-like receptor 4 (TLR4), the main receptor of LPS by RT-PCR techniques (data not shown). Concerning the endothelial RPMVEC cells, previous studies report that ADM expression in endothelial cells in response to LPS varies greatly in endothelial cells from different origins (37). Although RPMVEC express TLR4 mRNA (RT-PCR data not shown), it has been previously reported that a combination of LPS and cytokines is needed to induce NOS2 expression in this cell line (43). It is probable, therefore, that combination of LPS with other stimuli might also be needed for ADM induction in RPMVEC. Concerning hypoxic conditions, a clear induction of ADM expression and secretion was found in the epithelial and endothelial cell lines studied herein, as we and others previously reported in epithelial cells from different sources (8, 38) and endothelial cells (26). When we subjected epithelial and endothelial cells to a combined treatment of hypoxia and LPS, the expression and secretion of ADM were similar to that obtained after exposure to hypoxia alone. This seems to correlate with the absence of ADM induction by treatment with LPS, indicating that in both cell lines, only the hypoxic stimulus induces the expression and secretion of ADM.

Other authors have shown basal ADM gene expression and release in macrophages and their related cells (18, 27), particularly in alveolar macrophages (28). In the present study, the

Fig. 8. Expression of ADM in the CRL-2192 alveolar macrophage cell line. A: representative Northern blot analysis for ADM. B: relative ADM mRNA expression after 12 h of treatment as the ratio of ADM to S9 mRNA densitometric values. To standardize between experiments, an arbitrary density of 1 was assigned to the value correspondent to cells exposed to normoxia. C: rat ADM peptide in the conditioned media by RIA analysis. D: ADM concentration was assessed by RIA analysis. The conditioned media of macrophages exposed to 24 h of treatment were incubated with exogenously added ADM (1.28 ng/ml) for 24 h at 37°C, together with 5 mM EDTA (dark gray bars) or 0.5 mM 1,10 phenanthroline (Phen., open bars) or absence of protease inhibitors (closed bars). Initial ADM content in the conditioned media (previous to ADM addition) is represented as light gray bars. E: RIA analysis of rat ADM in the conditioned media of macrophages treated with (open bars) or without (closed bars) 0.5 mM 1,10 Phen. at the beginning of a 24-h exposure to each experimental condition. Values are expressed as means ± SD (bars) (n = 3 for each group). *P < 0.05, **P < 0.01 compared with the normoxia group; ††P < 0.01 compared with the hypoxia + LPS group.
expression of ADM mRNA in the rat alveolar macrophage cell line (CRL-2192) after hypoxic exposure was similar to that in normoxic conditions, although a great overexpression of ADM transcripts was assessed after LPS treatment. The stimulatory effect of LPS on ADM expression and secretion has also been observed in monocyte-derived macrophages and in the mouse peritoneal macrophage-derived RAW 264.7 cell line (18, 27). On the other hand, in relation to hypoxic stimulation and in agreement with our results, it has been reported that hypoxic exposure alone does not induce ADM expression in human peritoneal macrophages unless proceeding from cirrhotic patients (4). After the simultaneous exposure to hypoxia and LPS, we found that ADM mRNA expression was even greater than in macrophages treated with LPS and exposed to normoxia, showing a synergistic effect between both stimuli. Despite this, RIA analyses of conditioned media from the CRL-2192 cell line showed no differences in the secretion of ADM peptide among the four experimental groups. In this regard, degradation of exogenously added ADM has been reported when incubated with lung, adrenal, and kidney tissue extracts (19). Besides, this degradation was prevented by addition of EDTA or phenanthroline (19) [a selective inhibitor of metalloproteinases (MP) (33)]. Moreover, it is also known that rat alveolar macrophages produce a wide spectrum of MP (9) and that ases (MP) (33). Moreover, it is also known that rat alveolar macrophages, the combined treatment of hypoxia and LPS treatments, and ADM degradation could be prevented by the addition of exogenous inhibitors (EDTA and phenanthroline) to the culture media (Fig. 8, D and E). Moreover, although cell viability was compromised, when phenanthroline was directly added to CRL-2192 cells, ADM degradation could be partially abrogated, and a significant increase in ADM in the culture medium was found after the combined treatment compared with the control group. The present study demonstrates that in rat alveolar macrophages, the combined treatment of hypoxia and LPS greatly induces the expression of ADM mRNA as well as the secretion of the mature peptide, thus paralleling the synergistic interaction of both factors observed in the in vivo model. This response in alveolar macrophages is presumably mediated by the hypoxia inducible transcription factor-1α, which has been found to be essential in macrophage response to hypoxia and inflammation (5). Further studies are needed to elucidate whether the ADM secreted by alveolar macrophages might subsequently be degraded by concomitantly secreted MP in ALI conditions. One might as well hypothesize that ADM peptide degradation by macrophage-derived proteases could also constitute a mechanism to regulate ADM levels, since the lung has been shown to be the main clearance organ for this peptide (29).

In summary, ADM expression is highly induced in the present rat model of ALI that combines exposure to hypoxia and treatment with LPS. In addition, there is a good correspondence between our findings in the in vitro experiments and the data obtained in the in vivo model. In this regard, hypoxic exposure induces ADM expression in endothelial and epithelial cells in both models, whereas LPS treatment per se does not have any inductor effect on ADM production in these cell types. In response to the hypoxia + LPS combined treatment, ADM expression is induced in a variety of key cell types such as alveolar macrophages and endothelial and epithelial cells, although the effects in other cell types, such as other inflammatory cells and type I pneumocytes, deserves further in vitro studies.

ACKNOWLEDGMENTS

The authors thank Dr. Rubén Pío (Div. of Oncology, Center for Applied Medical Research, University of Navarra) for help with radioimmunoassay. We are also grateful to Paz Zamora and Silvia González (Dept. of Histology and Pathology, University of Navarra) for assistance with histological techniques.

GRANTS

This work was supported by Spanish Ministry of Health Grants FIS 00/0698 and RTIC 03/10 and the UTE project Center for Applied Medical Research.

REFERENCES


