Monoamine Oxidases Are Mediators of Endothelial Dysfunction in the Mouse Aorta

Adrian Sturza, Matthias S. Leisegang, Andrea Babelova, Katrin Schröder, Sebastian Benkhoff, Annemarieke E. Loot, Ingrid Fleming, Rainer Schulz, Danina M. Muntean, Ralf P. Brandes

Abstract—Monoamine oxidases (MAOs) generate $\text{H}_2\text{O}_2$ as a by-product of their catalytic cycle. Whether MAOs are mediators of endothelial dysfunction is unknown and was determined here in the angiotensin II and lipopolysaccharide-models of vascular dysfunction in mice. Quantitative real-time polymerase chain reaction revealed that mouse aortas contain enzymes involved in catecholamine generation and MAO-A and MAO-B mRNA. MAO-A and -B proteins could be detected by Western blot not only in mouse aortas but also in human umbilical vein endothelial cells. Ex vivo incubation of mouse aorta with recombinant MAO-A increased $\text{H}_2\text{O}_2$ formation and induced endothelial dysfunction that was attenuated by polyethylene glycol-catalase and MAO inhibitors. In vivo lipopolysaccharide (8 mg/kg IP overnight) or angiotensin II (1 mg/kg per day, 2 weeks, minipump) treatment induced vascular MAO-A and -B expressions and resulted in attenuated endothelium-dependent relaxation of the aorta in response to acetylcholine. MAO inhibitors reduced the lipopolysaccharide- and angiotensin II–induced aortic reactive oxygen species formation by 50% (ferrous oxidation xylenol orange assay) and partially normalized endothelium-dependent relaxation. MAO-A and MAO-B inhibitors had an additive effect; combined application completely restored endothelium-dependent relaxation. To determine how MAO-dependent $\text{H}_2\text{O}_2$ formation induces endothelial dysfunction, cyclic GMP was measured. Histamine stimulation of human umbilical vein endothelial cells to activate endothelial NO synthase resulted in an increase in cyclic GMP, which was almost abrogated by MAO-A exposure. MAO inhibition prevented this effect, suggesting that MAO-induced $\text{H}_2\text{O}_2$ formation is sufficient to attenuate endothelial NO release. Thus, MAO-A and MAO-B are both expressed in the mouse aorta, induced by in vivo lipopolysaccharide and angiotensin II treatment and contribute via the generation of $\text{H}_2\text{O}_2$ to endothelial dysfunction in vascular disease models. (Hypertension. 2013;62:140-146.) • Online Data Supplement

Key Words: endothelium • hypertension • monoamine oxidase • mouse models of disease • nitric oxide • nitric oxide synthase (endothelial) • oxidative stress

R eactive oxygen species (ROS) contribute to endothelial dysfunction by limiting NO availability and by inducing endothelial cell activation. Several enzyme systems are considered as being responsible for the elevated vascular ROS production in endothelial dysfunction, including NADPH oxidases, xanthine oxidase, electron leakage from the mitochondrial respiratory chain, cyclooxygenases, and the uncoupled endothelial NO synthase.

Monoamine oxidases (MAOs) are another source of ROS but their relevance for vascular ROS formation has not gained much attention. Although MAOs in part mediate cardiac ischemia/reperfusion injury, it is not known whether MAO-dependent ROS production also contributes to vascular dysfunction and thus the development of endothelial dysfunction.

MAOs are flavoenzymes that are located at the outer mitochondrial membrane, where they catalyze oxidative deamination of amine neurotransmitters and vasoactive amines virtually in all mammalian tissues. Two isoforms with different tissue distribution, substrate affinities, and inhibitor sensitivities exist: MAO-B is the major enzyme in brain, whereas MAO-A is present not only in brain but also in other tissues, including the heart and vessels. By catalyzing the electron transfer from biogenic amines to molecular oxygen, aldehydes, ammonia, and hydrogen peroxide are formed as by-products.

Although the substrate specificity of both MAO isoforms is similar, MAO-A has a higher affinity to serotonin and norepinephrine than MAO-B, which in turn prefers benzylamine and 2-phenylethylamine. Nevertheless, both enzymes degrade dopamine, tryptamine, and norepinephrine if present in sufficient concentration. In addition to being involved in a broad spectrum of mental and neurodegenerative diseases,

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MAO-A–mediated H₂O₂ production has been shown to be relevant for ischemia–reperfusion injury of the kidney¹¹ and the heart. Moreover, MAO-A is thought to be involved in myocyte hypertrophy ex vivo¹²,¹³ and also in maladaptive myocardial hypertrophy and transition to heart failure in vivo.¹⁴

The unfavorable effects of MAO activation are antagonized by a couple of relatively selective MAO inhibitors, which are either irreversible, such as clorgyline for MAO-A and selegiline for MAO-B, or reversible, such as moclobemide for MAO-A and lazabemide for MAO-B, respectively.¹⁵ Systemic MAO inhibition leads to the accumulation of catecholamines with subsequent increase in sympathetic activity and hypertension.¹⁶ This aspect limits the use of MAO inhibitors in a vascular scenario, and therefore, MAO inhibitors have not been considered an approach to improve vascular function.

Another prototypic hypertensive agent is angiotensin II (Ang II). Interestingly, potential interactions of Ang II and MAOs have been reported in the central nervous system. In coculture systems of hypothalamic and brain stem neurons, Ang II stimulated MAO activity, but the underlying mechanism was not studied.¹⁶ More recently, it was reported that inhibition of the renin–angiotensin system decreases cardiac MAO activity.¹⁷ Whether there is an interaction between Ang II and MAO in vessels is not known. Ang II is well known to activate and induce other sources of ROS like vascular NADPH oxidases,¹⁸ and Ang II also increases vascular xanthine oxidase activity.¹⁹ Moreover, there is even evidence that Ang II increases superoxide production in mitochondria of endothelial cells.²⁰ By these mechanisms, Ang II is a well-characterized inducer of endothelial dysfunction. Given these different, well-established sources of ROS, it is hard to predict whether MAO and the subsequent ROS formation by the enzyme have a role in Ang II–induced vascular dysfunction.

In the present study, we tested whether MAOs are a source of vascular ROS production in healthy and diseased vessels and whether the enzymes contribute to the development of endothelial dysfunction.

**Materials and Methods**

Endothelial function was determined by organ chamber experiments, gene expression was determined by quantitative real-time polymerase chain reaction, and protein expression by Western blot. Cyclic GMP (cGMP) was determined by radio immuno assay. For further details, please see the online-only Data Supplement.

**Results**

**Ex Vivo MAO-A Incubation Attenuates Endothelium-Dependent Relaxation by Forming H₂O₂**

Although MAO-A is a known source of H₂O₂, it is unknown whether the enzyme contributes to the development of endothelial dysfunction. To address this aspect, murine lung endothelial cells and mouse aortic rings were incubated with a commercially available preparation of MAO (MAO-A, Promega, 0.2–1 mU/mL for 12 hours). As demonstrated by Western blot analysis in endothelial cells, MAO incubation increased the enzyme content of the cell preparation (Figure 1A). Endothelium-dependent relaxation of vascular segments incubated with MAO was significantly attenuated. This effect was prevented by cotreatment with the MAO-A inhibitor clorgyline, although the compound had no effect on responses in control segments (Figure 1B). To elucidate whether the attenuation was a consequence of MAO-dependent H₂O₂ formation, experiments were repeated after incubation with polyethylene glycol–catalase. Indeed, polyethylene glycol-catalase in part prevented the attenuation of acetylcholine-induced relaxation (Figure 1C). Accordingly, after ex vivo MAO treatment, vascular H₂O₂ formation increased by 60% as determined by ferrous oxidation xylene orange (FOX) assay (Figure 1D). These findings indicate that MAO could contribute to vascular ROS formation even without supplementation of catecholamines, suggesting that sufficient amount of substrates are produced within the vessel. Therefore, expression of enzymes involved in catecholamine biosynthesis was determined by real-time polymerase chain reaction. Although expressed to a much lower degree than in murine adrenal glands and brain, tyrosine hydroxylase, DOPA decarboxylase (DDC), and dopamine B hydroxylase (DBH) relative to the house keeping gene EEF2α in the murine tissues indicated (EC indicates murine endothelial cells), n=4. *P<0.05 MAO-A vs CTL; #P<0.05 with and without Clorg and PEG-catalase, respectively.

"Figure 1. Effects of ex vivo monoamine oxidase (MAO-A) on vascular function. A, Western blot analysis of MAO-A of mouse lung endothelial cells incubated with MAO-A (0.2 mL/mL) or H₂O₂ (80 μmol/L) for the durations indicated. GAPDH served as loading control (CTL). B and C, Acetylcholine-induced relaxation in phenylephrine-preconstricted mouse aortic segments with (MAO-A) and without (CTL) preincubation with MAO-A (1 mL/mL, 12 h) in the presence or absence of clorgyline (Clorg, 10 μmol/L, B) or polyethylene glycol (PEG)-catalase (100 U/mL, C), n=6. D, Aortic H₂O₂ formation determined by ferrous oxidation xylene orange assay, n=6. E, Quantitative real-time polymerase chain reaction for tyrosine hydroxylase (TH), DOPA decarboxylase (DDC), and dopamine B hydroxylase (DBH) relative to the house keeping gene EEF2α in the murine tissues indicated (EC indicates murine endothelial cells), n=4. *P<0.05 MAO-A vs CTL; #P<0.05 with and without Clorg and PEG-catalase, respectively."
that MAO can be a mediator of endothelial dysfunction and that vessels generate sufficient amounts of catecholamines to facilitate MAO-dependent H$_2$O$_2$ production.

**Vascular Expression of MAO Increases in Response to Ang II and Lipopolysaccharide**

Because MAO inhibition had no effect on vascular function in control vessels, we wondered whether MAO could be a mediator of endothelial dysfunction in situations of increased vascular oxidative stress, that is, after a potential induction of the enzyme. To address this aspect, the expressions of MAO-A and MAO-B were determined by real-time polymerase chain reaction and Western blot. Under resting conditions, MAO-A, as judged from the computed threshold (ct) value difference of the real-time polymerase chain reaction as well as the intensity of the staining in the Western blot, was greatly more abundant than MAO-B. Ex vivo incubation of mouse aortic segments in organic culture with Ang II (100 nmol/L) or lipopolysaccharide (LPS; 1 μg/mL) increased the expression of both homologues by ≈2-fold (Figure 2A and 2B). Similar responses were observed after removal of the endothelium (Figure S1A in the online-only Data Supplement). Also in cultured lung endothelial cells, Ang II induced a significant increase in MAO-A and MAO-B expressions, whereas LPS had little effect (Figure S1B). Interestingly, in these cells, also incubation with H$_2$O$_2$ (30 μmol/L) resulted in an increase of endothelial MAO-A protein, potentially suggesting that MAO-A is generally induced in situations of oxidative stress (Figure 1A). To determine whether mRNA induction also translates into changes in protein expression, immunohistology (Figure 2C) and Western blot analyses (Figure 2D) were performed. A pronounced increase in vascular MAO-A expression was readily observed with both techniques, with most prominent changes occurring in the medial layer of the vessel. For MAO-B, potentially as consequence of the lower abundance of the protein, the available antibodies yielded numerous bands on Western blot analyses. Thus, although it could be concluded that MAO-B protein expression also increased in response to Ang II and LPS, histological analysis was infeasible because of the significant nonspecific staining of the available antibodies.

**MAO Is a Mediator of Endothelial Dysfunction After Ang II Treatment**

To address the pathophysiological relevance of Ang II–mediated MAO induction, mouse aortic segments were studied after in vivo treatment with Ang II (1 mg/kg per day, 2 weeks by minipump). Similar as for the ex vivo stimulation, this approach resulted in an induction of MAO-A and MAO-B (Figure 3A). Importantly, determination of H$_2$O$_2$ formation in the isolated mouse aorta indicated that ≈50% of the Ang II–induced H$_2$O$_2$ formation was sensitive to MAO inhibition (Figure 3B). Accordingly, endothelium-dependent relaxation in response to acetylcholine was attenuated after in vivo Ang II treatment and incubation with inhibitors for MAO-A, as well as MAO-B in part restored normal endothelium-dependent relaxation (Figure 3C–3F). Coincubation with both inhibitors had an additive effect and completely normalized endothelium-dependent relaxation. Given the well-established role of endothelial NO synthase (eNOS) uncoupling and Nox activation in response to Ang II, these findings were unexpected and point toward a potential antioxidant or nonspecific effect of MAO inhibition. By 2 different assays for H$_2$O$_2$ (Amplex red and FOX assay), however, no significant antioxidant effect of the MAO inhibitors was observed (Figure S2A). Moreover, MAO inhibition had no effect on xanthine oxidase–driven H$_2$O$_2$ formation (Figure S2B); also Nox activity in cells overexpressing active Nox1, Nox2, and Nox4, respectively, was not affected by MAO inhibition (data not shown). Collectively, these observations identify MAO-A and B as mediators of endothelial dysfunction.

**MAO Is a Mediator of Endothelial Dysfunction After LPS Treatment**

To further establish the principle of MAO-mediated endothelial dysfunction, we sought for a second independent pathway and studied vascular responses to in vivo LPS treatment. Similar to the response to Ang II, LPS treatment resulted in endothelial dysfunction and increased H$_2$O$_2$ formation (Figure 4A and 4B). MAO inhibition attenuated vascular H$_2$O$_2$ formation (Figure 4B) and partially restored normal responses...
to acetylcholine after LPS treatment (Figure 4C–4F). These data may indicate that MAO is of a general importance in the control of endothelium-dependent relaxation in vascular disease conditions.

Vascular MAO Induction Is Mediated by Nuclear Factor Kappa B but Not NADPH Oxidase

Because little is known regarding the mechanisms leading to MAO induction in the vasculature, a restricted expression screen was performed using pharmacological inhibitors and Ang II as well as LPS ex vivo incubation in isolated aortic segments. Expression control of MAO-A and MAO-B was similar. The induction of both enzymes was insensitive to mitogen-activated protein kinase inhibitors, protein kinase C inhibition, JAK2 (Janus kinase-2) inhibition, or blockade of mitochondria or elements of the respiratory chain. In contrast, compounds that interfere with nuclear factor κB signaling and the phosphatidylinositol kinase inhibitor wortmannin blocked Ang II and LPS-stimulated MAO-A and MAO-B induction (Figure S3). Importantly, it was noted previously that phosphatidylinositol kinase inhibitors prevent nuclear factor κB signaling, suggesting that this pathway is most relevant for MAO induction. No evidence for a role of NADPH oxidases in MAO induction was observed. The nonspecific Nox inhibitor apocynin had no effect on MAO induction (Figure S3), and Ang II–stimulated MAO-A and MAO-B induction was readily detectable in the aorta of Nox1, and 4 triple knockout mice (MAO-A: 1.9±0.2-fold; MAO-B: 1.8±0.2-fold; n=3).

MAO-A Limits Endothelial cGMP Accumulation

In the present concept of endothelial dysfunction, the production of $\text{O}_2^-$ and the subsequent reaction with NO is the starting point of a vicious cycle. In this, a continuous production of peroxynitrite leads to an ever increasing eNOS uncoupling and thus attenuation of NO formation and further increases in $\text{O}_2^-$ release. Importantly, MAO, as a flavine dehydrogenase, can entertain only 2 electron transfer and thus does not produce significant amounts of $\text{O}_2^-$.

Therefore, we tested whether MAO limits endothelial NO release. Because direct NO measurements are of questionable reliability (NO electrode, nitrite accumulation), endothelial cGMP was determined as a biomarker of NO generation. These experiments were performed in human umbilical vein
endothelial cells because cultured murine lung endothelial cells contain very little guanylyl cyclase. Importantly, upon stimulation with histamine and thus increases in endothelial calcium level and subsequently eNOS activity, cGMP levels more than doubled in human umbilical vein endothelial cells. This effect was not observed after MAO incubation. Cotreatment with MAO inhibitors, however, restored histamine-induced cGMP accumulation. This demonstrates that MAO activity and not contaminants possibly contained in the commercial enzyme preparation block endothelial cGMP accumulation (Figure 5). Thus, MAO-derived products directly limit endothelial NO formation.

Discussion

In the present study, we focused on the role of MAOs for the development of endothelial dysfunction. We detected MAO expression in murine vessels and found the enzymes to be induced in response to Ang II and LPS by pathways involving phosphatidylinositol kinase and nuclear factor κB. Blockade of endogenous MAO activity reduced the vascular formation of H2O2 and partially restored normal endothelium-dependent relaxation in vessels pre-exposed to Ang II or LPS. MAO-A limited endothelial cGMP accumulation, suggesting that products of the enzyme attenuate endothelial NO formation.

ROS-induced endothelial dysfunction is a well-established pathomechanism, but usually this phenomenon is linked to increased formation of O2·−, but not H2O2. In fact, only O2·− can scavenge NO and thereby give rise to the formation of peroxynitrite, which is a prerequisite for eNOS uncoupling.5 In contrast, there is ample evidence to suggest that vascular H2O2 formation might even be beneficial for the vascular system. H2O2 induces and activates eNOS23. H2O2 is also an endo- thelial-derived hyperpolarizing factor in many vessels and can directly oxidize and thus activate protein kinase GIα as the

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Nevertheless, beyond a certain concentration, ≈30 μmol/L in the extracellular space, H2O2 promotes inflammatory activation, induces endothelial dysfunction, and may even promote induction of apoptosis. Two important mechanisms may underlie this effect: glutathionylation of eNOS26 and proline-rich tyrosine kinase 2 (PYK2)-mediated phosphorylation of eNOS on Tyr657.25 PYK2 is known to be activated by H2O2 through thiol oxidation,28 and the subsequent PYK2-mediated tyrosine phosphorylation of eNOS seems to transfer the enzyme into an insoluble, inactivate state.27 Previously, it was noted that this pathway is stimulated by H2O2 and activated by NADPH oxidases in response to Ang II. Because MAO-A incubation limited endothelial cGMP accumulation, it is appealing to speculate that thiol oxidation is also operative in the present scenario and mediates endothelial dysfunction. Indeed, PYK2 inhibition in part prevented the effect of MAO-A on endothelium-dependent relaxation (Sturza, unpublished observation, 2012). Obviously, these findings are mechanistically interesting, as they were, however, obtained with ex vivo MAO incubation, their physiological relevance is questionable. Nevertheless, because MAO inhibition in models of ROS-induced endothelial dysfunction improved endothelium-dependent relaxation in the present study, we suggest that a similar mechanism is operative under physiological conditions.

Polyethylene glycol–catalase failed to completely prevent the effects of MAO on vascular function. A possible explanation could be that the large molecule did not sufficiently penetrate the vessel but additional mechanisms might also be operative. Because we have excluded that other important vascular sources of ROS are nonspecifically inhibited by MAO blockers and because the compounds used in the present study had only a minor antioxidant effect, it is tempting to speculate that MAO by a second mechanism might promote development of endothelial dysfunction. A potential explanation is the degradation of β-receptor stimulating catecholamines at the endothelial surface. Adrenaline by increasing endothelial cAMP promotes endothelial NO formation by a protein kinase A–mediated phosphorylation on eNOS-Ser 1177.29 Moreover, a cross talk between cAMP and cGMP on the level of phosphodiesterases is well established.30 Thus, removal of locally produced catecholamines by MAOs has the potential to impair endothelium-dependent relaxation. There is, however, a second fascinating alternative to explain potential deleterious effects of MAOs on the endothelium, which is by the formation of NH3. NH3 is known to be a mediator of cerebral vascular dysfunction in hepatic encephalopathy. Ammonia stimulates the formation of ROS by cerebral endothelial cells,31 and reduction of ammonia levels in a liver failure model improved endothelial function.32

For the formation of H2O2 and ammonia, MAOs have to be supplied with substrate. Previous studies have demonstrated that the increased vascular formation of ROS after supplementation with serotonin was in part MAO mediated.33 It was, however, not studied whether this effect occurs without supplementation of substrate, that is, whether endogenous vascular catecholamines are sufficient to fuel MAOs. Adventitial nerves produce norepinephrine, and platelets positioned at the endothelial surface could serve as a source of serotonin. Moreover, vascular cells express serotonin
transmitters and are known to store significant amounts of this biogenic amine. Another less well studied alternative could be the direct production of catecholamine by vascular cells. Although this was not directly tested and was not a focus of the present study, at least the expression of several enzymes involved in catecholamine synthesis could be detected by real-time polymerase chain reaction albeit at lower levels than in the adrenal medulla. The present observation that MAO inhibition restores endothelial function in situations of increased MAO expression, therefore, could be interpreted as support for sufficient autonomous production or storage of yet to be defined MAO substrates in diseased vessels.

Because of local pools and an inhomogeneous distribution of target molecules, ROS signaling is compartmentalized. This aspect is of relevance because mean tissue-wide concentrations of ROS may differ greatly from those present in hot spots of ROS signaling. On the cellular level, the present study seems to suggest that vascular MAO is predominantly expressed in smooth muscle cells with fewer enzyme being present in the endothelium. Indeed, the total vascular mRNA expression of MAO was not affected by endothelial denudation. Moreover, cultured endothelial cells expressed significantly lower amounts of MAO and responded less well to MAO-inducing stimuli as compared with the whole vessel. Nevertheless, exposure of murine lung endothelial cells to $\text{H}_2\text{O}_2$, which stimulates nuclear factor $\kappa B$ signaling, was sufficient to increase MAO protein expression as detected by Western blot. On the cellular level, MAO is expressed at the outer mitochondrial membrane and thus is another source of mitochondrial ROS in addition to the respiratory chain and p66shc. In this context, it should, however, be mentioned that an intense cross talk between the different ROS generators within mitochondria but also between the mitochondrion and other cellular compartments is present. It seems that cellular stimulation with ROS in general triggers a uniform ROS formation by several sources, and interfering with a single ROS generator therefore often lowers the ROS formation by the other systems. Although this concept seems rather theoretical, in the present study, we observed that 50% of the increased ROS formation in response to Ang II or LPS treatment was sensitive to MAO inhibition even if it was previously reported that NAPDH oxidase, NOS uncoupling, or xanthine oxidase are the sources of ROS under these conditions. An alternative interpretation of the finding that virtually any form of ROS generator contributes to total vascular ROS formation in disease conditions is the threshold hypothesis. It assumes that increased ROS levels become only apparent once the antioxidant defense, built up by peroxiredoxin and glutathione peroxidase has been exhausted. Obviously, in such a model, inhibition of an individual source of ROS may lower the total detectable ROS level again below the postulated threshold level of the antioxidant capacity.

An important limitation of the present study is that we based a significant part of our observations on pharmacological MAO inhibition. Although the compounds used here had relatively little antioxidative effects and did not inhibit the closely related xanthine oxidase, we cannot completely exclude that off-target effects of the MAO inhibitors contribute to that normalization of endothelial function. Indeed, we restricted our functional analysis to isolated vessels and did not perform in vivo MAO inhibition or used MAO knockout mice. Obviously, such strategies and animals are available, but systemic MAO inhibition in the disease models used in the present study is not suited to address the role of MAO in endothelial function. Catecholamine production or signaling is increased in septic shock and also after LPS and Ang II treatments, conditions that at least sensitize the sympathetic nervous system. Because MAOs are a main pathway of catecholamine degradation, the MAO inhibitor–induced accumulation of these vasoactive compounds will alter the blood pressure response present in the model of vascular dysfunction used here and interfere with the development of endothelial dysfunction. Accordingly, an appropriate analysis of individual MAO enzymes in the vascular system would require tissue-specific, inducible genetic deletion models, which have not been generated, yet.

Perspectives
With the present study, we have established MAOs as novel mediators of endothelial dysfunction in the mouse LPS and Ang II model. MAO-A and MAO-B are both expressed in the vascular system and are both induced in response to LPS and Ang II. MAO-mediated endothelial dysfunction is in part mediated by $\text{H}_2\text{O}_2$ and limits endothelial cGMP accumulation. Inhibition of MAOs restored normal endothelial function in diseased vessels ex vivo. Despite this, MAO inhibitors are not suited to attenuate vascular dysfunction because the global increase in catecholamine levels resulting from MAO inhibit will lead to severe side effects like hypertension. With novel therapeutic strategies like local drug delivery or targeted siRNA approaches, this problem might be overcome and then MAOs could become suitable targets to improve vascular function.

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Disclosures
None.

References


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**Novelty and Significance**

**What Is New?**

- Monoamine oxidases (MAOs) are identified as a mediator of endothelial dysfunction.
- The enzymes are induced in vascular inflammation and hypertension.
- Inhibition of MAOs ex vivo normalized endothelial function in the murine angiotensin II and lipopolysaccharide model.

**What Is Relevant?**

- MAOs are enzymes involved in the metabolism of catecholamines, which generate H2O2 and ammonium as by-products.

**Summary**

We identified MAOs as novel mediators of endothelial dysfunction. Targeted inhibition of MAOs might be used to treat vascular dysfunction in hypertension and inflammation.
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**Supplemental Material**

**Monoamine oxidases are mediators of endothelial dysfunction in the mouse aorta**

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**Expanded Material and Methods Section**

**Study design and animal procedures**
Male C57/BL6 mice were obtained from Charles River Laboratories, Sülzfeld, Germany. At the age of 8 weeks, animals were subjected to sham or angiotensin II infusion by osmotic minipumps (1 mg/kg/d, two weeks) or treatment with lipopolysaccharide (LPS, 8 mg/kg, single injection, overnight exposure, approx. 16 hours). Experiments conformed to the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health and were approved by the local government.

**Organ Chamber Experiments**
Organ chamber experiments were performed in aortic rings in the presence of diclofenac (10 μmol/L). Diclofenac was used to prevent the formation of endothelium-derived eicosanoids impacting on endothelial function. This approach may influence the extent of endothelium-dependent vasodilator responses. After diclofenac, prostacyclin and in particular less thromboxane A2/endothelium-derived constrictor factor will be produced in response to acetylcholine. Nevertheless, from our past experiments on the role of Nox in endothelium-dependent relaxation, we know that redox-mediated effects are more obvious in the aorta after cyclooxygenase inhibition and that experiments are less affected by unstable constrictor responses to phenylephrine. We acknowledge that this approach might, however, lead to an overestimation of the role of endothelium-derived ROS sources other than Cox such as Nox or MAOs.

The concentration of phenylephrine, used for precontraction, was adjusted to obtain an identical preconstriction level of 80% of the contraction elicited by KCl (80 mmol/L). Endothelium-dependent relaxation to cumulatively increasing concentrations of acetylcholine was registered in the presence or absence of several MAO inhibitors (MAOI-clorgyline, moclobemide and selegiline – 10 μmol/L).

**Organ Culture**
Murine aortic segments were dissected under sterile conditions, cleaned, and incubated for the times indicated at 37°C in EBM culture medium containing 0.1% BSA, in the presence or absence of LPS (1 μg/mL), AngII (100 nmol/L) or MAO-A (1 mU/mL) with or without clorgyline (10 μmol/L) or PEG-Catalase (100 U/mL). In some cases the endothelium was removed by a short treatment with CHAPS (5 mg/mL dissolved in glucose solution 50 g/L, exposure for 30 seconds). Subsequently, the tissue was studied in organ chamber experiments, was embedded in tissue Tek for immunohistological analyses or was snap frozen in liquid nitrogen for qRT-PCR and Western blot analyses.

**Immunoblotting**
Western blot analyses were performed with an infrared-based detection system (Odyssey, Licor, Bad Homburg, Germany). All primary antibodies were purchased from Abcam and infrared-fluorescent-dye-conjugated secondary antibodies were obtained from Licor (Bad Homburg). The following lysis buffer was used (pH 7.4, concentrations in mmol/L): Tris-HCl (50), NaCl (150), sodium pyrophosphate (10), sodium fluoride (20), nonidet P40 (1%), sodium desoxycholate (0.5%), proteinase inhibitor mix, phenylmethylsulfonyl fluoride (1), orthovanadate (2), okadaic acid (0.00001).

**Real-Time PCR**
Primers against MAO isoforms, DBH (dopamine-beta-hydroxylase), DDC (DOPA-decarboxylase) and TH (tyrosin-hydroxylase) were designed using the sequence information of the NCBI database (5’->3’: mice MAO-A fw TCT CAG GAT TGG CTG CTG CCA AAC; rev CAG GTG GAA ATG CAC CAC GGA ATG; mice MAO-B fw TGG GCC AAG AGA AGA TTC CCA GTG ATG; rev AGA GCG TGG CAA TCT GCT TTG TAG; mice DBH fw ACC ACA ACC CAC GGA AGA TAG AAG; rev GTG CAG TAG CCG TTC AAC ACA AAG; mice DDC fw CTG GCT CGG ACT AAA GTT ATC; rev CCA CCT TCT TTT ACA GAG AAA TAG; mice TH fw AGT TCT CCC AGG ACA TGA GGT TTG; rev GAA GTA CAC CCG GTT GTA GGT TTG. Total RNA was isolated from aortic rings and cells with the "Absolutely RNA RT PCR Miniprep kit" (Stratagene Europe), and used for reverse transcription (Superscript III RT, Invitrogen). The polymerase chain reaction (PCR) conditions were as follows: initial denaturation, 95°C, 10 minutes; 40 cycles of denaturation (95°C, 30 seconds), annealing (55°C, 60 seconds), and elongation (72°C, 60 seconds).

**Reactive oxygen species measurements**
H2O2 production was measured in aqueous solutions and mouse aortic segments by Amplex Red (Invitrogen) / horse radish peroxide (HRP) oxidation or the Ferric iron xylenol orange oxidation method (Sigma Aldrich) as reported previously. In cells, the
inhibitory effect of compounds was determined as the relative decrease of luminol / HRP chemiluminescence as reported previously 3.

**Immunohistology**
MAO-A tissue localization was determined in frozen section of the murine aorta, brain and heart by a MAO-A antibody from Abcam (1:50) in triton x-100 permeabilized PFA (4%) fixed sections after peroxidase block (H₂O₂ + NaN₃ incubation). For confocal fluorescence microscopy with the Zeiss LSM 510 meta, nuclei were counterstained with DAPI and muscle was stained by a directly FITC-labeled smooth muscle alpha actin antibody (Sigma, 1:100) and MAO-A was visualized by an Alexa 565 nm anti-rabbit secondary antibody. For conventional histology, a HRP-linked anti-rabbit antibody was used and staining was carried out by diaminobenzidine technique. Tissue was counterstained with hematoxylin.

**Quantitative in vitro determination of 3',5'-cyclic guanosine monophosphate (cGMP)**
Human umbilical vein endothelial cells (HUVEC) were cultured in 24 well plates in endothelial growth medium (EGM, Lonza) supplemented with 8% fetal bovine serum (Biochrom) and 1% Penicillin/Streptomycin (Sigma Aldrich) at 37°C with 5% CO₂. Prior to analysis, cells were washed with PBS (PAA) and serum deprived in EGM containing 2% fetal bovine serum. After three hours, cells were incubated with isobutylmethyl xanthine (0.5 mmol/l, AppliChem) for five minutes at 37°C to block phosphodiesterase activity followed by the addition of MAO-A (0.2 mU/ml, Promega) or MAO-A (0.2 mU/ml) in combination with the MAO inhibitors selegiline (10 µmol/l, Sigma Aldrich) and clorgyline (10 µmol/l, Sigma Aldrich) for 30 minutes. After 25 minutes, histamine (1 µmol/l, Sigma Aldrich) was added to the cells to stimulate endothelial cell intracellular calcium increase and thus eNOS activity. Serum-deprived medium served as negative control, whereas sodium nitroprusside dihydrate (30 µmol/l, Merck) was used as positive control. To stop the reaction, trichloroacetic acid (6%, Roth) was added to the cells. The extraction and determination of cGMP was performed with a specific radioimmunoassay (Izotop) according to the manufacturer’s protocol.

**Statistics**
All values are mean±SEM. Relaxations were calculated from individual dose-response curves. Statistical analysis was carried out after testing for normal distribution by ANOVA or ANOVA for repeated measurements as appropriate followed by Fisher LSD post hoc test with Bonferroni correction. Values of p<0.05 were considered statistically significant.

**Reference List**
Figure S1: qRT-PCR for MAO-A and MAO-B in the samples indicated relative to EEF2α. LPS (1 µg/mL, 12 hours), AngII (100 nmol/L, 12 hours) vs. control (CTL). n=4
Figure S2: Antioxidant activity of MAO inhibitors. (A-B) FOX and Amplex Red Assay for hydrogen peroxide measurements in the presence of increasing concentrations of MAOI (0.01, 0.1, 1, 10, 100 μM) – Clorgyline, Selegiline, Moclobemide. PEG-Catalase (100 U/ml) and glutathione (100 μM, 1 mM, 10 mM) served as positive control. (C) Effect of Clorgyline on ROS production by xanthine oxidase (0.1 munit/mL) and MAO A (0.1 munit/mL). Xanthine (10 μmol/L) and serotonin (10 μmol/L) were used as substrates. n=3
Figure S3. Mechanisms of AngII/LPS-induced MAO expression in aortic rings (A&B). qRT-PCR for MAO-A/B expression in mice aortic segments with and without ex vivo stimulation with Ang II (100 nmol/L) or LPS (1 µg/mL) and the inhibitors indicated: irbesartan (100 µmol/L; AT1 receptor antagonist), Wortmannin (20 nmol/L, PI3-kinase inhibitor), N\^\textsubscript{\textomega}Nitro-L-arginine-methylester (L-NAME 100 µmol/L, NOS inhibitor), AG490 (10 µmol/L, Janus kinase 2 inhibitor), pyrolidin dithiocarbamate (PDTC, 50 µmol/L, NF\^\textkappaB inhibitor), BAY117085 (5 µmol/L, NF\^\textkappaB inhibitor), RO-31-8220 (1 µmol/L - PKC inhibitor), U0126 (10 µmol/L, ERK1/2 kinase inhibitor), SB203580 (10 µmol/L, p38 MAPK inhibitor), apocynin (10-100 µmol/L, Nox inhibitor), carbonyl cyanide 4-(trifluoromethoxy)phenylhydrazone (FCCP 10 µmol/L, respiratory chain uncoupler), oligomycin (Oligo, 10 µM, complex V inhibitor), myxothiazol (Myxo, 10 µmol/L) + Uridine (50 mg/ml, complex III inhibitor), dinitrophenol (DNP, 10 µmol/L, respiratory chain uncoupler). n=4, *p<0.05 with and without AngII/LPS, #p<0.05 with and without inhibitor.