Potentiation of Norepinephrine-Induced Contractions by Endothelin-1 in the Rabbit Aorta

Daniel Henrion, Ismail Laher

Subthreshold concentrations of endothelin-1 potentiated the norepinephrine-induced contraction in isometrically mounted rings of the rabbit aorta. Pretreatment with endothelin-1 (0.1 nM) for 10 minutes increased the sensitivity of the aortic rings to norepinephrine without affecting the maximal contraction. This amplification was unaffected by removal of the endothelium but was prevented by the protein kinase C inhibitors staurosporine (0.01 μM) and calphostin C (0.1 μM). Pretreatment of the aortic rings for 24 hours with phorbol 12-myristate 13-acetate (0.1 μM) also abolished the potentiation. Norepinephrine-induced contraction was potentiated by pretreating with phorbol 12-myristate 13-acetate (10 nM) and by increasing the concentration of K+ in the bath solution from 4.6 to 8.6 mM. The potentiation of the norepinephrine-induced contraction by endothelin-1 (0.1 nM) or by phorbol 12-myristate 13-acetate (10 nM) was not associated with an increase in norepinephrine-induced 45 Ca2+ uptake or influx, whereas the potentiation due to an increase in the concentration of K+ in the bath solution from 4.6 to 8.6 mM was associated with an increase in norepinephrine-induced 45 Ca2+ uptake. We conclude that endothelin-1 potentiation of the norepinephrine-induced contraction occurs in the absence of changes in stimulated Ca2+ entry and is endothelium independent. It is probable that endothelin-1 increases the sensitivity of the contractile apparatus to Ca2+ by activating protein kinase C-dependent mechanisms. (Hypertension 1993;22:78-83)

KEY WORDS • endothelins • drug synergism • aorta • norepinephrine • protein kinase C • calcium

Endothelin-1 (ET-1) is a potent vasoconstrictor produced by endothelial cells. Its direct contractile effect has been widely studied, although it is not yet completely understood. On the other hand, subthreshold concentrations of ET-1, compatible with the plasma level, potentiate the contractile effect of different agonists such as norepinephrine in human arteries and rat mesenteric beds and serotonin in rat aortic rings and pulmonary arteries. Such a phenomenon might have a pathological importance since it could be involved in hypertension and vasospastic syndrome. Indeed, the potentiation of serotonin-induced contractions by ET-1 might increase the vasoconstrictions induced by aggregating platelets. Moreover, there is a positive correlation between ET-1 plasma level and systolic blood pressure in humans, and the vascular production of ET-1 under angiotensin II (Ang II) stimulation is higher in hypertensive than in normotensive rats. The amplification is nevertheless blocked by Ca2+ entry blocker in human arteries and in the rat mesenteric bed. In contrast, the direct effect of ET-1 is relatively insensitive to Ca2+ entry blockers. Finally, low concentrations of ET-1 have been shown to activate the conversion of angiotensin I into Ang II in endothelial cells.

We have previously shown in the rabbit facial artery, a muscular blood vessel, that Ang II potentiates the contractions induced by norepinephrine, histamine, and caffeine (in the absence of extracellular Ca2+). The potentiation depends on protein kinase C (PKC) activation and is not associated with changes in 45 Ca2+ uptake. A similar phenomenon was found in the rabbit aorta.

In the present study, we investigated the role of PKC in the phenomenon of potentiation by ET-1 of the norepinephrine-induced contractions. In addition, we compared the increase in 45 Ca2+ uptake induced by norepinephrine after potentiation by ET-1, by the PKC activator phorbol 12-myristate 13-acetate (PMA), or by an increase in K+ in the extracellular medium. The present study suggests that ET-1 amplified the norepinephrine-induced contraction without changing the 45 Ca2+ uptake. The amplification was prevented by PKC inhibition and was not affected by the removal of the endothelium. Our results suggest that vascular intracellular sensitivity to Ca2+ is enhanced during contractile amplification by ET-1 through a PKC-dependent mechanism.

Methods

Aorta Preparation

The thoracic aorta was isolated from adult New Zealand male rabbits (2-4 kg) that were exsanguinated.
and decapitated under pentobarbital anesthesia (50 mg/kg IV combined with heparin 1000 IU/kg). Ring segments 3 mm in length were cleaned of fat and connective tissues and were mounted between two stainless steel wires in a 30-mL organ bath containing physiological salt solution (PSS) of the following composition (in mM): NaCl 160, KCl 4.6, CaCl2 1.5, MgSO4 1.2, N-[2-hydroxyethyl]piperazine-N'-[2-ethanesulfonic acid] (HEPES) 5.0, and glucose 11.0. The pH of the PSS was adjusted to 7.4 with NaOH (1 M), and the solution was bubbled with 100% oxygen. The PSS contained propanolol (1 µM) to inhibit β-adrenergic receptors and desmethylimipramine (0.1 µM) and deoxycorticosterone (10 µM) to reduce neuronal and extraneuronal norepinephrine uptakes. A PSS containing 8.6 mM K+ was prepared by increasing the amount of KCl and by proportionally decreasing the amount of NaCl in the PSS. One wire was attached to a fixed support, and the second wire was connected to a moveable holder supporting a tension transducer (model FT 03, Grass Instruments, Inc., Quincy, Mass) so that isometric force measurements could be recorded on a physiograph (model SD90, Grass). The artery segments were allowed to recover for 60 minutes, and the PSS was replaced at 15-minute intervals during this time. After this recovery period, a 1 g preload, resulting in optimal stretch, was applied to the aortic segments, which were then allowed to equilibrate for an additional 90 minutes.

Contractile Response to Norepinephrine

A concentration-response curve to norepinephrine was made by cumulative additions of norepinephrine to the PSS. The PSS was replaced several times until tissues returned to baseline tension. The PSS was replaced at 15-minute intervals throughout the experiment. Several dose-response curves to norepinephrine were performed at 90-minute intervals until successive concentration-response curves no longer changed in sensitivity. A final concentration-response curve to norepinephrine after log/logit transformation. A value of P<.05 was considered significant.

Calcium-45 Uptake

Measurements of the uptake of 45Ca2+ were made at 37°C using the methods described by Meisher et al.16 and modified so that 45Ca2+ uptake and wall force could be measured simultaneously.14 After stabilization of the contractile response to norepinephrine (0.1 µM), 45CaCl2 (0.67 µCi/mL) was added to the PSS for 90 minutes. Tissues were then exposed to norepinephrine (0.1 µM) for 3 minutes, either in the absence or presence of ET-1 (0.1 nM), PMA (10 nM), or K+ (8.6 mM). Resting values of 45Ca2+ uptake were determined by adding 45CaCl2 (0.67 µCi/mL) to the PSS for 93 minutes and by omitting the addition of norepinephrine (0.1 µM). In some experiments, arteries were incubated with 45CaCl2 for 93 minutes and ET-1 (0.1 nM), PMA (10 nM), or K+ (8.6 mM). After exposure to 45CaCl2, either with or without norepinephrine and/or ET-1 (0.1 nM), PMA (10 nM), or K+ (8.6 mM), the 45Ca2+ content was determined as described below.

Calcium-45 Influx

Unidirectional influx measurements were made according to the method of Meisher et al.18 After the response to norepinephrine (1 µM) reached a maintained level, in either the absence or the presence of endothelin (0.1 nM, 10 minutes), the tissues were exposed to a PSS containing 45CaCl2 (0.67 µCi/mL) but otherwise identical to the experimental solution. After exposure to 45Ca2+ for 90 seconds, 45Ca2+ content was determined as described below.

Calcium-45 Content

The PSS containing 45CaCl2 (0.67 µCi/mL) was changed for an ice-cold Ca2+-free PSS containing EGTA (0.1 mM). Simultaneously, the organ bath temperature was decreased to 0°C. Tissues were then removed and placed in 100 mL of ice-cold bubbled PSS for 45 minutes to remove the extracellularly free bound 45Ca2+. Artery segments were then blotted dry, weighed, and incubated overnight in EDTA (5 mM) before counting in a liquid scintillation counter (model LS 7800, Beckman Instruments, Carlsbad, Calif). Values of net uptake of 45Ca2+ are expressed as micromoles per kilogram and as micromoles per kilogram per minute for 45Ca2+ influx measurement.

Statistical Analysis

Results are expressed as mean±SEM. EC50 was calculated for each individual concentration-response curve to norepinephrine after log/logit transformation. Comparisons between groups were made using a one-way analysis of variance followed by a Scheffe’s F test when significant. A value of P<.05 was considered significant.

Drugs

ET-1, norepinephrine, captopril, PMA, and 4a-PMA were purchased from Sigma Chemical Co., St. Louis, Mo. Stauroporine was purchased from Kyowa Hakko USA Inc., New York, NY. Calphostin C was purchased.
Vol 22, No 1 July 1993

TABLE 1. Sensitivity of Rabbit Aorta Rings to Norepinephrine Before and After Pretreatment With Endothelin-1 and Effect of Staurosporine, Calphostin C, or Endothelium Removal

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Before ET-1 (EC50, μM)</th>
<th>After ET-1 (EC50, μM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent</td>
<td>0.48±0.04 (11)</td>
<td>0.16±0.07 (8)*</td>
</tr>
<tr>
<td>Staurosporine (0.01 μM)</td>
<td>0.62±0.11 (6)</td>
<td>0.52±0.05 (6)†</td>
</tr>
<tr>
<td>Calphostin C (0.1 μM)</td>
<td>0.55±0.09 (8)</td>
<td>0.50±0.06 (8)†</td>
</tr>
<tr>
<td>Endothelium removal</td>
<td>0.22±0.08 (5)†</td>
<td>0.08±0.03 (5)‡</td>
</tr>
<tr>
<td>24 h at 4°C</td>
<td>0.36±0.07 (6)†</td>
<td>0.07±0.04 (6)†</td>
</tr>
<tr>
<td>24 h at 4°C+PMA (0.1 μM)</td>
<td>0.91±0.17 (6)†</td>
<td>0.75±0.11 (6)†</td>
</tr>
</tbody>
</table>

ET-1, endothelin-1; PMA, phorbol myristate acetate. Values represent mean ±SEM. Numbers in parentheses are number of rings.

*P<.05, one-way analysis of variance (ANOVA) compared with the value before ET-1.
†P<.05, one-way ANOVA compared with the solvent group.
‡Some arteries were stored for 24 hours of incubation at 4°C either in the absence or presence of PMA.

Results

Effect of Endothelin-1 on Norepinephrine-Induced Contractions

Norepinephrine contracted the aortic ring segments (Fig 1) with an EC50 of 0.48±0.05 μM (n=11) and a maximal response of 7.3±0.28 g (n=11). ET-1 (0.1 nM) pretreatment did not modify the maximum force obtained (7.53±0.15 g, n=8) but increased the sensitivity to norepinephrine (Table 1). Pretreatment of the aorta with staurosporine (0.01 μM) or calphostin C (0.1 μM) affected neither the maximum response to norepinephrine nor the EC50 but did abolish the potentiation effect of ET-1 (0.1 nM) (Fig 1). The norepinephrine EC50 in the presence of ET-1 (0.1 nM) after staurosporine (0.01 μM) or calphostin C (0.1 μM) pretreatment was not significantly different from the control values (Table 1).

The expression of the concentration-response curve to norepinephrine after ET-1 (0.1 nM) as a percentage of the control concentration-response curve (Fig 1) allowed the quantification of the potentiating effect of ET-1. It was the highest when the concentration of norepinephrine was low. Potentiation by ET-1 (0.1 nM) expressed as a percentage of the control values was 314±53%, 219±28%, 206±28%, and 131±10% at norepinephrine concentrations of 0.01, 0.03, 0.1, and 0.3 μM, respectively (n=8 per group, P<.05) when the data were expressed as a percentage of the control.

Removal of the endothelium did not affect the maximum response to norepinephrine (7.35±0.40 g, n=5 versus 7.30±0.28 g, n=11), but it decreased the EC50 (Table 1) and suppressed the ability of acetylcholine (10 μM) to relax the norepinephrine (1 μM)-induced contraction (5±5% versus 85±12% relaxation before removal of the endothelium, n=5, P<.05). However, the removal of the endothelium did not affect the potentiating effect of ET-1 (0.1 nM): after endothelium removal, the potentiation by ET-1 (0.1 nM), expressed as a percentage of the control, was 300±58%, 325±75%, 238±38%, and 131±10% at norepinephrine concentrations of 0.01, 0.03, 0.1, and 0.3 μM, respectively (n=5 per group, P<.05).

Preincubation of the Aorta With PMA

After 24 hours at 4°C in a PSS, the concentration-response curve to norepinephrine was not significantly modified. The maximal response was 6.80±0.39 g (n=6), and the EC50 was 0.46±0.07 μM (n=6). However, although incubation of the segments for 24 hours...
at 4°C in PSS containing PMA (0.1 μM) did not change the maximal response (7.35±0.25 g, n=5), it significantly increased the EC_{50} (Table 1). This procedure abolished the contractile response to PMA (1 μM), which was 2.20±0.42 g in the control (n=6) and 0.15±0.10 g (n=5, P<.05) after preincubation. The inactive phorbol ester 4α-PMA (0.1 μM) did not affect either the concentration-response curve to norepinephrine or the potentiation effect of ET-1 (0.1 nM) (not shown).

The potentiation of the norepinephrine-induced contraction by ET-1 (0.1 nM) was still present after 24 hours at 4°C (Fig 1) as well as after preincubation with 4α-PMA (expressed as a percentage of the control, it was 285±80%, 244±70%, and 145±25% at norepinephrine concentrations of 0.03, 0.1, and 0.3 μM, respectively, n=4 per group, P<.05). By contrast, preincubation of the aorta segments with PMA (0.1 μM) for 24 hours at 4°C greatly attenuated the amplification of the norepinephrine-induced contraction by ET-1 (0.1 nM) (Fig 1).

**Table 2. 45Ca^{2+} Uptake in Rabbit Aorta Rings and Effect of Endothelin-1, Phorbol Myristate Acetate, and K^{+}**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Force (g) before treatment</th>
<th>Force (g) after treatment</th>
<th>45Ca^{2+} uptake (μmol/kg) after treatment</th>
<th>45Ca^{2+} uptake (μmol/kg) after treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent</td>
<td>1.38±0.13</td>
<td>1.49±0.14</td>
<td>127.9±7.6 (17)*</td>
<td>100.7±5.4 (9)</td>
</tr>
<tr>
<td>ET-1 (0.1 nM)</td>
<td>1.23±0.14</td>
<td>1.65±0.15*</td>
<td>110.3±5.6 (13)*</td>
<td>95.9±6.6 (9)</td>
</tr>
<tr>
<td>PMA (10 nM)</td>
<td>1.33±0.08</td>
<td>1.91±0.15*</td>
<td>125.0±10.0 (8)*</td>
<td>103.3±6.3 (6)</td>
</tr>
<tr>
<td>K^+ (8.6 mM)</td>
<td>0.90±0.35</td>
<td>1.58±0.14*</td>
<td>150.0±19.5 (5)*</td>
<td>98.0±5.4 (8)</td>
</tr>
</tbody>
</table>

ET-1, endothelin-1; PMA, phorbol myristate acetate. The increase in wall force due to norepinephrine (0.1 μM) was determined before (first column) and after pretreatment with either ET-1 (0.1 nM), PMA (10 nM), or K^+ (8.6 mM) (second column). 45Ca^{2+} uptake was determined after the pretreatment in response to norepinephrine (third column, in which the 45Ca^{2+} uptake corresponds to the increase wall force given in second column) or after the pretreatment in the absence of norepinephrine (fourth column). Values represent mean±SEM. Numbers in parentheses are number of rings.

**Figure 2. Bar graph shows changes in the 45Ca^{2+} uptake per unit force developed (micromoles per kilogram of weight per gram of force developed) after ET-1 (0.1 nM) or PMA (10 nM) exposure for 10 minutes.** Enlarge bar graph shows changes in the 45Ca^{2+} uptake per unit force developed after exposure to ET-1 (0.1 nM) or PMA (10 nM) exposure for 10 minutes. Values are mean±SEM. *P<.05, one-way analysis of variance, compared with the control.
minute, n=22) by prior exposure of the arteries to ET-1 (0.1 nM) for 10 minutes.

**Discussion**

The present study provides evidence that the amplification of vascular tone due to norepinephrine by a subthreshold concentration of ET-1 depends on a direct effect of ET-1 on smooth muscle cells. The present findings are (1) ET-1 (0.1 nM) increased the sensitivity of aortic segments to norepinephrine, (2) the potentiation due to ET-1 (0.1 nM) and to PMA (10 nM) was not associated with an increase in norepinephrine-induced 
\[ \text{Ca}^{2+} \] uptake or \[ \text{Ca}^{2+} \] influx, and (3) staurosporine (0.01 \( \mu \)M) and calphostin C (0.1 \( \mu \)M), as well as a long-term incubation with PMA (0.1 \( \mu \)M), suppressed the potentiation.

Several studies have shown a positive interaction between ET-1 and norepinephrine. Subthreshold concentrations of ET-1 amplify the contractile effect of different agonists such as norepinephrine, 
\[ \text{angiotensin II (Ang II)}, \]
Bay K 8644, and serotonin. The amplification phenomenon requires receptor stimulation to take place and is independent of factors released by the endothelium. Moreover, the modulation of blood vessel tone by ET-1 might be of physiological and pathological importance since it takes place at subthreshold concentrations compatible with circulating ET-1 levels and since this phenomenon might be involved in hypertension and vasospastic syndromes. The possibility that ET-1 amplifies the norepinephrine-induced contraction by depolarizing vascular smooth muscle cells and consequently by increasing the influx of \[ \text{Ca}^{2+} \] into these cells during the contraction elicited by norepinephrine is unlikely since ET-1 (0.1 nM) and PMA (10 nM) both potentiated the norepinephrine-induced contraction without increasing the associated uptake or influx of \[ \text{Ca}^{2+} \]. A small increase in the amount of \[ \text{Ca}^{2+} \] in the extracellular medium potentiated both the norepinephrine-induced contraction and uptake of \[ \text{Ca}^{2+} \] from the extracellular medium. This is consistent with our previous finding that another vasoactive peptide, Ang II, amplifies the caffeine-induced contraction in a medium free of extracellular \[ \text{Ca}^{2+} \]. Since the transient contractile response to caffeine is due to the release of \[ \text{Ca}^{2+} \] from internal stores, amplification of vascular responses by Ang II and ET-1 might not depend on alterations in release and possibly extrusion of \[ \text{Ca}^{2+} \]. Nevertheless, such an issue should be examined more directly. Such a proposal can best be examined with direct measurements of free \[ \text{Ca}^{2+} \], for example, by using fluorescent recorder dyes for \[ \text{Ca}^{2+} \].

The ability of small increases in extracellular \[ \text{K}^{+} \] to augment norepinephrine-induced tone and \[ \text{Ca}^{2+} \] uptake may be related to the effect of changes in \[ \text{K}^{+} \] on the open state probability of voltage-gated \[ \text{Ca}^{2+} \] channels, as demonstrated by Nelson et al. If ET-1 does not increase the \[ \text{Ca}^{2+} \] entry to potentiate the norepinephrine-induced contraction, it could act by increasing the sensitivity of the contractile apparatus to \[ \text{Ca}^{2+} \]. This mechanism might be involved in the contractile response to several agonists (see above). Indeed, in support of a possible direct effect of ET-1, Tabushi et al. have shown that ET-1 potentiated norepinephrine-induced contractions together with a decrease in the release of norepinephrine from the rat mesenteric artery. Laher et al. have suggested that tonic modulation of PKC activity increases the sensitivity of intracellular contractile mechanisms associated with \[ \text{Ca}^{2+} \]-dependent vasoconstriction, providing a nonspecific mechanism for agonist amplification. The present study showed that staurosporine and calphostin C, two mechanistically distinct inhibitors of PKC, suppress the amplifying effect of ET-1. We have also been shown a similar effect of these inhibitors on the Ang II potentiating property in the rabbit facial artery and aorta. Thus, Ang II and ET-1 might share a common mechanism to potentiate the norepinephrine-induced contraction. The concentrations and incubation times of staurosporine and calphostin C used in the present study were similar to those used in the latter studies. In all cases, they did not affect the norepinephrine-induced contraction. Moreover, in such conditions, they presumably do not inhibit myosin light chain kinase activity since they do not influence the response to readmission of \[ \text{Ca}^{2+} \] in the depolarized rabbit femoral artery, basilar artery, and aorta, as well as in rat midcerebral artery and mesenteric arterioles. These biochemical and functional studies have shown that calphostin C is more specific for PKC than staurosporine. Our results indicate that after pretreatment with PMA for 24 hours at 4°C, the potentiating effect of ET-1 in the rabbit aorta was abolished. A similar protocol decreases the contractility to serotonin, norepinephrine, \[ \text{K}^{+} \], and phorbol esters in dog carotid artery rings without decreasing the PKC activity. By contrast, in our present study, as well as in a previous one, the contractile response to PMA (1 \( \mu \)M) and the potentiation phenomenon were abolished after this procedure. In isolated cells, chronic exposure to phorbol esters has been shown to downregulate PKC as a consequence of an increased rate of degradation of the enzyme.

A loss of PKC activity was not observed by Merckel et al. in carotid segments, suggesting either a difference due to the technique (isolated cells versus whole artery segment) or a difference in the PKC subtypes involved. Huwiler et al. have shown a different recovery of PKC isoforms after a 24-hour treatment with a phorbol ester, and in rabbit aortic cells, the subtype III of PKC disappears completely after such a treatment. The potentiation phenomenon we observed could depend on a PKC subtype sensitive to such a procedure since no more contraction to PMA was detected in the present study after incubation (24 hours at 4°C) with PMA (0.1 \( \mu \)M). Such an issue should be examined by measuring the PKC isoforms involved in the potentiation phenomenon. The specificity of action of PMA was controlled by the lack of downregulation effect (contraction to PKC and potentiation phenomenon still present) after incubation with the inactive phorbol ester 4α-PMA.

Additional support for a role of PKC activation in the potentiation effect of ET-1 is provided by the demonstration that the exogenous acute activation of PKC by PMA amplified the norepinephrine-induced contraction while decreasing the ratio of \[ \text{Ca}^{2+} \] uptake per unit of force (present study). This reproduced the amplification due to ET-1. Particularly, in both cases, less \[ \text{Ca}^{2+} \] was necessary to obtain a contraction on addition of norepinephrine. Phorbol esters have also been shown to amplify the vasoconstriction due to serotonin, to \( \alpha \)-adrenergic receptor stimulation, and to \[ \text{K}^{+} \] depolarization.
tion. In porcine coronary arteries, both ET-1 and a phorbol ester amplify serotonin-induced contraction without any significant increase in free cytosolic Ca\(^{2+}\). A finding that is in keeping with our observation that ET-1 and PMA potentiate norepinephrine-induced contraction without increasing the uptake of 45Ca\(^{2+}\).

In a recent study made in the rat, Yoshida et al demonstrated a pressor response when Ang II and ET-1 were infused in combination and not separately. However, combined infusion of ET-1 and norepinephrine failed to increase blood pressure. This contrasts with our findings, since our results and those of others, eg, Yang et al, Consigny, and Dohi et al, indicate a nonspecific increase in vascular constriction after exposure to ET-1.

In conclusion, we provided evidence that ET-1-induced potentiation of the norepinephrine-induced contraction depends on the activation of PKC without involving an increase in Ca\(^{2+}\) uptake in the vascular smooth muscle cells.

Acknowledgments

This research was supported by grant HL-42880 from the National Institutes of Health, US Public Health Service, Bethesda, Md (Dr Laher), and from the Fondation pour la Recherche Médicale (French Foundation for Medical Research, Paris, France) (Dr Henrion).

References

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Hypertension. 1993;22:78-83
doi: 10.1161/01.HYP.22.1.78

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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