Nitric Oxide–Independent Relaxations to Acetylcholine and A23187 Involve Different Routes of Heterocellular Communication
Role of Gap Junctions and Phospholipase A₂

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Abstract—NO- and prostanoid-independent relaxations are generally assumed to be mediated by an endothelium-derived hyperpolarizing factor (EDHF) that has been postulated to be an arachidonic acid metabolite. Recent evidence also suggests that direct heterocellular gap junctional communication (GJC) between endothelium and smooth muscle contributes to NO-independent relaxations. In the present study we have investigated the contribution of phospholipase A₂ (PLA₂)-linked metabolites and GJC to EDHF-type relaxations in rabbit mesenteric artery. In isolated rings preconstricted with 10 μmol/L phenylephrine in the presence of N⁶-nitro-L-arginine methyl ester (L-NAME) and indomethacin, acetylcholine (ACh) and the Ca²⁺ ionophore A23187 evoked relaxations that were markedly attenuated by the Ca²⁺-dependent PLA₂ inhibitors 2-(p-amylcinnamoyl)amino-4-chlorobenzoic acid (3 μmol/L) and arachidonyl trifluoromethyl ketone (3 μmol/L), but were potentiated by the sulfhydryl agent thimerosal (300 nmol/L). In intact rings, relaxations to ACh were attenuated synergistically by L-NAME and Gap 27 peptide, an inhibitor of GJC, whereas ACh-evoked relaxations of “sandwich” preparations were unaffected by the peptide but were abolished by L-NAME. In both ring and sandwich preparations A23187-induced relaxations were attenuated by inhibition of PLA₂ but were insensitive to L-NAME and Gap 27 peptide. We conclude that EDHF-type relaxations of rabbit mesenteric artery to ACh and A23187 depend on a common pathway that involves activation of PLA₂. In the case of ACh, relaxation requires transfer of a factor or factors from the endothelium to smooth muscle via gap junctions, whereas A23187 permits release directly into the extracellular space. (Circ Res. 1999;84:53-63.)

Key Words: EDHF ▪ phospholipase A₂ ▪ gap junction ▪ acetylcholine ▪ A23187

The endothelium plays a central role in the control of vascular tone through the release of vasoactive autacoids in response to agonist stimulation and shear stress.¹ Mediators include NO, prostanoids, and in many vessel types a distinct endothelium-derived hyperpolarizing factor (EDHF).²,³ The chemical identity of EDHF remains controversial, although it seems probable that it mediates smooth muscle hyperpolarization by activating K⁺ channels (see References 2 and 3 for review). Recent reports suggest that epoxyeicosatrienoic acids (EETs), which are cytochrome P-450 monoxygenase metabolites of arachidonic acid, and the endocannabinoid anandamide, which is also derived from arachidonic acid, possess the characteristics of EDHF in certain artery types.⁴–⁶ EDHF has been detected both in cascade bioassay⁹,¹⁰ and in sandwich preparations,¹¹ suggesting that this factor can diffuse freely in the extracellular space. However, recent evidence suggests that NO-independent relaxations in rabbit mesenteric artery and aorta could involve the preferential direct transfer of a mediator through gap junctions, rather than via/by an extracellular route.¹²,¹³ Intercellular continuity is facilitated by gap junctions that are assembled when 2 connexon hemichannels supplied by neighboring cells interact and dock. Each connexon consists of 6 connexin protein subunits arranged around a central pore,¹⁴ and the characteristic pentalaminar appearance of sections of gap junction plaques has previously been demonstrated in rabbit conduit arteries.¹⁵ Connexin 43 is the most prevalent subtype in endothelium-denuded rabbit superior mesenteric artery, and connexins 37, 40, and 43 have been identified in endothelial cells.¹⁶,¹⁷ Previous studies have shown that the inhibitory Gap 27 peptide (amino acid sequence SRPTEKTIFI), which possesses conserved sequence homology with a region of the...
second extracellular loop of these connexins, rapidly and reversibly attenuates NO-independent relaxations to the agonists ACh and adenosine triphosphate and also to cyclopropanonic acid. Direct heterocellular communication may therefore contribute to EDHF-mediated smooth muscle relaxations evoked by receptor-dependent and -independent activation of the endothelial cell. Although the exact mode of action of Gap 27 peptide remains to be elucidated at the molecular level, possibilities include (1) inhibition or reversal of connexon docking before or after penetration of the peptide into the intercellular gap and (2) induction of a conformational change that results in channel closure.

In the present study we have used isolated ring and sandwich preparations to evaluate the contributions of gap junctional communication (GJC) and PLA$_2$ to NO-independent relaxations evoked by ACh and the calcium ionophore A23187 in rabbit superior mesenteric artery. Arachidonyl trifluoromethyl ketone (AACOCF$_3$), an inhibitor of the cytosolic form of PLA$_2^{19}$; [E-6-(bromomethylene)-tetrahydro-3-(1-naphthalenyl)-2H-pyran-2-1] (HELSS), a specific inhibitor of the secretory form of PLA$_2^{20}$; 2-(p-amlycinnamoyl)amino-4-chlorobenzonic acid (ONO-RS-082), an inhibitor of both forms of PLA$_2^{21}$; 1-(6-{[17β-3-methoxyestra-1,3,5(10)-triene-17-y]laminio}hexyl)-1H-pyrrole-2,5-dione (U-73122), a specific inhibitor of phospholipase C (PLC)$_2^{22}$; and thimerosal, an organic mercury pyrrole-2,5-dione (ONO-RS-082), an inhibitor of guanylate cyclase. Although the exact mode of action of Gap 27 peptide remains to be elucidated at the molecular level, possibilities include (1) inhibition or reversal of connexon docking before or after penetration of the peptide into the intercellular gap and (2) induction of a conformational change that results in channel closure.

Materials and Methods

Isolated Ring Preparations

Experiments were performed with superior mesenteric arteries from male New Zealand White rabbits (2.5 kg) that had been sacrificed by injection of sodium pentobarbitone (120 mg/kg IV). The tissues were transferred to cold Holman’s solution of the following composition (in mmol/L): NaCl 120, KCl 5, NaH$_2$PO$_4$ 1.3, NaHCO$_3$ 25, CaCl$_2$ 2.5, glucose 11, and sucrose 10. Rings (2 to 3 mm wide) were cut and transferred to cold Holman’s solution of the following composition (in mmol/L): NaCl 120, KCl 5, NaH$_2$PO$_4$ 1.3, NaHCO$_3$ in distilled water). All data are given as mean±SEM, and n denotes the number of animals studied for each data point. Concentration-response curves were assessed by 1-way ANOVA followed by the Bonferroni multiple comparisons test. EC$_{50}$ and maximal responses were compared by the Student’s t test for paired and unpaired data as appropriate. P<0.05 was considered as significant.

Results

Effects of PLA$_2$ and PLC Inhibition on ACh- and A23187-Induced Relaxations in Intact Rings

ACh and A23187 both evoked endothelium-dependent relaxations of mesenteric rings that were maximal at ~3 μmol/L and ~300 nmol/L, respectively. Addition of L-NAME (300 μmol/L) to the organ bath increased tone by 18.8±1.5% (n=20) and attenuated ACh-induced relaxations, causing an increase in the EC$_{50}$ value from 0.16±0.02 to 0.76±0.11 μmol/L (P<0.001, n=25) and a reduction in the maximal response (control, 70.9±2.8%; L-NAME, 26.4±2.7%; P<0.001, n=25). The EC$_{50}$ value for relaxation to A23187 was similarly increased from 50.0±1 to 134.5±30 nmol/L following incubation with L-NAME (n=21), and there was a smaller but significant reduction in maximal
relaxation from 73.4±3.4% to 61.1±2% (n=21, P<0.01). These values were obtained by pooling data from all experiments. Addition of ODQ (10 μmol/L) in the presence of L-NAME had no further inhibitory effect on either ACh- or A23187-induced relaxations (Figure 1). Similarly, indomethacin was without effect on the EC50 values and maximal relaxations to ACh or A23187 both in the absence and presence of L-NAME (Figure 1). Indomethacin was included in the buffer for all remaining studies.

In the absence of L-NAME, inhibition of PLA2 with ONO-RS-082 (3 μmol/L) had no effect on ACh-induced relaxations (Figure 2A) in terms of either the EC50 value (control, 0.16±0.01 μmol/L; ACOCCF3, 0.13±0.03 μmol/L; n=3 for both) or maximal relaxations (control, 70.8±4.7%; ACOCCF3, 72.5±2.1%; n=3 for both), but this agent significantly increased the EC50 value for A23187 from 51±0.3 to 122±29 nmol/L (P<0.05, n=3) and caused a small but not significant reduction in the maximal response from 67.3±2.9% to 53.3±7.9% (n=3). In the presence of L-NAME, ONO-RS-082 almost abolished ACh-induced relaxations, with maximal responses being reduced from 37.7±4.6% to 8.8±3% (P<0.01, n=8, Figure 2A). ACOCCF3 also virtually abolished relaxations to ACh, with maximal responses being reduced from 26.4±3.2% to 6.6±1.4% (P<0.01, n=4, Figure 2A). Furthermore, both ONO-RS-082 and ACOCCF3 significantly attenuated the maximal L-NAME-insensitive relaxations to A23187 from 54.2±7% to 23.4±7.2% (P<0.01, n=5, Figure 2B) and from 66.5±3.4% to 27.3±7.8% (P<0.05, n=6, Figure 2B), respectively. HELSS (300 nmol/L) had no effect on ACh-induced relaxations in the presence of L-NAME either in terms of the EC50 value (control, 0.18±0.03 μmol/L; HELSS, 0.27±0.07 μmol/L; n=4) or maximal response (control, 23.1±5.1%; HELSS, 24.4±6%; n=4). Similarly, HELSS was without effect on the L-NAME-insensitive responses to A23187, with EC50 values (control, 108±21 nmol/L; HELSS, 93.5±32 nmol/L; n=4) and maximal responses (control, 66.5±3.4%; HELSS, 60.5±9.5%; n=4) being unchanged.

Preincubation with U-73122 (500 nmol/L), a specific PLC inhibitor, in the presence of L-NAME attenuated relaxations to ACh, with EC50 values being increased from 0.36±0.12 to 1.06±0.3 μmol/L and maximal relaxations reduced from 29.6±7.6% to 10.2±3.1% (P<0.05, n=4, Figure 2C). U-73122 had no significant effect on the L-NAME-insensitive response to A23187 (Figure 2D).

Effects of Gap 27 Peptide on ACh- and A23187-Induced Relaxations in Intact Rings

Preincubation of rings with Gap 27 peptide (300 μmol/L) had no effect on phenylephrine-induced tone (not shown) but significantly attenuated relaxations to ACh, reducing the maximal response from 81.3±4% to 58.8±5.5% (P<0.01, n=8) and causing a rightward shift in the concentration-response curve and an increase in the EC50 value from 200±20 to 480±80 nmol/L (P<0.01, n=8, Figure 3A). By contrast, A23187-induced relaxations were completely unaffected by pretreatment with Gap 27 peptide (n=4, Figure 3B), with no change in either EC50 values (52±3 to 50±4 nmol/L) or maximal responses (75.9±6% to 67.5±2%). In the presence of L-NAME (300 μmol/L), Gap 27 peptide significantly attenuated the residual relaxation to ACh, causing a further increase in the EC50 value from 281±93 to 428±52 nmol/L (n=4) and a significant reduction in the maximal response from 54±3.2% to 33.3±4.9% (P<0.05, n=4, Figure 3A). Gap 27 peptide was without effect on the L-NAME-insensitive component of the relaxations to A23187 either in terms of the EC50 values (54±6 to 58±8 nmol/L, n=4) or maximal response (61.5±1.3% to 61.8±4.1%) (n=4, Figure 3B). Figure 3C illustrates that for relaxations greater than ~20%, the time taken from onset to
maximum relaxation was substantially longer for A23187 than for ACh in the presence of L-NAME.

**Correlations With the Initial Relaxant Response to ACh**

Figure 4 illustrates that in any given preparation there was an inverse relationship between the magnitude of the initial relaxations to ACh and those subsequently obtained in the presence of L-NAME. Linear regression analysis confirmed a negative correlation between maximal responses to ACh in the presence and absence of L-NAME ($P<0.01$, $n=19$, $r=0.60$). There was a direct relationship between the magnitude of the initial relaxations to ACh and those subsequently obtained in the presence of Gap 27 peptide, with a positive correlation coefficient being confirmed by linear regression analysis ($P<0.001$, $n=8$, $r=0.94$).

**Effects of Thimerosal on ACh- and A23187-Induced Relaxations in Intact Rings**

Thimerosal (300 nmol/L) did not affect phenylephrine-induced tone (not shown). Incubation of rings for 20 minutes with this agent, in the absence of L-NAME, enhanced relaxations to ACh (Figure 5A), with a significant reduction in $EC_{50}$ values from $0.11\pm0.03\text{ mol/L}$ to $21\pm0.3\text{ mol/L}$ ($P<0.05$, $n=5$) but no effect on maximal responses (control, 73.5±5.5%; thimerosal, 76.6±5.3%; $n=5$). Gap 27 peptide (300 μmol/L) had no effect on the thimerosal-induced enhancement in terms of the $EC_{50}$ value (25±0.4 nmol/L, $n=4$) but significantly reduced the maximal relaxations to 51.9±2.5% ($n=4$). Similarly, A23187-induced relaxations were enhanced by thimerosal in the absence of L-NAME (Figure 5B), with $EC_{50}$ values being reduced from 70±9 nmol/L to 33±10 nmol/L ($P<0.05$, $n=4$) and the maximal response showing a small, but not significant, rise from 75.1±8.7% to 86.2±4.3% ($n=4$). In the presence of L-NAME, thimerosal significantly reduced the $EC_{50}$ values for both ACh (from 0.51±0.13 to 0.13±0.05 μmol/L, $P<0.05$, $n=10$) and A23187 (from 0.18±0.06 to 0.083±0.03 μmol/L, $n=6$, Figure 5C and 5D). Furthermore, thimerosal increased the maximal response of the residual relaxations to both ACh (from 29.8±8.1% to 42.1±6.1%, $P<0.05$, $n=10$, Figure 5C) and A23187 (from 56.9±3.5% to 70.4±3.5%, $P<0.05$, $n=5$, Figure 5D).

Concentration-response curves to ACh in the presence of L-NAME (300 nmol/L) and thimerosal (300 nmol/L) showed significant reductions in maximal responses to 18.8±4.9% ($n=4$) in the presence of Gap 27 peptide (300 μmol/L) although $EC_{50}$ values remained similar at
A23187-induced relaxations observed in the presence of L-NAME and thimerosal were not significantly affected by Gap 27 peptide in terms of either the EC50 value (35 ± 17 nmol/L, n = 4) or maximal response (66.9 ± 2.1%, n = 4, Figure 5).

Sandwich Preparations

Relaxations of sandwich preparations to ACh exhibited an EC50 of 1.1 ± 0.27 μmol/L and a maximal relaxation of 21.8 ± 2.7% of phenylephrine-induced tone (n = 4, Figure 6A). In marked contrast to the intact ring studies, ACh-induced relaxations were almost abolished in the presence of L-NAME, whereas preincubation with Gap 27 peptide was without effect (Figure 6A). A23187 caused concentration-dependent relaxations of the sandwich preparations, with maximal relaxations constituting 25.4 ± 3.0% of developed tension with an EC50 value of 0.24 ± 0.09 μmol/L (n = 8, Figure 6B). In contrast to intact ring studies, preincubation with L-NAME had no effect on A23187-induced relaxations, whereas ONO-RS-082 had no effect on the EC50 value (0.16 ± 0.08 μmol/L, n = 4) but markedly attenuated the maximal relaxation to 11 ± 5.8% (P < 0.05, n = 4, Figure 6B). As in the case of ACh, Gap 27 peptide was without effect on either L-NAME–sensitive or –insensitive relaxations to A23187 in sandwich preparations (Figure 6B).

Vascular Effects of EETs

The effects of 3 EET regioisomers, 5,6-, 11,12-, and 14,15-EET, were examined in rabbit superior mesenteric arterial ring preparations. Only 5,6-EET evoked concentration-dependent relaxations of endothelium-intact rings that were abolished following endothelial denudation of the vessel (Figures 7 and 8). Addition of either L-NAME (300 μmol/L) or Gap 27 peptide (300 μmol/L) significantly attenuated these endothelium-dependent responses (P < 0.05 [n = 4], and P < 0.05 [n = 6], respectively), and in combination L-NAME...
and Gap 27 peptide abolished 5,6-EET-induced relaxations (n=4, Figures 7 and 8A). Preincubation of ring preparations with either 5,6-, 11,12-, or 14,15-EET (5 μmol/L for each agent) had no effect on either ACh- or A23187-induced relaxations or maximal relaxations (n=4 for each agent, Figure 9).

Discussion

We have used isolated ring and sandwich preparations to characterize the role of GJC in the NO-independent responses of the rabbit mesenteric artery to ACh and A23187. The major findings are that EDHF-type relaxations evoked by ACh are attributable to an agent that preferentially crosses between endothelium and smooth muscle via gap junctions, and that a similar agent also mediates relaxation to A23187, but transfer to smooth muscle then involves diffusion via the extracellular space. The formation and/or mode of action of this mediator(s) is intimately related to the metabolism of phospholipids by a Ca²⁺-dependent PLA₂.

Previous studies have shown that heterocellular GJC between the endothelium and smooth muscle contributes to NO-independent relaxations of rabbit conduit arteries. The present experiments confirm that Gap 27 peptide, which contains the SRPTEK motif common to the second extracellular loop of connexins present in the vascular wall, attenuates L-NAME-insensitive relaxations to ACh in rabbit mesenteric artery. In ring preparations, ≈60% of the initial relaxation to ACh was mediated by NO, whereas in sandwich preparations, in which GJC cannot contribute to responses, relaxations were exclusively NO dependent. In marked contrast, only ≈15% of the relaxation evoked by A23187 was mediated by NO in rings, and in sandwich preparations relaxation was not susceptible to inhibition by L-NAME. Furthermore, Gap 27 peptide was completely without effect on the responses to A23187 either in rings or in sandwich preparations. These findings indicate that, unlike ACh, A23187 mediates relaxation predominantly through the release of a freely diffusible factor, which is not NO, into the extracellular space. This conclusion is supported by comparison of the time course of the relaxations to the 2 agents. At concentrations producing equivalent mechanical responses in the presence of L-NAME, relaxations to A23187 were ap-

Figure 4. A and B, Representative traces demonstrating an inverse relationship between initial ACh relaxations and the subsequent L-NAME-insensitive component of the ACh response. C, Negative correlation between maximal responses to ACh in the absence and presence of L-NAME (P<0.01, n=19, r=-0.60). D, Positive correlation between maximal responses to ACh in the absence and presence of Gap 27 peptide (P<0.001, n=8, r=0.94).
approximately twice as slow as those to ACh. This is consistent with the idea that the EDHF released by A23187 would have to negotiate 2 cell membranes before exerting a relaxant effect on vascular smooth muscle.

Our findings are consistent with observations by Plane and coworkers, who found that A23187, but not ACh, evokes the release of a diffusible, L-NAME–insensitive factor from the endothelium in sandwich preparations of rabbit femoral artery. These authors suggested that the EDHF released from this artery type was stimulus specific. In the present study, however, NO-independent relaxations to ACh and A23187 were both abolished by the structurally unrelated Ca\(^{2+}\)-dependent PLA\(_2\) inhibitors ONO-RS-082 and AACOCF\(_3\) but not by the Ca\(^{2+}\)-independent PLA\(_2\) inhibitor, HELSS. Although the experimental protocols cannot differentiate between activation of PLA\(_2\) within the endothelium or smooth muscle cell, the simplest explanation of these findings is that a closely similar agent mediates EDHF-type responses to ACh and A23187. Alternatively, if different mediators are involved, the production and/or action of both are crucially dependent on activation of PLA\(_2\) by Ca\(^{2+}\) ions. Inhibition of the Ca\(^{2+}\)-dependent cytosolic form of PLA\(_2\) has also previously been shown to attenuate L-NAME–insensitive relaxations to ACh, histamine, and bradykinin in the perfused rat coronary and mesenteric beds. Cohen and colleagues have suggested that residual NO synthesis in the presence of the NO synthase inhibitors L-NAME and L-\(N^\delta\)-nitroarginine could account for endothelium-dependent hyperpolarization. We excluded this possibility, however, by demonstrating that the selective inhibitor of guanylate cyclase, ODQ, did not modulate the relaxations to ACh and A23187 observed in the presence of L-NAME. The ability of ONO-RS-082 and AACOCF\(_3\) to virtually abolish L-NAME–insensitive relaxations, without affecting NO-mediated relaxations, provides further evidence that L-NAME completely inhibits NO formation in the rabbit mesenteric artery at the concentration used.

Several possibilities may be advanced to explain why A23187-induced relaxations were not susceptible to inhibition by Gap 27 peptide. First, it is possible that incorporation of A23187 into the plasmalemma alters local membrane structure and phospholipid metabolism, allowing easier access of an EDHF linked to the activity of a Ca\(^{2+}\)-dependent PLA\(_2\) to the extracellular space. Second, there is evidence that molecules of A23187 aggregate in lipid bilayers to form channels, as well as behaving as a carrier ionophore with selectivity for Ca\(^{2+}\) ions, that could potentially allow egress of an EDHF into the extracellular space and its subsequent diffusion to adjacent smooth muscle, thereby “bypassing” gap junctions. Third, A23187 has been shown to cause closure of gap junctions between endothelial cells, a mechanism that could promote the egress of an EDHF via the membrane. In

Figure 5. Concentration-response curves showing the effects of thimerosal and Gap 27 peptide on ACh- and A23187-induced relaxations in endothelium-intact rings. A and B, Thimerosal (300 nmol/L) significantly increased the potency of ACh (n=5) and A23187 (n=4) but did not affect maximal relaxations. Gap 27 peptide (300 \(\mu\)mol/L) did not reverse the thimerosal-induced increase in potency to ACh but significantly reduced the maximal relaxation. C and D, Thimerosal significantly enhanced L-NAME–insensitive relaxations to both ACh (n=10) and A23187 (n=6). Gap 27 peptide significantly reduced the thimerosal-enhanced relaxations to ACh but not to A23187 (n=4 for both agents).
other cell types, ACh has also been reported to promote closure of gap junctions, but clearly this cannot be an important factor in our experiments, as Gap 27 peptide was highly effective in reducing relaxations to ACh. Conventionally, increases in \([\text{Ca}^{2+}]_\text{i}\) have been thought to mediate closure of gap junctions. However, a G-protein/tyrosine kinase-dependent mechanism linked to activation of receptors has recently been shown to promote the closing of gap junctions in cells expressing connexin 43, independently of elevations in local \([\text{Ca}^{2+}]_\text{i}\). Conversely, other evidence suggests that elevated \([\text{Ca}^{2+}]_\text{i}\) may also open gap junctions. In cardiac myocytes, which express connexin 43 as the dominant connexin protein, channel permeability increases monotonically as a function of \([\text{Ca}^{2+}]_\text{i}\), over the physiological range of 0.1 to 1 \(\mu\text{mol/L}\), and decreases only for \([\text{Ca}^{2+}]_\text{i}\) within the supraphysiological range. Further experiments are therefore necessary to elucidate the principal mechanisms gating heterocellular GJC between endothelial and vascular smooth muscle cells.

Cascade bioassay experiments have demonstrated that NO inhibits the formation and/or release of EDHF by endothelial cells. This inverse relationship between the activities of the 2 mediators may explain why ONO-RS-082 and AACOCF3 had no effect on ACh-evoked relaxations in ring preparations in the absence of L-NAME but reduced the potency of A23187. Under these conditions, ACh-induced responses were substantially more dependent on NO synthesis than those evoked by A23187, thus suggesting that NO masks the effects of PLA2 inhibition by suppressing EDHF activity. In the presence of L-NAME, however, EDHF activity will be enhanced, and relaxations to ACh then become susceptible to ONO-RS-082 and AACOCF3, as observed experimentally. The positive correlation between the magnitude of the ACh-

![Figure 6](image)

**Figure 6.** Concentration-response curves showing the effect of L-NAME, Gap 27 peptide, and ONO-RS-082 on relaxations to ACh and A23187 in sandwich preparations of rabbit mesenteric artery. A, L-NAME, but not Gap 27 peptide, markedly attenuated the relaxations to ACh \((n=4)\). B, ONO-RS-082 significantly reduced A23187-evoked relaxations \((n=4)\), whereas L-NAME, Gap 27 peptide, and their combination were each completely without effect \((n=4\) for all curves).

![Figure 7](image)

**Figure 7.** Representative traces demonstrating relaxations to 5,6-EET in endothelium-intact preparations (A), endothelium-denuded preparations (B), endothelium-intact preparations in the presence of L-NAME \((300\ \mu\text{mol/L})\) (C), and endothelium-intact preparations in the presence of Gap 27 peptide \((300\ \mu\text{mol/L})\) (D). Relaxation was slightly attenuated by L-NAME but almost abolished by Gap 27 peptide. Transient constriction after drug administration was attributable to the vehicle (ethanol).
induced relaxations obtained in the presence and absence of Gap 27 peptide is also consistent with a dynamic interaction between NO and EDHF, with inhibition of GJC having a smaller effect in the presence of high levels of NO release. A new observation was that in preparations exhibiting large relaxations to ACh in the absence of L-NAME, the subsequent L-NAME–insensitive response to this agonist was small. This suggests that EDHF-type relaxations are chronically diminished in preparations exhibiting high NO activity, although the mechanisms underlying this downregulation remain to be determined.

Activation of PLC following agonist stimulation results in generation of inositol trisphosphate (IP₃) and release of Ca²⁺ from internal stores. The resulting increase in [Ca²⁺]ᵢ activates the Ca²⁺-dependent cytosolic form of PLA₂ resulting in cleavage of arachidonic acid from membrane glycerophospholipids. Activation of PLC also generates diacylglycerol (DAG), which can be hydrolyzed by a DAG lipase to provide a second source of arachidonic acid. Inhibition of NO-independent relaxations to ACh by U-73122 is unlikely to reflect loss of DAG as a substrate for arachidonic acid production, as the DAG lipase inhibitor, RHC-80267, has no effect on EDHF-type responses in the perfused rat heart and mesenteric prearteriolar bed.

Further evidence for the common identity of the EDHF released by ACh and A23187 was obtained with the sulfhydryl agent thimerosal, which has previously been reported to hyperpolarize porcine coronary arterial smooth muscle in an endothelium-dependent manner and enhance the release of an EDHF from canine carotid artery in cascade bioassay. In the present study, low concentrations of thimerosal enhanced relaxations to ACh and A23187 both in the absence and presence of L-NAME and indomethacin. Importantly, the potentiation of EDHF-type relaxations to ACh in the presence of L-NAME remained susceptible to inhibition by Gap 27 peptide, whereas those to A23187 were not. The effects of thimerosal can consequently be attributed to factors other than alterations in the pathways allowing transfer of EDHF between the endothelium and smooth muscle by ACh and through second-messenger–independent mechanisms.
ACh and A23187. Two known mechanisms of action of thimerosal could contribute to an apparent increase in EDHF activity. First, thimerosal inhibits the acyl-coenzyme A:lyssolecithin acyltransferase,23 thereby elevating free levels of arachidonic acid within the cell,33 an action that would be consistent with the inhibition of relaxation observed with ONO-RS-082 and AACOCF₃. Second, nanomolar concentrations of thimerosal equivalent to those used in the present study studied (5 μmol/L, n=4 for all 3 agents) on relaxation to either ACh (A) or A23187 (B).

Figure 9. Concentration-response curves showing the effect of EETs on relaxations to ACh and A23187 in endothelium-intact rings. There was no effect of a 30-minute preincubation with any of the EETs studied (5 μmol/L, n=4 for all 3 agents) on relaxations to either ACh (A) or A23187 (B).

ACh and A23187. The similarity of the effects of 2 structurally dissimilar Ca²⁺-dependent inhibitors of PLA₂ and thimerosal on relaxations obtained to ACh and A23187 point to the operation of common mechanistic pathways. The primary signaling mechanism for relaxation appears to be chemical rather than electrical in nature. The exact identity of the EDHF(s) has yet to be established, and it remains to be determined at which point distal to activation of PLA₂ an active agent is mobilized and within which cell type. Since the central pore of gap junctions is aqueous and thought to allow preferential diffusion of small, water-soluble charged molecules, a role for hydrophobic arachidonate acid derivatives, such as EETs, might be challenged on a purely physiochemical basis.

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References


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