Acrolein-induced vasomotor responses of rat aorta

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Acrolein-induced vasomotor responses of rat aorta. Am J Physiol Heart Circ Physiol 285: H727–H734, 2003. First published May 1, 2003; 10.1152/ajpheart.00269.2003.—Acrolein is a highly reactive aldehyde pollutant and an endogenous product of lipid peroxidation. Increased generation of, or exposures to, acrolein incites pulmonary and vascular injury. The effects of acrolein on the vasomotor responses of rat aortic rings were studied to understand its mechanism of action. Incubation with acrolein (10–100 μM) alone did not affect the resting tone of aortic vessels; however, a dose-dependent relaxation of phenylephrine-precontracted aortic rings was observed. Acrolein-induced relaxation was slow and time dependent and the extent of relaxation after 100 min of application was 44.7 ± 4.1% (10 μM), 56.0 ± 5.6% (20 μM), 61.0 ± 7.9% (40 μM), and 96.1 ± 2.1 (80 μM), respectively, versus 14.2 ± 3.3% relaxation in the absence of acrolein. Acrolein-induced vasorelaxation was prevented by endothelial denudation and was abolished on pretreatment with the nitric oxide synthase inhibitor N'-nitro-L-arginine methyl ester, the guanylyl cyclase inhibitor 1H-[1,2,4]oxadiazolo[4,3-a]quinoxaline-1-one, or the cyclooxygenase inhibitor indomethacin. Inhibition of K+ channels (by tetrabutylammonium) or Na+-K+-ATPase (by ouabain) did not significantly prevent acrolein-mediated vasorelaxation. Exposure to acrolein in the presence or absence of other compounds elicited slow wave vasomotor effect in 77% of aortic vessels versus 1.4% in control. Vasomotor responses were also studied on aortic rings prepared from rats fed 2 mg·kg⁻¹·day⁻¹ acrolein for 3 alternate days by oral gavage. These vessels developed a significantly lower contractile response to phenylephrine compared with controls. Together, these results indicate that acute acrolein exposure evokes delayed vasorelaxation due to a nitric oxide-and prostacyclin-dependent mechanism, whereas in vivo acrolein exposure compromises vessel contractility.

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Several studies have implicated acrolein in vascular injury. Acrolein produces cytotoxic effect on pulmonary artery endothelial cells (27, 32) and induces platelet aggregation (40). Alteration of vascular reactivity is considered to be earliest event in vascular injury (37). Lipid peroxidation products, including unsaturated aldehydes, modulate vascular reactivity (28, 30, 35). The present study evaluates the effects of acrolein on vascular tone and reactivity in a rat thoracic aorta preparation. Our results demonstrate that in vitro acrolein induces vasorelaxation of the precontracted vessels and that this effect is mediated via nitric oxide (NO) and prostacyclin production. Vasocontraction was highly compromised in animals fed with acrolein.

MATERIALS AND METHODS

Reagents and Chemicals

All components of physiological salt solution (PSS), phenylephrine, acetylcholine bromide, Nω-nitro-L-arginine methyl ester (L-NAME), and Nω-nitro-D-arginine methyl ester (D-NAME) were purchased from Sigma (St. Louis, MO). 1H-[1,2,4]oxadiazolo[4,3-a]quinoxaline-1-one (ODQ), indomethacin, tetraethylammonium iodide (TBA), and ouabain were purchased from Sigma (St. Louis, MO). L-NAME, D-NAME, TBA, and ouabain were dissolved in the distilled water; ODQ and indomethacin were dissolved in dimethylsulfoxide. Aqueous acrolein was prepared fresh from the redistilled reagent acrolein (Sigma-Aldrich). In some experiments, free acrolein was prepared by the acid hydrolysis (pH 3.0) of the diethyl acetal for 1 h at room temperature. Acrolein solutions prepared by these methods yielded the same results. Acrolein was resuspended in distilled water at a concentration of 10 mM before use. Anti-endothelial nitric oxide (NO) synthase (eNOS) monoclonal antibody and horseradish peroxidase-conjugated anti-mouse IgG were from the Transduction Laboratories (Lexington, KY). A bicinchoninic acid (BCA) protein assay kit was purchased from Pierce (Rockford, IL), and electrochemiluminescence detection reagents were purchased from Amersham Pharmacia Biotech (Piscataway, NJ).

Animals

Male Sprague-Dawley rats (7 to 12 wk, 180–340 g, Harlan; Indianapolis, IN) were housed in a temperature- and humidity-controlled room of the Association for the Accreditation of Laboratory Animal Care-approved animal care facility with a 12:12-h light-dark cycle and fed with rat chow and water ad libitum. A separate group of rats was fed with acrolein (2 mM/l) in PSS for 12 wk. Animals were euthanized. The descending thoracic aorta was excised libitum. A separate group of rats was fed with acrolein (2 mM/l) in PSS for 12 wk. Animals were euthanized. The descending thoracic aorta was excised after the aortic rings were washed at the end of each experiment, allowed to equilibrate for 15 min, contracted with phenylephrine, and then relaxed with acetyicholine (see Animals). An identical protocol was used with vessels denuded of endothelium to establish that the responses were endothelium mediated.

To elucidate the mechanisms involved in acrolein-induced response, the rings were preincubated with inhibitors of endothelium-derived vasodilators: 1) L-NAME, a blocker of NOS (100 μM); 2) ODQ, a selective inhibitor of soluble guanylyl cyclase (1 μM); 3) indomethacin, an inhibitor of the cyclooxygenase (COX) pathway of arachidonic acid metabolism (0.25, 0.5, 1, 5, and 10 μM); 4) TBA, nonselective blocker of potassium channels (3 mM); and 5) ouabain, inhibitor of Na+–K+–ATPase (5 μM). Each of the compounds was incubated with aortic rings for 10 min, after which the rings were contractured with phenylephrine (1 μM). When the contraction reached plateau, acrolein (20 μM) was administered and incubated for an additional 90 min. Aortic rings incubated with 20 μM acrolein alone served as the control. In the L-NAME experiments, D-NAME (100 μM), an isomer devoid of NOS-inhibiting activity, was used as a negative control. To ensure that the contraction that followed NOS inhibitor administration was not due to a lack of substrate availability, an additional set of experiments was conducted in the presence of L-arginine, which is a NOS substrate. Maximal contraction evoked by phenylephrine detected at 10 min was taken as 100% and responses at 20, 40, 60, 80, and 100 min of incubation were expressed as a percentage of initial tonus. Maximal relaxation (E_{max}) was determined after 100 min of incubation and expressed as a percentage of the maximal contraction evoked by phenylephrine. The time required to produce half-maximal vasoactive effect (T_{1/2}) was determined from experimental data and was considered to reflect the vasorelaxant capacity of the compound.

Western blot analysis. Aortic rings were precontracted with phenylephrine, incubated in PSS in the absence (control) or presence of acrolein (10, 20, and 40 μM) for 10 min at 37°C, frozen immediately after the experiment, and kept at –86°C. Vessels were homogenized on ice in homogenization buffer containing 25 mM Tris, 1 mM EDTA, 1% SDS, and 0.5% soybean trypsin inhibitor. After centrifugation at 12,000 revolutions/min for 30 min, protein concentration was measured in supernatant using BCA protein assay kit to ensure equal protein loading on the gel. After 10% SDS-
PAGE and transfer, the membranes were probed with anti-eNOS monoclonal antibody. Horseradish peroxidase-conjugated anti-mouse IgG was used as the secondary antibody. An electrochemiluminescence detection system was used for protein visualization.

Aortic reactivity after in vivo treatment with acrolein. Aortic rings obtained from the rats treated orally with acrolein (2 mg/kg by oral gavage three times on alternate days over 5 days) were incubated in PSS and increasing concentrations of phenylephrine (10⁻¹⁰–10⁻⁸ M) were administered at 5-min intervals. Maximal contraction elicited by 80 mM KCl was taken as 100% and the response to each concentration expressed as a percentage. Aortic rings from animals gavaged with an equal volume of water were used as controls.

Statistical Analysis

Data are presented as means ± SE. Changes in vascular tone, expressed as the percentage of maximal contraction evoked by phenylephrine, were compared separately at each time point by one-way ANOVA and Dunnett’s test when significant differences existed between groups. Differences were considered statistically significant when the P value was <0.05.

RESULTS

Characterization of Vasorelaxation Induced by Acrolein

No significant change in vascular tone was observed when 10–100 μM acrolein was applied to the resting aortic rings equilibrated in PSS (data not shown). However, when applied to precontracted vascular rings, 10–80 μM acrolein induced dose-dependent relaxation during 100 min of total incubation time (Fig. 1A). The relaxation induced by 10–40 μM acrolein was apparent at 40 min and reached maximum at 100 min of incubation (total observation time). However, vasorelaxation in the presence of 80 μM acrolein was apparent at 20 min, and by 100 min it almost reached the baseline. Precontracted intact aortic rings (n = 14) incubated in PSS in the absence of acrolein for 100 min served as controls. After 40 min of incubation, the vascular tone of aortic rings treated with 10, 20, 40, and 80 μM acrolein decreased by 4.2 ± 2.8%, 16.3 ± 4.3%, 12.6 ± 3.8%, and 56 ± 4.5%, respectively (in each case, P < 0.05 vs. control), whereas in control vessels vascular tone remained unchanged. The value of E_max, determined at 100 min of incubation, was 44.7 ± 4.1, 56.0 ± 5.6, 61.0 ± 7.9, and 96.1 ± 2.1% for the vessels treated with 10, 20, 40, and 80 μM acrolein, respectively, and 14.2 ± 3.3% for control vessels (in each case P < 0.05 vs. control). T_{1/2} was significantly shorter in

Fig. 1. A: effect of acrolein on vascular tone of aorta rings precontracted with phenylephrine. Intact aortic rings were precontracted with 1 μM phenylephrine. After 10 min, when vasoconstriction reached plateau, acrolein (10, 20, 40, and 80 μM) was added to the bath and incubated for an additional 90 min. Maximal contraction evoked by phenylephrine at 10 min was taken as 100% and maximal response at 20, 40, 60, 80, and 100 min was expressed as the percentage of that initial vascular tone. Control curve was established during incubation of precontracted intact aortic rings in physiological salt solution (PSS) in the absence of acrolein. B: half-maximal relaxation time (T_{1/2}). The time required to produce half-maximal vasorelaxation was determined from the concentration-response curve. C: effect of acrolein on vascular tone of aorta rings denuded of endothelium and precontracted with phenylephrine. Aortic rings denuded of endothelium were precontracted with 1 μM phenylephrine. Incubation conditions, experimental procedure, and data interpretation were as described in A. Control curve was established during incubation of precontracted denuded aortic rings in PSS in the absence of acrolein. Data are means ± SE (n = number of vessels in each data series). *P < 0.05 vs. control.
Acrolein-treated vessels compared with controls (Fig. 1B). Although not many differences were found among vessels exposed to 10–40 μM acrolein, \( T_{1/2} \) for 80 μM acrolein was considerably shorter. However, in our subsequent experiments with inhibitors, we chose to use 20 μM acrolein to avoid cytotoxicity.

The endothelium-denuded vessels did not respond to acrolein (Fig. 1C), indicating that acrolein-mediated vasorelaxation was endothelium dependent. The values of \( E_{\text{max}} \) were 21.0 ± 8.9, 21.3 ± 5.2, and 14.9 ± 8.9% in vessels exposed to 10, 20, and 40 μM acrolein, respectively, versus 6.3 ± 2.5% in control (vessels denuded of endothelium and precontracted with phenylephrine incubated in PSS for 100 min in the absence of acrolein). Although the isometric tension of the denuded vessels exposed to acrolein had a tendency to decrease, it did not differ significantly from control vessels.

**Mechanism of Acrolein-Mediated Vasorelaxation**

To examine the mechanisms of acrolein-induced vasorelaxation, the aortic ring preparations were pretreated with inhibitors of endothelium-derived vasodilators before adding phenylephrine and acrolein (20 μM). Pretreatment with the eNOS inhibitor L-NAME (100 μM) completely prevented the vasodilator response induced by acrolein (Fig. 2A). The isometric tension of the vessels in the presence of L-NAME corresponded to 103.8 ± 11.8% after 100 min of incubation with acrolein. Pretreatment with D-NAME (100 μM), an inactive isomer of L-NAME, did not significantly affect acrolein-evoked vasodilation and the \( E_{\text{max}} \) observed was 49.6 ± 6.3. These data indicate that acrolein-mediated vasorelaxation is mediated by endothelium-derived NO. Addition of L-arginine did not change the vascular tone (data not shown), indicating that vasorestriction in this case is not caused by the lack of availability of eNOS substrate. The role of NO in acrolein-evoked vasodilation was further probed with the use of ODQ, which is a relatively specific inhibitor of NO-mediated activation of guanylyl cyclase (6). Treatment with 1 μM ODQ abolished acrolein-induced vasodilation (Fig. 2B), and the vascular tone of the rings preincubated with ODQ slightly increased to 102.0 ± 4.2% after 100 min of incubation (\( P < 0.05 \)). These observations further support the view that acrolein-mediated vasorelaxation is in part NO mediated.

Pretreatment with the COX inhibitor indomethacin also abolished acrolein-induced vasodilation (Fig. 3).

![Fig. 2. A: effect of N^\text{\textsuperscript{-}hydroxy}-L-arginine methyl ester (l-NAME) on acrolein-induced vasorelaxation. Aortic rings were preincubated with l-NAME or \( N^\text{\textsuperscript{-}nitro-d-arginine methyl ester (d-NAME, 100 μM). Aortic rings incubated with 20 μM acrolein alone served as control in these data series. B: effect of 1H-\{1,2,4\}-oxidazolo[4,3-\text{α}]-quinoxaline-1-one (ODQ) on acrolein-mediated vasorelaxation. Aortic rings were preincubated with ODQ (1 μM). Vasorelaxation in the presence of 20 μM acrolein served as a control for this series. Data are means ± SE (n = number of vessels in each data series). *P < 0.05 vs. control.](http://ajpheart.physiology.org/)

![Fig. 3. Effect of indomethacin on acrolein-mediated vasorelaxation. Aortic rings were preincubated with indomethacin (0.25, 0.5, 1, 5, and 10 μM) and then treated with acrolein as described in Fig. 1A. Data are means ± SE (n = number of vessels in each data series). *P < 0.05 vs. control (relaxation curve obtained with 20 μM acrolein).](http://ajpheart.physiology.org/)
Concentration of indomethacin applied in inhibitor studies in the rat aorta is 10 μM (17). However, in our experiments, 1 and 5 μM indomethacin yielded complete inhibition and 0.5 μM caused partial inhibition, whereas at 0.25 μM no inhibition was observed. The $E_{\text{max}}$ values obtained from the rings exposed to 20 μM acrolein in the presence of 0.25, 0.5, 1, 5, and 10 μM indomethacin were 35.0 ± 6.2%, 54.1 ± 4.5%, 5.0 ± 5.3%, 5.2 ± 2.1%, and 2.0 ± 0.9%, respectively, compared with an $E_{\text{max}}$ value of 56.0 ± 5.6% obtained with 20 μM acrolein alone ($P < 0.05$ in each case). These data suggest that acrolein activates the COX pathway of arachidonic acid and prostacyclin production.

Application of a nonselective blocker of potassium channels, TBA, slightly potentiated the vasodilator response to acrolein (Fig. 4). The value of $E_{\text{max}}$ obtained from vessels incubated with 3 mM TBA and 20 μM acrolein was 73.2 ± 6.1%.

Inhibition of Na+-K+-ATPase by ouabain did not significantly affect acrolein-mediated vasodilation. Interestingly, acrolein has been reported to mimic the effect of ouabain, causing loss of Na+-K+-ATPase (32), in which case it would have been expected to potentiate the effect of ouabain. However, we noted no significant changes. The $E_{\text{max}}$ value obtained from rings incubated with 5 μM ouabain and 20 μM acrolein was 41.3 ± 4.8%, which is not significantly different from that obtained from aortic rings treated with acrolein alone (data not shown).

Reversibility of Effect of Acrolein on Vessel Wall

To ensure structural and functional integrity of the vessel, after each experiment, aortic rings were washed three times, allowed to equilibrate and then contracted with 1 μM phenylephrine. The maximal contraction was recorded after 5 min of addition of phenylephrine. The aortic rings were relaxed by adding 10 μM acetylcholine to the bath. The response to phenylephrine in vessels exposed to acrolein (with or without other reagents) corresponded to 80.1 ± 4.5% of the maximal contraction, whereas in control rings it was 95.4 ± 3.5% ($P < 0.05$), indicating that vascular contractility was compromised by acrolein. Endothelium-dependent relaxation was not significantly different between these groups: 93.7 ± 3.9% (acrolein-treated vessels) versus 94.0 ± 0.63 (control).

Slow Wave Vasomotion

Slow wave vasomotion with frequency of 1–4/min and variable amplitude was present in 77% of aortic rings exposed to acrolein (in the presence of the absence of other additives) and 1.4% of the vessels incubated in PSS alone. Although preincubation with ouabain only slightly decreased the incidence of slow-wave vasomotor effects of acrolein (it was observed in 62% of the aortic rings), we noted that it attenuated the amplitude of vasomotion. Interestingly, acrolein-induced vasomotion was only present when endothelium of the vessel was preserved. None of the aortic rings denuded of endothelium displayed such behavior on prolonged acrolein exposures. From these observations, we infer that slow wave vasomotion observed in our experiments is a result of acrolein-mediated endothelial dysfunction (12) and indicates that acrolein primarily affects endothelial function.

Western Blot Analysis

Expression of eNOS was only slightly increased in vessels exposed to acrolein compared with control rings (by ~20% in vessels exposed to 40 μM acrolein) (data not shown). This suggests that protein is not degraded, whereas new protein synthesis of eNOS occurs only to minor extent over this relatively short incubation time and acrolein probably modifies the activity of the preformed enzyme.

Aortic Reactivity After In Vivo Treatment With Acrolein

As shown in Fig. 5, the response to phenylephrine was decreased in the aortic rings obtained from the rats exposed to acrolein in vivo. The response to $10^{-8}$ M phenylephrine was decreased by 74%, $10^{-7}$ M by 50%, and $10^{-6}$ M by 33%, respectively. This is consistent with the in vitro data and indicates that acrolein feeding compromises the contractility of thoracic aorta. Animals treated with acrolein did not exhibit any gross physical changes, such as weight or hair loss.

DISCUSSION

The main findings of the present study are that exposure to acrolein induces a dose-dependent vasorelaxation of precontracted rat aortic rings and that the response to acrolein was abolished by endothelial denudation of the aortic rings. These observations clearly indicate that acrolein-induced vasorelaxation is due to increased generation of endothelial vasodilators. Our results further show that inhibition of NOS or COX...
proves the response to acrolein, indicating that increased endothelial generation or availability of NO and prostaglandins is the underlying mechanism by which acrolein induces relaxation of the in vitro preparations of aortic rings.

Impairment of vascular reactivity induced by the reactive aldehyde species has been reported. Previous studies (30, 35) show that HNE induces vasorelaxation in cerebral, coronary, and mesenteric arteries through a NO/prostacyclin-dependent mechanism. In contrast, it has been reported that acrolein and allylamine produce vasoconstriction and attenuate acetylcholine-induced relaxation in the rat thoracic aorta and coronary artery in vitro (11, 12). These findings are in accord with the hypothesis that allylamine (a dye that generates acrolein during metabolism) induces vasospasm, leading to myocardial ischemia and necrosis. However, our results are in contrast to the latter findings. This variability may be due to differences in experimental design and protocol. In contrast to the study by Conklin et al. (12), in our study 1) acrolein was applied to the precontracted vessels; 2) concentrations of acrolein were in a much lower range (10–40 μM vs. 0.1–1 mM); and 3) the incubation period was longer. Thus, together with the results of our studies performed in the aortic vessels obtained from the rats fed acrolein, these results are consistent with the idea that acrolein compromises the contraction capacity of the vessel. These data suggest that acrolein may interfere with autoregulation of blood flow, which may have pathophysiological implications under different conditions.

Because reactive aldehydes readily interact with proteins resulting in modification of their structure and enzymatic activity, we hypothesize that acrolein interacts with the components of NO and/or prostacyclin synthesis pathways and thus induces vasorelaxation. Alternatively, acrolein could modify the responsiveness of vascular smooth muscle cells to the vasodilator stimuli. Interestingly, ifosfamide (which generates acrolein during in vivo metabolism) was found to induce NO production by iNOS, mediating development of the hemorrhagic cystitis in mice (34). Acrolein also stimulates eicosanoid release from the bovine airway epithelial cells (15). Several reports (31, 39, 41) indicate a cross-talk between NO and COX pathways. NO-induced COX activation has been demonstrated in several different cell types, including cardiac myocytes (42) and the ischemic brain (31). The interaction may also occur in the reverse direction. COX products prostaglandin G2 and hydroperoxyeicosatetraenoic acid stimulated NOS activity in the rat brain (19). Thus it is possible that activation of one pathway takes place first and is followed by the induction of the other. Surprisingly, we found that both L-NAME and indomethacin completely blocked vasorelaxation, raising the question of the relative contribution of each pathway to the vasodilator response in the rat aorta both under physiological conditions and after exposure to acrolein.

The releases of NO and prostacyclin are coupled at the receptor level (14), and several stimuli that release NO also release prostacyclin (47). Inhibition of iNOS was found to abrogate prostanooid synthesis, whereas inhibition of COX-2 did not affect iNOS activity (42). Our results indicate that inhibition of each pathway causes reciprocal inhibition of the other and suggests bidirectional nature of NO-COX interactions.

As one of the main components of cigarette smoke, acrolein may be partly responsible for the increased risk of vascular disease in smokers. Several reports implicate the potential role of acrolein in vascular injury and atherogenesis. Acrolein immunoreactivity was demonstrated in human atherosclerotic plaque (45), whereas HNE- and malonaldehyde-conjugated proteins were reported earlier in atherosclerotic lesions (23, 36). Allylamine, which is converted to acrolein in cardiovascular tissues, is an established cardiovascular toxin that induces acute myocardial necrosis and intimal proliferation reminiscent of the early atherosclerosis lesion in several mammalian species (6). Acrolein is produced during biotransformation of allylamine by the enzyme semicarbazide-sensitive amino oxidase. Cardiovascular toxicity of allylamine is considered to be mediated mainly through action of acrolein, because semicarbazide, an inhibitor of semicarbazide-sensitive amino oxidase, prevents or significantly reduces the cardiovascular toxicity of allylamine (11). Interestingly, although single in vitro exposure to acrolein inhibited cell growth, repeated treatment with allylamine resulted in significant enhancement of the growth capacity of the smooth muscle cells, implicating its role in chemical atherogenesis (33).

Modulation of vascular reactivity and impairment of endothelial function is one of the earliest events in the development of atherosclerosis, preceding the morphological changes of the arterial wall (37). Impairment of NO-mediated, endothelium-dependent arterial relax-
vation has been demonstrated in the earliest stage of atherosclerosis (50), whereas impairment of endothelium-independent relaxation occurs at the later stage (48). Atherosclerosis and hypercholesterolemia are associated with the hypersensitivity to the contractile stimuli and impairment of the endothelium-mediated vasorelaxation through inhibition of NO production, whereas high-density lipoprotein plays a beneficial role in normalization of endothelial function (13, 16, 24).

Cigarette smoke causes impairment of vasmotor function with a differential effect in different vascular beds: vasoconstriction in the coronary and peripheral circulation and vasodilation in pulmonary circulation (20, 51), the latter finding being in accord with our results.

In an attempt to interpret our present data in this context, we hypothesize that acrolein, although causing early vasodilation, may result in the consumption of the available pool of NO and/or prostacyclin (or their precursors and/or substrates), thereby reducing bioavailability and later compromising the relaxation capacity of the vascular wall. Further studies are needed to better characterize acrolein-mediated molecular effects, including the specific mechanisms involved in the production of NO and PG12.

DISCUSSIONS

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