Endothelin (ET)-1-Induced Inhibition of ATP Release from PC-12 Cells Is Mediated by the ET<sub>B</sub> Receptor: Differential Response to ET-1 on ATP, Neuropeptide Y, and Dopamine Levels

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ABSTRACT

During sympathetic neurotransmitter release, there is evidence for differential modulation of cotransmitter release by endothelin (ET)-1. Using nerve growth factor (NGF)-differentiated PC12 cells, the effects of ET-1 on K<sup>+</sup>-stimulated release of ATP, dopamine (DA), and neuropeptide Y (NPY) were quantified using high-pressure liquid chromatography or radioimmunoassay. ET-1, in a concentration-dependent manner, inhibited the release of ATP, but not DA and NPY. Preincubation with the ET<sub>A</sub> antagonist, PD 142893 ([N-(acetyl-β-phenyl)-d-Phe-Leu-Asp-Ile-Ile-Trp], reversed the inhibitory effect of ET-1 on ATP release, which remained unaffected in the presence of the ET<sub>B</sub> specific antagonist BQ123 [cyclo[ d-Asp-Pro-Val-Leu-d-Trp]]. The ET<sub>B</sub> agonists, sarafotoxin 6c (Cys-Thr-Cys-Asn-Asp-Met-Thr-Asp-Glu-Glu-Cys-Leu-Asn-Phe-Cys-His-Gln-Asp-Val-Ile-Trp), BQ 3020 ([N-acyl-[Ala<sub>11,15</sub>]-endothelin 1 fragment 6-21Ac-Leu-Met-Asp-Lys-Ala-Val-Tyr-Phe-Ala-His-Leu-Asp-Ile-Ile-Trp], and IRL 1620 ([N-succinyl-[Glu<sub>9</sub>, Ala<sub>11,15</sub>]-endothelin 1 fragment 8-21Suc-Asp-Glu-Ala-Val-Tyr-Phe-Ala-His-Leu-Asp-Ile-Ile-Trp], decreased K<sup>+</sup>-stimulated release of ATP in a dose-dependent manner, and this effect was reversed by the ET<sub>B</sub> antagonists RES 701-1 [cyclic (Gly1-Asp9) (Gly-Asn-Trp-His-Gly-Thr-Ala-Pro-Asp-Trp-Phe-Phe-Asn-Tyr-Tyr-Trp)] and BQ 788 ([N-[2,6-dimethyl-1-piperidinyl]carboxyl]-4-methyl-L-leucyl]-1-(methoxy carbonyl)-D-tryptophyl]-D-norleucine sodium salt). Preincubation of PC12 cells with pertussis toxin reversed the ET-1-induced inhibition of the K<sup>+</sup>-evoked ATP release. Real-time intracellular calcium level recordings were performed on PC-12 cell suspensions, and ET-1 induced a dose-dependent decrease in the K<sup>+</sup>-evoked calcium levels. Nifedipine, the L-type voltage-dependent Ca<sup>2+</sup> channel antagonist, caused inhibition of the K<sup>+</sup>-stimulated ATP release, but the N-type Ca<sup>2+</sup> channel antagonist, ω-conotoxin GVIA, did not reverse the effect on ATP release. These data suggest that ET-1 modulates the release of ATP via the ET<sub>B</sub> receptor and its associated G<sub>i/o</sub> G-protein through attenuation of the influx of extracellular Ca<sup>2+</sup> through L-type channels.

Evidence has accumulated indicating that in addition to the coexistence of NE, NPY, and ATP in sympathetic nerves, there is differential cotransmission of each of these transmitters (Lundberg, 1996). Each neurotransmitter can be released independently under appropriate conditions, and the application of each transmitter mimics a phase of sympathetic nerve stimulation with each phase inhibited by appropriate antagonists (Todorov et al., 1994). Each of the transmitters, NE, NPY, and ATP, negatively modulate their own release from sympathetic nerves, as well as the release of each other (Lundberg, 1996). At the vascular

Precise regulation of sympathetic neurotransmission is mediated through the concerted action of neurotransmitters and neuromodulators. At the neuroeffector junction during sympathetic transmitter release, it is established that the neurotransmitters, norepinephrine (NE), neuropeptide Y (NPY), and ATP, are coreleased from sympathetic neurons.

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ABBREVIATIONS: NE, norepinephrine; NPY, neuropeptide Y; ET, endothelin; NGF, nerve growth factor; DMEM, Dulbecco’s modified Eagle’s medium; ir, immunoreactivity; PTX, pertussis toxin; HPLC, high-pressure liquid chromatography; AM, acetoxymethyl ester; PD 142893, N-acetyl-β-phenyl-d-Phe-Leu-Asp-Ile-Ile-Trp; BQ123, cyclo[ d-Asp-Pro-Val-Leu-d-Trp]; sarafotoxin 6c, Cys-Thr-Cys-Asn-Asp-Met-Thr-Asp-Glu-Glu-Cys-Leu-Asn-Phe-Cys-His-Gln-Asp-Val-Ile-Trp; BQ 3020, [N-acyl-[Ala<sub>11,15</sub>]-endothelin 1 fragment 6-21Ac-Leu-Met-Asp-Lys-Ala-Val-Tyr-Phe-Ala-His-Leu-Asp-Ile-Ile-Trp], and IRL 1620, [N-succinyl-[Glu<sub>9</sub>, Ala<sub>11,15</sub>]-endothelin 1 fragment 8-21Suc-Asp-Glu-Ala-Val-Tyr-Phe-Ala-His-Leu-Asp-Ile-Ile-Trp], decreased K<sup>+</sup>-stimulated release of ATP in a dose-dependent manner, and this effect was reversed by the ET<sub>B</sub> antagonists RES 701-1 [cyclic (Gly1-Asp9) (Gly-Asn-Trp-His-Gly-Thr-Ala-Pro-Asp-Trp-Phe-Phe-Asn-Tyr-Tyr-Trp)] and BQ 788 ([N-[2,6-dimethyl-1-piperidinyl]carboxyl]-4-methyl-L-leucyl]-1-(methoxy carbonyl)-D-tryptophyl]-D-norleucine sodium salt); ANOVA, analysis of variance; CTX, ω-conotoxin; RES 701-1, cyclic (Gly1-Asp9) (Gly-Asn-Trp-His-Gly-Thr-Ala-Pro-Asp-Trp-Phe-Phe-Asn-Tyr-Tyr-Trp); BIBP3226, N2-(diphenylacetyl)-N-[4-(4-hydroxyphenyl)ethy]-D-arginine amide; BSS, buffered salt solution.
neuroeffector junction of the guinea pig vas deferens and rabbit ileocolic artery, stimulation of α2-adrenergic receptors inhibited the release of NE and, to a lesser extent, ATP (Bulloch and Starke, 1990; Driessan et al., 1993). ATP has been observed to inhibit nerve-stimulated release of NE from the guinea pig heart (Haass et al., 1989). In the rat mesenteric arterial bed and guinea pig vas deferens, NE not only negatively regulated its own release but also produced a negative feedback modulation of NE and ATP release (Ellis and Burnstock, 1990; Westfall et al., 1995).

Evidence indicates that release of neurotransmitters at the neuroeffector junction is subject to differential modulation by various mechanisms. During electrical field stimulation of the guinea pig vas deferens, temporal differences in the release of ATP and NE from the sympathetic nerves have been demonstrated. At lower frequencies of stimulation, ATP levels reached a peak at 20 s, after which levels diminished with continued stimulation; however, peak levels of NE were not observed until 40 s and remained constant during the period of stimulation (Todorov et al., 1994). In contrast, NE release from sympathetic nerves required higher frequencies of stimulation, which can be inhibited by the NPY Y1-specific antagonist BIBP3226 (Smyth et al., 2000).

There is also evidence for modulation of sympathetic neurotransmission at the vascular neuroeffector junction by non-neuronal mediators. The vasoactive peptide endothelin (ET)-1 attenuates sympathetic neurotransmission prejunctionally by decreasing nerve stimulation induced release of NE. This has been observed in the guinea pig pulmonary and femoral arteries (Wiklund et al., 1989), rat and guinea pig vas deferens (Wiklund et al., 1990), dog coronary artery (Aarnio et al., 1993), and rat mesenteric artery (Tabuchi et al., 1989). In the rat mesenteric bed, ET-1 negatively modulates the release of NPY, but not NE (Hoang et al., 2002). Postjunctionally, ETs modulate sympathetic neurotransmission by enhancement of the contractile effect of both nerve stimulation and a variety of vasoactive agents (Henrion and Laber, 1993; Hoang et al., 2003). ET-1, through activation of the ETα receptor, potentiates the postjunctural contractile effects of ATP (Mutafova-Yambolieva and Radomirov, 1993; Hoang et al., 2003).

The present investigation endeavored to delineate the molecular signaling mechanism by which ET-1 modulated sympathetic neurotransmitter release. Nerve growth factor (NGF)-differentiated rat pheochromocytoma (PC12) cells were chosen as a functional model of sympathetic neurotransmission because they phenotypically resemble sympathetic neurons and contain both small vesicles and dense core granules (Greene and Tischler, 1976). They are a well-established model to study intracellular mechanisms related to sympathetic neurotransmission signaling because they synthesize and release catecholamines, specifically dopamine (Chen and Westfall, 1994), purines (Kasai et al., 2001), and NPY (Chen et al., 1997). PC12 cells express G-proteins (Li et al., 1995), voltage-dependent ion channels (McCullough et al., 1998), and various second messenger systems (Vaudry et al., 2002).

NPY is costored with catecholamines, NE and dopamine, in large dense core vesicles, and ATP is costored with catecholamines in small synaptic vesicles (Lundberg, 1996) in sympathetic neurons. Release of these transmitters is modulated by spatial differences in calcium concentrations (Lundberg, 1996). ATP and catecholamines are costored and coreleased from secretory granules of adrenal chromaffin cells from which PC12 cells are derived. Much work has been carried out on vesicle exocytosis coupled with neurotransmitter release from both chromaffin and PC12 cells (Ahnert-Hilger et al., 1985; Strasser et al., 1999).

We report that ET1 differentially modulates the release of the sympathetic cotransmitters. Specifically, ET-1 functions as a negative modulator of sympathetic neurotransmission and inhibits the release of the sympathetic cotransmitter ATP from NGF-differentiated PC12 cells. The mechanism of inhibition involves a specific endothelin receptor subtype and G-protein family, which modulate intracellular calcium levels.

Materials and Methods

Growth and Differentiation of PC12 Cells. PC12 cells were grown directly on six-well plates (treatment C; MatTek, Ashland, MA) in Dulbecco’s modified Eagle’s medium (DMEM) and differentiated with NGF (50 ng/ml) for 5 days as described previously (Chen and Westfall, 1994).

Neurotransmitter Release Measurements. The media surrounding the cells were removed and replaced with 1.5 ml of warmed (37°C) Krebs’ buffer. The composition of the Krebs’ buffer was as follows: 119 mM NaCl, 2.5 mM KCl, 1.3 mM MgSO4, 2.5 mM CaCl2, 1.0 mM NaH2PO4, 26.2 mM NaHCO3, and 10 mM HEPES, pH 7.4. The plates were then placed in a shaking water bath at 37°C for 15 min to allow for equilibration. ET-1 or the ETB agonists were added 5 min prior to exposure to buffer containing KCl (50 mM). If an antagonist was to be studied, then it was added 5 min prior to the addition of ET-1. After a further 5 (catecholamine and ATP studies) or 15 (NPY studies) min of incubation with KCl (50 mM), the plates were removed from the water bath and placed on ice. The buffer from each well was removed and spun at 1000 rpm for 2 min to remove any cells. The supernatant was then assayed for catecholamine, NPY, or ATP content. The cells remaining on the plates were extracted with 1 ml of 0.4 N perchloric acid and added to the pellets in the tubes for determination of protein by the Lowry method or total catecholamine or NPY content.

The Krebs’ solution was initially altered so as to account for alterations in ionic content. However, in comparison, in experiments where KCl was simply added to give a final concentration of 50 mM, no differences in neurotransmitter release or cell function were observed. As a result, all subsequent experiments were carried out in this manner.

The K+-stimulated neurotransmitter release was stable over time. Depending on the neurotransmitter analyzed, KCl was added for variable times. The rationale for the different periods was based on previous studies where it has been observed that the peak release of NPY immunoreactivity (ir) occurred after incubation with the high-K+ buffer for 15 min (Chen et al., 1997), and the peak release of ATP and catecholamine occurred after incubation with the high-K+ buffer for 5 min (Chen et al., 1994). Cells were pretreated with pertussis toxin (PTX) for 20 h before the peak ribosylation of Gα subunits was shown to occur between 18 and 20 h (Chen et al., 1994; McCullough et al., 1998).

Analysis of Purines. Purines were analyzed according to the method described previously by Levitt et al. (1984). Chloroacetalddehyde was used to form fluorescent 1,N6-ethenopurine (E-purine) analogs, which can be simultaneously separated from the same sample by reverse-phase HPLC and quantified by fluorescence detection.

Chloroacetalddehyde (50 μl) synthesized according to the modified method by Socris et al., (1972) was added to each cell sample, which was then incubated in a dry bath at 80°C for 40 min. The reaction was stopped by placing the samples on ice, and the samples were then analyzed by HPLC-fluorometric detection.

Separation of purine compounds was achieved on a reverse-phase C-18 column. A dual buffer gradient system was used to separate and...
elute the purines from the column by gradually increasing the concentration of buffer B while decreasing the concentration of buffer A (Varian 9010 solvent delivery system; Varian, Inc., Palo Alto, CA). Buffer A, pH 6.0, consisted of 0.1 M phosphate buffer, and buffer B, pH 6.0, consisted of 75% 0.1 M phosphate buffer and 25% methanol. The fluorescent purine derivatives were detected at an excitation wavelength of 300 nm and an emission wavelength of 420 nm (Varian 9070 Fluorescence Detector). Identification of the purine peaks was carried out by comparison of retention times of purine standards. Sample purine content was quantified by peak integration (Varian Star Workstation Software). ATP analysis was performed on perfusates and normalized against protein concentrations.

**Catecholamine Measurements.** Endogenous catecholamines in cell extracts were identified and quantified by HPLC with electrochemical detection as previously published (Chen and Westfall, 1994). Separation of catecholamines was achieved on a reverse-phase C-18 column. The system consists of a Varian model 2510 solvent delivery system and a model 9909 autosampler (Varian, Inc.) coupled to a C-18 column and an ESA Coulochem II detector. Separations were performed isocratically using a filtered and degassed mobile phase consisting of 10% methanol, 0.1 M sodium phosphate, 0.2 mM sodium octyl sulfate, and 0.1 mM EDTA, adjusted to pH 2.8 with phosphoric acid. The HPLC system is coupled to a computer with which chromatograms were recorded and analyzed with Varian Star workstation software. Dopamine analysis was performed on both cells (total release) and perfusates (fractional release), and amounts of neurotransmitter released were calculated on the basis of: (fractional release/fractional release + total release).

The dominant catecholamine neurotransmitter synthesized and released from the NGF-differentiated PC12 cell is dopamine (Greene and Tischler, 1976). Although the NGF-differentiated PC12 cell has all the major enzymes necessary to produce all catecholamines, it lacks the essential cofactor ascorbate that is necessary in the conversion of dopamine to norepinephrine. Consequently, in the NGF-differentiated PC12 cell model, dopamine is the major catecholamine synthesized, and negligible amounts of NE and epinephrine are produced. Dopamine, therefore, is utilized as an index of neurotransmitter released from the PC12 cell.

**NPY Measurements.** NPYir was determined using the protocol of Chen et al. (1997) directly in acid extracts of release medium by radioimmunoassay using a specific antiserum, which was raised in rabbit against porcine NPY. Radioimmunoassays were performed using a 5-day disequilibrium method. Duplicated samples were incubated with the NPY antiserum. Twenty-four hours later, 125I-NPY was added to each tube. Following a 72-h (at 4°C) incubation period, antibody-bound NPY and free NPY were separated by a second antibody method, and the radioactivity was measured by a gamma counter. Triplicates were used in standard curves with a sensitivity range of 1 to 100 fmol. NPYir analysis was performed on both cells (total release) and perfusates (fractional release), and amounts of neurotransmitter released calculated on the basis of: (fractional release/fractional release + total release).

**Intracellular Calcium ([Ca2+]i) Measurements.** Real-time [Ca2+]i recording was performed on PC-12 cell suspension loaded with fura acetoxymethyl ester (Fura-2/AM) during a 60-min incubation. A cell suspension of 5 × 10⁶ cells/ml in DMEM-HEPES (10 mM) was loaded with Fura-2/AM during a 60-min incubation with 10 μM Fura-2/AM in DMEM at room temperature. Following the incubation period, the cells were microcentrifuged and resuspended in 1 ml of BSS (139 mM NaCl, 5.5 mM KCl, 1 mM MgCl₂, 0.75 mM CaCl₂, and 8 mM HEPES), and the wash and BSS suspension were repeated twice. Cells were then aliquoted into a new microcentrifuge tube at 1.5 × 10⁶ cells/ml, and the volume was increased to 2 ml with BSS. The cells were then incubated at room temperature for 45 min to allow for esterase cleavage of the AM-ester. The suspension was then microcentrifuged, suspended in 1 ml of BSS, and resuspended twice. A dual-excitation spectrofluorometric system (model CM111; Spex Industries, Edison, NJ) was used. In these experiments, the system was programmed to alternate between 340- and 380-nm excitation every second to obtain 1-s data points for each wavelength. After subtraction of background noise (see below), the 340:380-nm ratio was subsequently calculated for each pair of data points to obtain the final tracing. A steady-state system was used in this study. After a stable base period, cells were exposed to KCl, which produced an increase in [Ca2+]i. Alternatively, the cells were exposed to endothelin-1 (porcine; Calbiochem, San Diego, CA) and then stimulated with KCl. The fluorescence signal was calibrated according to Grynkiewicz et al. (1985). The concentration of buffer B while decreasing the concentration of buffer A elute the purines from the column by gradually increasing the concentration of buffer B while decreasing the concentration of buffer A. The fluorescent purine derivatives were detected at an excitation wavelength of 300 nm and an emission wavelength of 420 nm (Varian 9070 Fluorescence Detector). Identification of the purine peaks was carried out by comparison of retention times of purine standards. Sample purine content was quantified by peak integration (Varian Star Workstation Software). ATP analysis was performed on perfusates and normalized against protein concentrations.

**Materials.** ET-1 was purchased from Peninsula Laboratories (Belmont, CA). ET-1 (Cys-Ser-Cys-Ser-Ser-Leu-Met-Asp-Lys-Glu-Cys-Val-Tyr-Phe-Cys-His-Leu-Asp-Ile-Ile-Trp) was made fresh from the lyophilized pure peptide, first as a concentrated solution in distilled water and then diluted with 0.1% bovine serum albumin in saline. The peptide was reconstituted prior to an experiment. Low concentrations of endothelin have been used in specific in vivo studies using this method (Mutafova-Yambolieva and Radomirov, 1993). PD 142893, BQ212, sarafotoxin 6c, BQ 3020, and IRL 1620 were all purchased from Sigma/RBI (Natick MA). RES-701-1 was kindly donated by Koywa Hakko Kogyo Co. Ltd. (Tokyo, Japan). BQ 788 was purchased from Alexis Corporation (Läufelfingen, Switzerland). PTX and all buffer salts were purchased from Sigma-Aldrich (St. Louis, MO). Perchloric acid (HClO₄) was purchased from Fisher Scientific. BQ 788 was purchased from Alexis Corporation (Läufelfingen, Switzerland). PTX and all buffer salts were purchased from Sigma-Aldrich (St. Louis, MO). Perchloric acid (HClO₄) was purchased from Fisher Scientific Co. (Pittsburgh, PA). NGF was purchased from Collaborator Biomedical Products (Bedford, MA). Reagents for tissue culture including DMEM, fetal calf serum, horse serum, glutamine, and pyruvate were obtained from JRH Biosciences (Lenexa, KS).

**Statistics.** Statistical analysis between treatments was determined by one-way analysis of variance (ANOVA), followed by Student-Newman-Keuls test. ANOVA was performed on raw data in experiments where controls were normalized to 100%. Statistical differences were accepted when P < 0.05.

**Results**

**Endothelin Differentially Modulates the Release of Neurotransmitters and Neuromodulators.** To determine whether ET-1 had a differential effect on the release of the neurotransmitters ATP, NPY, and dopamine, the effects of ET-1 on the K⁺-evoked release of ATP from NGF-differentiated PC12 cells was investigated. Incubation of PC12 cells with 50 mM KCl caused an increase in the release of ATP over basal. This increase in release was inhibited in a dose-dependent manner in the presence of ET-1 (Fig. 1A). In contrast, in the presence of ET-1 the release of the sympathetic cotransmitters dopamine, and NPY was not significantly inhibited at these concentrations of the peptide (Fig. 1, B and C, respectively). These initial set of experiments indicated that the ET-1-induced inhibition was specific, for ATP, and thus in this case sympathetic cotransmission was differentially modulated.

**A Specific Endothelin Receptor Subtype Mediates ET-1 Inhibition of ATP Release.** A pharmacological approach was utilized to elucidate the mechanism by which ET-1 modulated the release of the cotransmitter ATP. In
tially, the effect of the ETA/ETB antagonist, PD 142893, on the K\(^+\)-evoked release of ATP from NGF-differentiated PC12 cells was examined to assess whether this agent could reverse the ET-1-induced inhibition on the K\(^+\)-evoked release of ATP from these cells. ET-1 reduced the K\(^+\)-evoked release of ATP (Fig. 2). Although the degree of inhibition was greater than the previous experiments, it should be noted that the response of PC12 cells to K\(^+\)-evoked depolarization was also variable in this experiment, and subsequent experiments and, therefore, their susceptibility to ET-1. Preincubation of the PC12 cells with the ETA/ETB antagonist PD 142893 (Fig. 2) reversed the inhibitory effect of ET-1 on ATP release.

To further elucidate the nature of the receptors involved in this effect, the ETA-specific antagonist BQ123 was used. In these experiments, ET-1 reduced the K\(^+\)-evoked release of ATP from the PC12 cells compared with basal. This reduction was not inhibited by BQ123 at two different concentrations (Fig. 3), suggesting that the ETA receptor does not mediate the ET-1-induced inhibition of ATP. To confirm whether the

**Fig. 1.** Endothelin-induced inhibition of sympathetic cotransmitters. ET-1 (10\(^{-15}\) to 10\(^{-8}\) M; solid bars) caused a dose-dependent inhibition (10\(^{-15}\) to 10\(^{-8}\) M; 353 ± 58%, 190 ± 36%, 132 ± 39% and 40 ± 17%, respectively) of the K\(^+\)-evoked release (open bars; 50 mM) of ATP (A) from NGF-differentiated PC12 cells. The fractional release of the catecholamine dopamine (B) and NPY (C) from NGF-differentiated PC12 cells was unaffected by the presence of ET-1. Each bar represents the mean ± S.E.M. of 12 wells from four individual experiments. *, P < 0.05 versus K\(^+\)-evoked release.

**Fig. 2.** The effect of an ETA/ETB antagonist on ATP release. The ETA/ETB antagonist PD 142893 (hatched bar; 10\(^{-5}\) M) reversed the inhibition, caused by ET-1 (solid bar; 10\(^{-10}\) M), of the K\(^+\)-evoked release (open bar; 50 mM) of ATP from NGF-differentiated PC12 cells from −6 ± 22% to 154 ± 43%. Each bar represents the mean ± S.E.M. of 12 to 15 wells from five individual experiments. *, P < 0.05 versus K\(^+\)-evoked release; †, P < 0.05 compared with ET-1.

**Fig. 3.** The effect of an ETA antagonist on ATP release. In NGF-differentiated PC12 cells, the ETA antagonist BQ123 (hatched bars; 10\(^{-6}\) to 10\(^{-5}\) M; −24 ± 13% and −16 ± 23%, respectively) did not reverse the inhibition caused by ET-1 (solid bar; 10\(^{-10}\) M) of the K\(^+\)-evoked release (open bar; 50 mM) of ATP from these cells. Each bar represents the mean ± S.E.M.; n = 6. *, P < 0.05 versus K\(^+\)-evoked release.
inhibitory effect of ET-1 on cotransmitter release was via the ET<sub>B</sub> receptor, the effects of the ET<sub>B</sub>-specific agonists, Sarafotoxin 6c (STX 6c), BQ 3020, and IRL 1620, on the K<sup>+</sup>-evoked release of ATP from PC12 cells were studied (Fig. 4). Each of the ET<sub>B</sub> agonists mimicked the inhibitory effect of ET-1 on ATP release. STX 6c, BQ 3020, and IRL1620 reduced the K<sup>+</sup>-evoked release of ATP in a concentration-dependent effect (Fig. 4, A–C, respectively).

To confirm that the ET<sub>B</sub> receptor subtype was indeed mediating the effects of ET-1 in these experiments, the effect of specific ET<sub>B</sub> receptor antagonists, RES 701-1 and BQ 788, was analyzed (Fig. 5). In these experiments ET-1 inhibited the K<sup>+</sup>-evoked ATP release from the PC12 cells, and the ET<sub>B</sub> antagonist RES 701-1 (Fig. 5A) reversed this inhibition. Similarly, BQ 788 reversed the effect of ET-1 (Fig. 5B).

**A Pertussis Toxin-Sensitive, Calcium-Dependent Pathway Mediates ET-1 Inhibition of ATP Release.** ET<sub>A</sub> and ET<sub>B</sub> receptors are members of the G-protein-coupled receptor superfamily; therefore, the next set of experiments investigated whether PTX could alter the ET-1-induced inhibition of ATP release. In the absence of PTX, ET-1 inhibited the K<sup>+</sup>-evoked ATP release from the PC12 cells (Fig. 6). Following preincubation of PC12 cells with 50 mM PTX, the ET-1-induced inhibition of the K<sup>+</sup>-evoked ATP release was reversed, which paralleled the K<sup>+</sup>-evoked ATP release control.

Essential to the exocytotic release of most neurotransmitters is the increase in intracellular calcium. If the mechanism of ET-1-induced inhibition of ATP release involves a decrease in the availability of Ca<sup>2+</sup>, then an effect on intracellular levels of calcium [Ca<sup>2+</sup>] should be evident. Therefore, to ascertain whether ET-1 does alter levels of [Ca<sup>2+</sup>], we examined the effect of ET-1 via quantitative analysis of [Ca<sup>2+</sup>]. Preincubation of a suspension of PC12 cells with ET-1 alone had no antagonistic effect on the baseline reading (data not shown). In the absence of ET-1, cells were exposed to KCll-induced depolarization, which produced a substantial increase in [Ca<sup>2+</sup>], release above baseline (Fig. 7A). Pretreatment of the total cell population with varying concentrations of ET-1 induced a dose-dependent decrease in the K<sup>+</sup>-evoked [Ca<sup>2+</sup>] response (Fig. 8). As shown in a representative tracing, 100 nM ET-1 resulted in ablation of the initial calcium spike but had no significant effect on the sustained phase of [Ca<sup>2+</sup>]<sub>i</sub>, release (Fig. 7B).

To further our understanding of the mechanism by which ET-1 attenuates the K<sup>+</sup>-evoked release of ATP, we examined the effect of the calcium channel antagonists, ω-conotoxin GVIA (CTX) and nifedipine, that are specific for N- and L-type voltage-dependent channels, respectively. As shown in Fig. 9A, the L-type Ca<sup>2+</sup> channel antagonist nifedipine caused a concentration-dependent inhibition of the K<sup>+</sup>-evoked release of ATP, which mimicked the effect of ET-1. In contrast, preincubation of PC12 cells with the N-type Ca<sup>2+</sup> channel antagonist CTX at concentrations of 5 × 10<sup>−8</sup> and 5 × 10<sup>−6</sup> M (Fig. 9B) showed no significant inhibitory effect on the K<sup>+</sup>-stimulated release of ATP. At a concentration of 10<sup>−8</sup> M, the inhibitor appeared to facilitate the K<sup>+</sup>-stimulated ATP release; however, analysis revealed that the apparent increase in K<sup>+</sup>-stimulated ATP release was not statistically significant. These results suggest that ET-1 may

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**Fig. 4.** Pharmacological characterization of the ET<sub>B</sub> agonists on ATP release. The ET<sub>B</sub> agonists (solid bars) STX 6c (A), BQ 3020 (B), and IRL 1620 (C) caused a dose-dependent inhibition of the K<sup>+</sup>-evoked release (open bars; 50 mM) of ATP from NGF-differentiated PC12 cells: STX6c (10<sup>−12</sup> to 10<sup>−8</sup> M), from 213 ± 63% to 69 ± 36%, 33 ± 26%, and −5 ± 26%, respectively; BQ 3020 (10<sup>−12</sup> to 10<sup>−8</sup> M), from 213 ± 63% to 39 ± 19%, 58 ± 22%, and −5 ± 21%, respectively; and IRL 1620 (10<sup>−12</sup> to 10<sup>−8</sup> M), from 213 ± 63% to 6 ± 22%, 16 ± 33%, and −24 ± 17%, respectively. Each bar represents the mean ± S.E.M. of 12 to 15 wells from five individual experiments. *, P < 0.05 versus K<sup>+</sup>-evoked release.
The ETB antagonists (hatched bars) RES 701-1 (A) and BQ 788 (B) reversed the inhibition caused by ET-1 (solid bar; 10^{-10} M, 11 ± 14%) of the K⁺-evoked release (open bars; 50 mM) of ATP from NGF-differentiated PC12 cells. RES 701-1 (10^{-7} to 10^{-5} M; to 114 ± 35%, 92 ± 23%, and 91 ± 20%, respectively) and BQ 788 (10^{-7} to 10^{-5} M; to 59 ± 30%, 107 ± 41%, and 91 ± 20%, respectively). Each bar represents the mean ± S.E.M. of 10 to 14 wells from five individual experiments. *, P < 0.05 versus K⁺-evoked release; †, P < 0.05 compared with ET-1.

Fig. 5. Pharmacological characterization of the ETᵦ antagonists on ATP release. The ETᵦ antagonists (hatched bars) RES 701-1 (A) and BQ 788 (B) reversed the inhibition caused by ET-1 (solid bar; 10^{-10} M, 11 ± 14%) of the K⁺-evoked release (open bars; 50 mM) of ATP from NGF-differentiated PC12 cells: RES 701-1 (10^{-7} to 10^{-5} M; to 114 ± 35%, 92 ± 23%, and 91 ± 20%, respectively) and BQ 788 (10^{-7} to 10^{-5} M; to 59 ± 30%, 107 ± 41%, and 91 ± 20%, respectively). Each bar represents the mean ± S.E.M. of 10 to 14 wells from five individual experiments. *, P < 0.05 versus K⁺-evoked release; †, P < 0.05 compared with ET-1.

Fig. 6. The effect of PTX on ATP release. PC12 cells were preincubated with PTX (50 mM, 20 h) and then stimulated with ET-1. PTX reversed the inhibition caused by ET-1 (solid bars; 10^{-10} M), of the K⁺-evoked release (open bars; 50 mM) of ATP from NGF-differentiated PC12 cells from 26 ± 50% to 249 ± 54%. Each bar represents the mean ± S.E.M. of 10 to 14 wells from five individual experiments. *, P < 0.05 versus K⁺-evoked release.

The results indicate that release of ATP from the NGF-differentiated PC12 cell can be modulated by ET-1. Furthermore, this modulation appears to be via the ETᵦ subtype of ET receptor and its associated Gᵦ G-protein by means of the attenuation of the influx of extracellular Ca²⁺, possibly through voltage-sensitive channels. Moreover, inhibition of ATP release appears to be mediated through L-type voltage-dependent Ca²⁺ channels.

Interestingly, in this model of sympathetic neurotransmission, it was demonstrated that ET-1 functions as a neuromodulator of transmitter release by differentially modulating the release of ATP, dopamine, and NPY. Until recently, the general consensus has been that ATP is costored and coreleased with catecholamines in vesicles in the sympathetic nerve ending. However, recent evidence would suggest a more complex picture of neurotransmission occurs and that differential release of the cotransmitters takes place at the neuroeffector junction. Todorov et al. (1994, 1996) demonstrated in the guinea pig vas deferens, there is a temporal difference in the release of ATP and NE, with the transient release of ATP at initiation of nerve stimulation, followed by a sustained release of NE. Moreover, the authors demonstrated the ratio of the released NE to released purine from the guinea pig vas deferens after sympathetic nerve stimulation did not remain constant, as would be expected if the cotransmitters originated from the same vesicle but instead changed indicating a difference in the source of the two neurotransmitters (Todorov et al., 1994). These data suggest that in sympathetic nerves, differential cotransmission occurs, and ATP and NE may in fact be stored in separate vesicles.

These observations may provide an explanation for the difference in modulation by ET-1 on the release of the neurotransmitters demonstrated in this study. The differential modulation of the release of NE and ATP has been demonstrated by other substances in a variety of preparations. The α₂ agonist clonidine inhibits the release of NE but not ATP from the mesenteric plexus of the guinea pig ileum (Hammond et al., 1988). In other preparations, including the mouse vas deferens (Von Kugelgen et al., 1989), rabbit ileocolic artery (Bulloch and Starke, 1990), and guinea pig vas deferens (Driessan et al., 1993), activation of prejunctional α₂-adrenoceptors appears to decrease the release of NE more than the release of ATP. Similarly, inhibition of α₂-adrenoceptors produces a greater overflow of NE than ATP, suggesting that endogenously released NE normally has a greater inhibitory effect on its own release than on the release of ATP (Todorov et al., 1996). Recently, in the mesenteric rat arterial bed, ET-1 was shown to differentially modulate the release of the cotransmitters NPY and NE by inhibiting the release of NPY but not NE (Hoang et al., 2002). The findings in this study, therefore, are consistent with the existing evidence for differential modulation of sympathetic neurotransmission.

As previously discussed, ETs have been shown to modulate sympathetic neurotransmission by enhancement of the postjunctional contractile effect of nerve stimulation or through a variety of vasoactive agents, possibly by way of the ETᵦ receptor (Henrion and Laher, 1993). The current findings in this paper and by other investigators show a prejunctional inhibition of sympathetic neurotransmission, possibly via the ETᵦ receptor (Matsuo et al., 1997). The study by Nakamura et al. (2003) on gastric sympathetic neurotransmission demonstrated that both ETᵦ and ETᵦ receptor sub-
types appear to participate in the inhibition of NE release from the rat stomach, although to different degrees. The selective ETA receptor antagonist, BQ123, attenuated the concentration-dependent ET-1-induced inhibition of NE release, but the selective ETB antagonist, BQ 788, had no effect. However, activation of the ETB receptor by the highly selective ETB receptor agonist, sarafotoxin S6c, inhibited NE release from the stomach to a small but significant degree (Nakamura et al., 2003). These observations raise the possibility that ET-1 and its receptor subtypes play a dual role in modulating sympathetic neurotransmission.

ET-1 is released from the vascular endothelium by a variety of stimuli. ATP is released both prejunctionally from the sympathetic nerves (Burnstock and Kennedy, 1986) and postjunctionally from smooth muscle upon contraction (Muramatsu et al., 1981). It is also known that the ATP metabolite, adenosine, can feed back through A1 receptors to inhibit the further release of ATP from the nerve endings (Dalziel and Westfall, 1994). This, coupled with the fact that ET-1 also appears to feed back negatively on ATP release through the ETB receptor, provides more insight into the control of the release of ATP at the neuroeffector junction. Moreover, these observations suggest that the release of ATP is modulated by independent mechanisms.

The ET-1 receptor is a G-protein-coupled receptor, and their associated G-proteins are pivotal in intracellular signaling events following agonist-induced receptor activation. The Gi or Go family of G-proteins can be differentiated from the Gq,G12/13 subtypes by PTX-mediated ADP-ribosylation of their G/H9251 subunits. In this study, pretreatment of NGF-differentiated cells with PTX reversed the ET-1-induced inhibition of the K/H11001-evoked ATP release, suggesting that PTX-sensitive G-proteins, Gi or Go, are involved in intracellular signaling events caused by ET-1 to inhibit ATP release. The observations in this study are consistent with other investigations that have shown involvement of PTX-sensitive G-proteins in the mechanism of ET-1-mediated events. PTX-sensitive G-proteins have been observed to prevent the ET-1-induced inhibition of NE release from the rat stomach (Nakamura et al., 2003), pig coronary artery smooth muscle contraction (Kasuya et al., 1992), and L-type voltage-dependent calcium currents in myocytes (Boixel et al., 2001).

Central to the exocytotic release of most neurotransmitters is the rise in intracellular Ca2/H11001 concentrations (Parnas et al., 2000). The release of ATP from the sympathetic nerve terminals has been determined to be a Ca2/H11001-dependent process and has been demonstrated in a variety of preparations including the bladder, vas deferens, and neuromuscular junc-
data not shown), inhibited voltage-dependent Ca\(^{2+}\) channels in NGF-differentiated PC12 cells, suggesting that these channels may have a key role in the mechanism by which ET-1 negatively modulates ATP release. This observation, although preliminary, is consistent with those who demonstrated that ET-1 inhibits voltage-dependent Ca\(^{2+}\) channels and that negative modulation of neurotransmitter release is mediated by these channels. N-type voltage-dependent Ca\(^{2+}\) channels have been shown to be involved in the mechanism by which ET-1 negatively modulates the release of NE from sympathetic gastric nerve terminals (Nakamura et al., 2003).

In this study, the L-type voltage-dependent Ca\(^{2+}\) channel may be mediating the ET-1-induced inhibition of ATP release as nifedipine, an L-type voltage-dependent antagonist, dose dependently inhibited ATP release. At concentrations of 5 \(\times\) 10\(^{-5}\) and 5 \(\times\) 10\(^{-6}\) M, the N-type Ca\(^{2+}\) channel antagonist, \(\omega\)-conotoxin GVIA, did not cause a statistically significant inhibition of the K\(^-\)stimulated ATP release.

The data presented indicate that ET-1-mediated attenuation of ATP is mimicked in a concentration-dependent manner by nifedipine, suggesting a potential role for the L-type voltage-dependent calcium channel in the molecular signaling mechanism. A possible mechanism for the inhibitory actions of ET-1 through the ET\(_B\) receptor could be through the inhibition of L-type voltage-dependent calcium channels in the nerve terminal, thereby preventing Ca\(^{2+}\) influx. Interestingly it has been shown that ET-1 inhibits L-type Ca\(^{2+}\) channels in the heart and that the ET-1-induced transient spike in [Ca\(^{2+}\)], was inhibited by nifedipine (Boixel et al., 2001), suggesting a potential role for this specific voltage-dependent channel in the ET-induced inhibition of ATP release. Presently, however, we do not know whether the linkage between the endothelin receptor and the calcium channel is direct or indirect. However, there are other studies where, in NGF-differentiated PC12 cells, NPY has been shown to indirectly inhibit extracellular Ca\(^{2+}\) influx through the L-type channel via a PKC and Ca\(^{2+}\) calmodulin-dependent protein kinase (McCullough and Westfall, 1996). Additionally, NPY can directly inhibit extracellular Ca\(^{2+}\) influx through the N-type voltage-dependent calcium channel (McCullough et al., 1998). Elucidation of the detailed molecular signaling mechanisms by which ET-1 has its effects is currently under investigation.

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**References**


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