Aldehyde Dehydrogenase Type 2 Activation by Adenosine and Histamine Inhibits Ischemic Norepinephrine Release in Cardiac Sympathetic Neurons: Mediation by Protein Kinase C Epsilon

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Running Title:

**ALDH2 Inhibits NE Release In Ischemic Heart Neurons**

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Text pages: 39
Figures: 9
References: 36
Abstract: 250 words
Introduction: 253 words
Discussion: 1,052 words

Non-standard abbreviations used in the paper:

**ALDH2**, aldehyde dehydrogenase type 2; **DMI**, desipramine hydrochloride; **GTN**, glyceryl trinitrate; **4-HNE**, 4-hydroxynonenal; **NE**, norepinephrine; **PKCε**, Protein Kinase Cε.

Recommended section assignment: **Cardiovascular**
Abstract

During myocardial ischemia/reperfusion, lipid peroxidation leads to the formation of toxic aldehydes that contribute to ischemic dysfunction. Mitochondrial aldehyde dehydrogenase 2 (ALDH2) alleviates ischemic heart damage and reperfusion arrhythmias via aldehyde detoxification. Since excessive norepinephrine release in the heart is a pivotal arrhythmogenic mechanism, we hypothesized that neuronal ALDH2 activation might diminish ischemic norepinephrine release. Incubation of cardiac sympathetic nerve endings with acetaldehyde, at concentrations achieved in myocardial ischemia, caused a concentration-dependent increase in norepinephrine release. A major increase in norepinephrine release also occurred when sympathetic nerve endings were incubated in hypoxic conditions. ALDH2 activation substantially reduced acetaldehyde- and hypoxia-induced norepinephrine release, an action prevented by inhibition of ALDH2 or Protein Kinase Cε (PKCε). Selective activation of Gi/o-coupled adenosine A1, A3- or histamine H3-receptors markedly inhibited both acetaldehyde- and hypoxia-induced norepinephrine release. These effects were also abolished by PKCε and/or ALDH2 inhibition. Moreover, A1-, A3- or H3-receptor activation increased ALDH2 activity in a sympathetic neuron model (i.e., differentiated PC12 cells stably transfected with H3-receptors). This action was prevented by inhibition of PKCε and ALDH2. Our findings suggest the existence in sympathetic neurons of a protective pathway initiated by A1-, A3- and H3-receptor activation by adenosine and histamine released in close proximity of these terminals. This pathway comprises the
sequential activation of PKCε and ALDH2 culminating in aldehyde detoxification and inhibition of hypoxic norepinephrine release. Thus, pharmacological activation of PKCε and ALDH2 in cardiac sympathetic nerves may have significant protective effects by alleviating norepinephrine-induced life-threatening arrhythmias that characterize myocardial ischemia/reperfusion.
Introduction

Acetaldehyde, the product of ethanol oxidation by alcohol dehydrogenase, has been known for quite some time to display sympathomimetic effects (Eade, 1959). Direct perfusion of the canine sinus node with acetaldehyde has been reported to elicit tachycardia that was inhibited by β-adrenergic blockade (James and Bear, 1967). Similarly, i.v. infusion of acetaldehyde in the rat caused tachycardia whose time course mimicked that of its blood level (Hellstrom and Tottmar, 1982). These effects were attributed to catecholamine release, since acetaldehyde appeared to enhance catecholamine secretion from bovine adrenal medulla (Schneider, 1971) and promote norepinephrine (NE) release from rat brain (Thadani and Truitt, Jr., 1977).

Of the toxic aldehydes known to be formed by lipid peroxidation during ischemia/reperfusion (Esterbauer et al., 1991; Cordis et al., 1993; Eaton et al., 1999), acetaldehyde and 4-hydroxynonenal (4-HNE) have been shown to degranulate mast cells (Koda et al., 2010) and release NE from cardiac sympathetic nerve endings (Morrey et al., 2010). Hence, we asked whether toxic aldehydes might be causally involved in the release of NE, which characterize ischemia/reperfusion (Imamura et al., 1994; Imamura et al., 1996), and whether selective activation of neuronal mitochondrial aldehyde dehydrogenase type 2 (ALDH2) (Chen et al., 2008) might bring about a beneficial decrease in NE release.

Our findings suggest that, in ischemic conditions, adenosine and histamine formed in close proximity of cardiac sympathetic nerve endings
activate G\textsubscript{i/o}-coupled receptors, such as A\textsubscript{1}, A\textsubscript{3} and H\textsubscript{3}. This initiates a signaling sequence involving activation/translocation of PKC\v and phosphorylation/activation of mitochondrial ALDH2, which disposes of toxic aldehydes and their NE-releasing effects.
Materials and Methods

NE release from cardiac synaptosomes

Male Hartley guinea pigs weighing 300-350 grams (Charles River Laboratories, Kingston, NY) were killed by cervical dislocation under light anesthesia with CO₂ vapor in accordance with institutional guidelines. The ribcage was dissected away and the heart was rapidly excised, freed from fat and connective tissue and transferred to a Langendorff apparatus. Spontaneously beating hearts were perfused through the aorta for 15 min at constant pressure (40 cm of H₂O) with Ringer’s solution at 37°C saturated with 5% CO₂ and 95% O₂. Ringer’s solution composition was (mM): NaCl 154, KCl 5.6, CaCl₂ 2.2, NaHCO₃ 6.0 and dextrose 5.6. This procedure ensured that no blood traces remained in the coronary circulation. At the end of the perfusion, the hearts were minced in ice-cold HEPES-buffered saline solution (HBS) which contained 50 mM HEPES, pH 7.4, 144 mM NaCl, 5 mM KCl, 1.2 mM CaCl₂, 1.2 mM MgCl₂ and 10 mM glucose. Synaptosomes were isolated as previously described (Seyedi et al., 1997). Minced tissue was digested with 40 mg collagenase (Type II, Worthington Biochemicals, Freehold, NJ) per 10 ml HBS per gram of wet heart weight for 1 hour at 37°C. HBS contained 1 mM pargyline to prevent enzymatic destruction of NE. After low-speed centrifugation (10 min at 120 g and 4°C), the resulting pellet was suspended in 10 volumes of 0.32 M sucrose and homogenized with a Teflon/glass homogenizer. The homogenate was spun at 650 g for 10 min at 4°C and the pellet was then re-homogenized and re-spun. The pellet containing cellular debris was discarded, and the
supernatants from the last two spins were combined and equally subdivided into tubes. Each tube was centrifuged for 20 min at 20,000 g at 4°C. This pellet, which contained cardiac synaptosomes, was resuspended in HBS to a final volume of 1 ml in the presence or absence of acetaldehyde for a total of 10 min in a water bath at 37°C. Each suspension functioned as an independent sample and was used only once. In every experiment, one sample was untreated (control, basal NE release), and others were incubated with drugs for 10-30 min. When antagonists were used, samples were incubated with the antagonists before incubation with the agonist. Controls were incubated for an equivalent length of time without drugs. At the end of the incubation period, each sample was centrifuged (20 min, 20,000 g, 4°C). The supernatant was assayed for NE content by high pressure liquid chromatography (HPLC) with electrochemical detection (Seyedi et al., 1997). The pellet was assayed for protein content by a modified Lowry procedure (Seyedi et al., 1997).

**Induction of ischemia-like conditions in cardiac synaptosomes**

Ischemia-like conditions (i.e., hypoxia) were generated by incubating synaptosomes for 30 min in glucose-free HBS bubbled with 95% N₂ and 5% CO₂, containing sodium dithionite (3 mM, PO₂ ≈0 mmHg, pH ≈7.4; ischemic-like release)(Sesti et al., 2003). Matched synaptosomes were incubated for an equivalent period with oxygenated (95% O₂ and 5% CO₂) HBS (normoxic basal release).
After incubation, each sample was centrifuged (20 min, 20,000 g, 4°C) and the supernatant was assayed for NE content by HPLC. The pellet was assayed for protein content by a modified Lowry assay using Bio-Rad DC Protein Assay kit (Bio-Rad Laboratories, Hercules, CA).

**Cell culture**

Rat pheochromocytoma PC12 cells were transfected with the human histamine H₃-receptor (donated by Dr. T. W. Lovenberg, Johnson & Johnson Pharmaceutical R&D, LLC, San Diego, CA) using Lipofectamine 2000 (Invitrogen, Carlsbad, CA) following the manufacturer’s protocol. PC12-H₃ cell lines were selected and maintained in selection media containing 500 μg/ml G-418 sulfate (Mediatech, Herndon, VA). PC12-H₃ cells were maintained in Dulbecco’s modified Eagle’s medium plus 10% fetal bovine serum, 5% donor horse serum, 1% L-glutamine, and antibiotics at 37°C in 5% CO₂. The differentiating protocol involved plating PC12-H₃ cells on tissue culture plates coated with collagen (rat tail type-VII; Sigma-Aldrich, St. Louis, MO) combined with exposure to low serum medium containing 1% fetal bovine serum, 0.5% donor horse serum, 1% L-glutamine, and antibiotics supplemented with 7S-NGF (BD Biosciences, Bedford, MA). For each experiment, the culture medium was aspirated and cells were washed twice with Na Ringer (mM): NaCl, 140; KCl, 5; HEPES, 10; MgCl₂, 1; glucose, 2 and CaCl₂, 2), then incubated with Alda-1 [N-(1,3-Benzodioxol-5-ylmethyl)-2,6-dichlorobenzamide], an ALDH2 activator (100 μM)(Chen et al., 2008), 2'-MeCCPA [2-Chloro-N-cyclopentyl-2'-
methyladenosine], an adenosine A<sub>1</sub>-receptor agonist (10 nM)(Franchetti et al., 1998), IB-MECA [1-Deoxy-1-[6-[[3-iodophenyl)methyl]amino]-9H-purin-9-yl]-N-methyl-β-D-ribofuranuronamide], an adenosine A<sub>3</sub>-receptor agonist (50 nM)(Gallo-Rodriguez et al., 1994), or methimepip [4-(1H-imidazol-4-ylmethyl)-1-methylpiperidine], a histamine H<sub>3</sub>-receptor agonist (1 nM)(Kitbunnadaj et al., 2005) for 20 min in an incubator at 37°C either in the absence or presence of GTN (glyceryl trinitrate; 2 μM), which causes desensitization of ALDH2 (Chen et al., 2008), DPCPX (8-Cyclopentyl-1,3-dipropylxanthine), an adenosine A<sub>1</sub>-receptor antagonist (300 nM)(von der Leyen H. et al., 1989), MRS1523 [3-Propyl-6-ethyl-5-[(ethylthio)carbonyl]-2phenyl-4-propyl-3-pyridine carboxylate], an adenosine A<sub>3</sub>-receptor antagonist (100 nM)(Li et al., 1998), JNJ5207852 [1-[3-[4-(Piperidin-1-ylmethyl)phenoxy]propyl]piperidine] a histamine H<sub>3</sub>-receptor antagonist (30 nM)(Barbier et al., 2004), peptide εV<sub>1-2</sub> (EAVSLKPT) a PKCε inhibitor (1 μM)(Johnson et al., 1996) or peptide ΨεRACK [HDAPIGYD; PKCε (85-92)] a PKCε activator (Dorn et al., 1999). When these drugs were used, PC12-H<sub>3</sub> cells were pre-incubated with them for 30 min. Controls were incubated for an equivalent length of time without drugs. At the end of each experiment, cell lysates were analyzed for ALDH2 activity.

**ALDH2 enzymatic activity assay**

Enzymatic activity of ALDH2 in PC12-H<sub>3</sub> cells was determined spectrophotometrically by monitoring the reductive reaction of NAD<sup>+</sup> to NADH at 340 nm as previously described (Koda et al., 2010). The assays were carried out
in 50 mM sodium pyrophosphate buffer, pH = 9.0, at 25°C. 300 μg of cell lysates and 2.5 mM NAD were added to the buffer. To start the reaction, 10 mM acetaldehyde was added and the accumulation of NADH was recorded for 3 min with measurements taken every 15 sec. ALDH2 reaction rates were calculated as μmol NADH/min/mg protein, and compared with control cells (i.e., treated with Na Ringer) and expressed as % increase from control.

Statistics

Values are expressed as means ± S.E.M. Unpaired t test, and one-way and two-way ANOVA were performed where appropriate, as indicated in figure legends. A value of p<0.05 was considered statistically significant.

Drugs and Chemicals

Acetaldehyde, desipramine hydrochloride (DMI), ω-conotoxin GVIA, IB-MECA, DPCPX and MRS1523 were purchased from Sigma-Aldrich Chemical Co (St Louis, MO). Methimepip dihydrobromide, JNJ5207852 and 2'-MeCCPA were purchased from Tocris Bioscience (Ellsville, MO). GTN was purchased from Hospira, Inc. (Lake Forest, IL). Peptide ΨεRACK, εV1-2 and Alda-1 were synthesized and kindly provided by the Mochly-Rosen lab (Stanford University School of Medicine, Palo Alto, CA). IB-MECA, Alda-1, MRS1523, JNJ5207852, ω-conotoxin GVIA and 2'-MeCCPA were dissolved in dimethyl sulfoxide (DMSO). Further dilutions were made with HBS; at the concentration used, DMSO did not affect mediator release.
Results

**ALDH2 activation reduces hypoxic NE release from cardiac sympathetic nerve endings: involvement of adenosine A₁ and A₃ receptors and PKCε.**

Incubation of cardiac synaptosomes in hypoxic conditions for 30 min caused a ≥50% increase in NE release above basal conditions. In the presence of the ALDH2 activator Alda-1 (20 µM; 12 min) (Chen et al., 2008) the hypoxic increase in NE release was reduced by ~60%. Preincubation with GTN (2 µM; 30 min), which causes ALDH2 desensitization (Chen et al., 2008), prevented the effect of Alda-1 (Fig. 1A). Selective PKCε activation with ΨεRACK (500 nM; 12 min) (Inagaki et al., 2003) attenuated the hypoxia-induced NE release by ~45%. ALDH2 desensitization with GTN (2 µM; 30 min) prevented the effect of ΨεRACK (Fig. 1B). Selective activation of adenosine A₁-receptors with 2'-MeCCPA (10 nM; 12 min) (Franchetti et al., 1998) reduced the hypoxia-induced increase in NE release by ~50%. ALDH2 desensitization with GTN (2 µM; 30 min) and PKCε blockade with εV₁-2 (1 µM; 20 min) (Johnson et al., 1996) each prevented the effects of 2'-MeCCPA (Fig. 1C). Blockade of adenosine A₁-receptors with DPCPX (300 nM; 12 min) (von der Leyen H. et al., 1989) enhanced hypoxia-induced NE release by ≥30% (Fig. 1D). Selective activation of adenosine A₃-receptors with IB-MECA (50 nM; 12 min) (Gallo-Rodriguez et al., 1994) reduced the hypoxia-induced increase in NE release by ~35%. ALDH2 desensitization with GTN (2 µM; 30 min) and PKCε blockade with εV₁-2 (1 µM; 20 min) each prevented the effects of IB-MECA (Fig. 1E). Blockade of adenosine A₃-receptors...
with MRS1523 (100 nM; 12 min)(Li et al., 1998) enhanced hypoxia-induced NE release by ~35% (Fig.1F).

These results suggested that activation of ALDH2 in cardiac sympathetic neurons reduces hypoxic NE release by removing toxic aldehydes which are known to be formed in ischemic conditions, most likely acetaldehyde (Esterbauer et al., 1991; Cordis et al., 1993). This process likely involves adenosine release, activation of $A_1$- and $A_3$-receptors and activation/translocation of PKCε.

**Administration of exogenous acetaldehyde to cardiac sympathetic nerve endings elicits NE release: inhibition by activation of ALDH2 and PKCε.**

Incubation of cardiac synaptosomes with acetaldehyde (100-1,000 µM; 10 min) elicited a concentration-dependent increase in NE release which was abolished by ALDH2 activation with Alda-1 (20 µM; 10 min). ALDH2 desensitization with GTN (2 µM; 30 min) prevented the effect of Alda-1 (Fig. 2A). PKCε activation with $Ψε$RACK (500 nM; 10 min; (Inagaki et al., 2003) attenuated the acetaldehyde-induced release of NE. ALDH2 desensitization with GTN (2 µM; 30 min) prevented the effect of $Ψε$RACK (Fig. 2B).

Thus, exogenous acetaldehyde elicits NE release from cardiac sympathetic nerve endings and activation of ALDH2 abolishes the effect of acetaldehyde. Activation/translocation of PKCε mimics the effect of Alda-1; this action is prevented by prior desensitization of ALDH2. This suggests that activation/translocation of PKCε in turn activates ALDH2, which then attenuates the NE-releasing effect of acetaldehyde.
Activation of adenosine A₁- and A₃-receptors inhibits the acetaldehyde-induced NE release from isolated cardiac synaptosomes: prevention by either PKCε inhibition or ALDH2 desensitization.

Activation of adenosine A₁-receptors with 2′-MeCCPA (10 nM; 10 min) shifted downwards and to the right the concentration-response curve for the NE-releasing effect of acetaldehyde in isolated sympathetic nerve endings (cardiac synaptosomes) (Fig. 3A). The effect of 2′-MeCCPA was prevented by the selective A₁-receptor antagonist DPCPX (300 nM; 10 min)(Fig. 3A), by the PKCε inhibitor εV₁-2 (1 µM; 10 min) (Fig. 3B) and by ALDH2 desensitization with GTN (2 µM; 30 min) (Fig. 3C).

Activation of adenosine A₃-receptors with IB-MECA (50 nM; 10 min) also shifted downwards and to the right the concentration-response curve for the NE-releasing effect of acetaldehyde (Fig. 3D). The effect of IB-MECA was prevented by the selective A₃-receptor antagonist MRS1523 (100 nM; 10 min) (Fig. 3D), by the PKC inhibitor εV₁-2 (1 µM; 10 min) (Fig. 3E) and by ALDH2 desensitization with GTN (2 µM; 30 min) (Fig. 3F).

Thus, activation of adenosine A₁- and A₃-receptors attenuates the NE-releasing effect of acetaldehyde in cardiac sympathetic nerve terminals, an action which depends on PKCε and ALDH2 activation.

ALDH2 activation prevents the acetaldehyde-induced release of NE and associated tachycardia in the ex vivo guinea pig heart
Perfusion of guinea pig hearts ex vivo with acetaldehyde (500 µM; 20 min) in a Langendorff apparatus elicited a ~6-fold increase in NE overflow that was associated with a ~30 beats/minute increase in heart rate. Both of these changes subsided at the end of the acetaldehyde perfusion. When acetaldehyde was preceded by a 10-min perfusion with the ALDH2 activator Alda-1 (20 µM) the increases in NE overflow and heart rate were both markedly reduced (Fig. 4). This indicated that acetaldehyde provokes the release of NE from cardiac sympathetic neurons, and NE is likely responsible for the associated tachycardia, since ALDH2 activation diminished both NE release and tachycardia.

**Mechanism of acetaldehyde-induced NE release**

Blockade of N-type Ca$^{2+}$ channels with ω-conotoxin GVIA (ω-CTX; 100 nM; 10 min) markedly reduced the acetaldehyde-induced NE release; in fact, the acetaldehyde concentration-response curve for the NE-releasing effect of acetaldehyde in isolated sympathetic nerve endings was significantly shifted to the right and downwards (Fig. 5). In contrast, pre-incubation of cardiac synaptosomes with the NE transporter inhibitor DMI (300 nM; 10 min) significantly potentiated the NE-releasing effect of acetaldehyde; this resulted in a marked upward and leftward shift of the concentration-response curve for the NE-releasing effect of acetaldehyde (Fig. 5). This indicated that acetaldehyde most likely promotes NE exocytosis.
Histamine H3-receptor activation attenuates hypoxic NE release from cardiac synaptosomes: prevention by PKCε inhibition or ALDH2 desensitization.

Incubation of cardiac synaptosomes in hypoxic conditions for 30 min caused a ≥50% increase in NE release above basal conditions (Figs. 1 and 6). In the presence of the selective histamine H3-receptor agonist methimipip (1 nM; 12 min) (Kitbunnadaj et al., 2005) the hypoxic increase in NE release was reduced by ~50%, an effect which was prevented by addition of the selective H3-receptor antagonist JNJ5207852 (30 nM; 12 min) (Barbier et al., 2004). Addition of the PKCε inhibitor εV1-2 (1 µM; 20 min) or of GTN (2 µM; 30 min), which causes ALDH2 desensitization, prevented the effect of methimipip (Fig. 6). These results suggested that, similar to A1- and A3-receptors, activation of H3-receptors in cardiac sympathetic neurons also reduces hypoxic NE release by an action that involves PKCε and ALDH2.

Activation of histamine H3-receptors attenuates acetaldehyde-induced NE release from cardiac sympathetic nerve endings: inhibition by blockade of PKCε or by desensitization of ALDH2.

Incubation of cardiac synaptosomes with acetaldehyde (100-1,000 µM; 10 min) elicited a concentration-dependent increase in NE release which was markedly attenuated by H3-receptor activation with methimepip (1 nM; 10 min). This effect was prevented by H3-receptor blockade with JNJ5207852 (30 nM; 10 min) (Fig. 7A). PKCε blockade with εV1-2 (1 µM; 10 min) or ALDH2 desensitization
with GTN (2 μM; 30 min) each prevented the effect of methimepip (Fig. 7B and 7C, respectively). Thus, exogenous acetaldehyde elicits NE release from cardiac sympathetic nerve endings; similar to A₁- and A₃-receptors, H₃-receptor activation reduces acetaldehyde-induced NE release by an action that involves PKCε and ALDH2.

**Activation of adenosine A₁- and A₃-receptors and histamine H₃-receptors increases ALDH2 activity in PC12-H₃ cells: prevention by ALDH2 desensitization or PKCε inhibition.**

As described above, activation of adenosine A₁- and A₃-receptors as well as histamine H₃-receptors in cardiac synaptosomes markedly reduced hypoxia- and acetaldehyde-induced NE release, and all these effects were abolished by PKCε inhibition or ALDH2 desensitization. This suggested that stimulation of A₁-, A₃- and H₃- receptors may sequentially increase PKCε and ALDH2 activity. We verified this hypothesis in NGF-differentiated pheochromocytoma PC12 cells stably transfected with H₃-receptors, a recognized model of peripheral sympathetic neuron (Morrey et al., 2008; Corti et al., 2011). We found that Alda-1 (100 μM; 20 min) elicited a ≥60% increase in ALDH2 activity (Fig. 8). Similar to Alda-1, activation of adenosine A₁- and A₃-receptors as well as histamine H₃-receptors with the respective selective agonists 2'-MeCCPA (10 nM; 20 min; Fig. 8A), IB-MECA (50 nM; 20 min; Fig. 8B) and methimepip (1 nM; 20 min; Fig. 8C) caused a ~40-55% increase in ALDH2 activity, which was abolished by the respective antagonists DPCPX (300 nM; 30 min), MRS1523 (100 nM; 30 min).
and JNJ5207852 (30 nM; 30 min) (Fig. 8A, B and C). Similar to Alda-1, the effects of 2'-MeCCPA, IB-MECA and methimepip were abolished by prior ALDH2 desensitization with GTN (2 μM; 30 min) (Fig. 8A, B and C). Prior blockade of PKCε with εV1.2 (1 μM; 30 min) also prevented the ALDH2-stimulating effect of 2'-MeCCPA, IB-MECA and methimepip (Fig. 8A, B and C). Thus, the prevention of the NE-releasing effects of hypoxia or acetaldehyde by A1-, A3- and H3-receptor activation likely results from an increase in ALDH2 activity in sympathetic nerve endings via PKCε activation/translocation.
Discussion

We hypothesized that toxic aldehydes formed in the heart during ischemia and reperfusion may elicit the release of NE from sympathetic nerve terminals, and that aldehyde detoxification by ALDH2 might inhibit this process. Our findings suggest that in myocardial ischemia, locally released endogenous mediators, such as adenosine and histamine, promote a receptor-initiated sequential activation of neuronal PKCε and ALDH2, culminating in an attenuation of NE release.

We had previously observed that incubation of cardiac sympathetic nerve endings in hypoxic conditions in vitro elicits a marked increase in NE release (Sesti et al., 2003). Here, we uncovered that selective pharmacologic activation of neuronal ALDH2 with Alda-1 (Chen et al., 2008) markedly diminishes hypoxic NE release, an action which is reversed by ALDH2 desensitization with GTN. This suggests that ALDH2 activation eliminates NE-releasing effect in ischemic conditions.

We had found that PKCε translocation/activation leads to ALDH2 activation in mast cell mitochondria (Koda et al., 2010). PKCε activation appears now to be an essential precursor of ALDH2 activation also in the ischemic sympathetic nerve terminal. Indeed, PKCε and ALDH2 activation each inhibited hypoxic NE release and both of these actions were prevented by ALDH2 desensitization with GTN. Since activation of G_{i/o}-coupled receptors leads to PKCε translocation/activation (Inagaki et al., 2006), and adenosine is formed copiously in the ischemic myocardium where it inhibits NE release (Endou et al.,
1994; Imamura et al., 1996), we hypothesized that activation of Gi/o-coupled adenosine receptors might initiate the PKCε-ALDH2 cascade culminating in the inhibition of NE release. Indeed, we found that blockade of adenosine A1- and A3-receptors enhanced NE release in hypoxic sympathetic nerve terminals, indicating that these receptors were already activated by an endogenous ligand, most likely adenosine. Alternatively, it is conceivable that hypoxia caused an increase of constitutive activity of these receptors and that the antagonists were acting as inverse agonists. In any event, activation of adenosine A1- or A3-receptors with selective exogenous ligands, 2′-MeCCPA (Franchetti et al., 1998) and IB-MECA (Gallo-Rodriguez et al., 1994) respectively, inhibited hypoxic NE release an action that was prevented by blockade of PKCε or ALDH2. This suggested a protective chain of events initiated by the sequential activation of A1- and A3-receptors, PKCε and ALDH2. Notably, activation of the Gs-coupled adenosine A2b-receptors with LUF5835 (Baraldi et al., 2008) failed to modify ischemic NE release (data not shown), confirming that Gi/o coupling is a prerequisite for the initiation of the PKCε/ALDH2-mediated inhibition of ischemic NE release. To strengthen this postulate, we resolved to activate another Gi/o-coupled receptor, i.e. the histamine H3-receptor which we had previously reported to be present in cardiac sympathetic nerve endings where it negative modulates ischemic NE release (Levi and Smith, 2000). Indeed, the selective H3-receptor agonist methimipip (Kitbunnadaj et al., 2005) significantly attenuated hypoxic NE release by an action involving both PKCε and ALDH2, since it was prevented by PKCε blockade and ALDH2 desensitization.
That acetaldehyde, produced in the heart in ischemic conditions, is at least in part responsible for the characteristic increase in NE release, is substantiated by our finding that the administration of exogenous acetaldehyde to isolated cardiac sympathetic nerve terminals elicits NE release. Notably, this NE release increases within a range of acetaldehyde concentrations known to be reached in the ischemic heart (Cordis et al., 1993; Eaton et al., 1999). Most important, in cardiac synaptosomes, acetaldehyde-induced NE release was inhibited by activation of PKCε and ALDH2, revealing that the same mechanisms modulate hypoxic and acetaldehyde-induced NE release from cardiac sympathetic nerve endings. Similar to what observed in sympathetic nerve endings subjected to hypoxia, selective activation of neuronal adenosine A1- and A3-receptors inhibited acetaldehyde-induced NE release and both of these effects were prevented by inhibition of PKCε and ALDH2. Analogous to A1- and A3-receptors, selective activation of neuronal histamine H3-receptors also decreased acetaldehyde-induced NE release, which again was prevented by PKCε and ALDH2 inhibition. It seems likely, therefore, that the inhibition of acetaldehyde-induced NE release initiated by the activation of Gi/o-coupled receptors entails a pathway in which PKCε and ALDH2 play a pivotal role. Indeed, we found that activation of these Gi/o-coupled receptors enhanced in each case the activity of ALDH2 in differentiated pheochromocytoma cells expressing a sympathetic phenotype. This enhancement in ALDH2 activity by adenosine A1- and A3-receptors and histamine H3-receptors mimicked the effect of the prototypical ALDH2 activator, Alda-1 (Chen et al., 2008), and was
abolished by inhibition of PKCε. This confirmed that translocation/activation of neuronal PKCε is essential for the phosphorylation/activation of ALDH2 initiated by stimulation of G_{i/o}-coupled receptors.

As to the mechanism by which acetaldehyde enhances NE release from cardiac sympathetic terminals, it likely involves a promotion of NE exocytosis. Indeed, we found that pharmacological inhibition of neuronal N-type Ca^{2+} channels with ω-conotoxin GVIA (Seyedi et al., 2005) markedly attenuated acetaldehyde-induced NE release. Moreover, pharmacological inhibition of the NE transporter at the level of the neuronal membrane with DMI (Aloyo et al., 1991) potentiated the acetaldehyde-induced NE release. Both of these findings suggest an acetaldehyde-induced enhancement of NE exocytosis. Indeed, were acetaldehyde to enhance a non-vesicular carrier-mediated mechanism of NE release, one would have expected an inhibition, rather than a potentiation of NE release upon blockade of the NE transporter (Levi and Smith, 2000). Moreover, perfusion of isolated Langendorff hearts with acetaldehyde elicited sinus tachycardia that was attenuated ALDH2 activation; arrhythmias, which typically arise with carrier-mediated NE release (Levi and Smith, 2000) did not occur. In protracted ischemic conditions, various locally produced endogenous factors enhance Na^{+}/H^{+} exchanger activity leading to non-vesicular carrier-mediated NE release and associated arrhythmic dysfunction (Levi and Smith, 2000). It is plausible that acetaldehyde formed in severe ischemia might contribute to Na^{+}/H^{+} exchanger activation, carrier-mediated NE release and arrhythmias, since
acetaldehyde was implied to stimulate $\text{Na}^+$/H$^+$ exchanger and increase intracellular Na$^+$ in liver cells (Carini et al., 2000).

In conclusion, our findings reveal a novel mechanism of inhibition of hypoxic NE release in cardiac sympathetic nerve terminals (Fig. 9). This involves the pivotal phosphorylation/activation of mitochondrial ALDH2 by PKC$\varepsilon$, which is translocated/activated when $G_{\text{i/o}}$-coupled receptors, such as $A_1$-, $A_3$- and $H_3$-receptors are activated by adenosine and histamine produced in the close proximity of sympathetic nerve endings. Since excessive NE release is a major cause of arrhythmic cardiac dysfunction, cardiac failure, and hypertension (Julius, 1993; Esler and Kaye, 2000; Selwyn and Braunwald, 2001), activation of ALDH2 may constitute an important new therapeutic target in these conditions.
Acknowledgments

The compounds alda-1, ΨεRack and εV_{1,2} were donated by Dr. Daria Mochly-Rosen, Stanford University School of Medicine, Palo Alto, CA.
Authorship Contributions:

*Participated in research design:* Robador, Chan, Koda and Levi.

*Conducted experiments:* Robador, Seyedi, Chan and Koda.

*Performed data analysis:* Robador, Seyedi, Chan and Koda.

*Wrote or contributed to the writing of the manuscript:* Robador, Chan and Levi.
References


norepinephrine exocytosis in myocardial ischemia. *J Pharmacol Exp Ther* 306:238-244.


Footnotes

* Pablo A. Robador and Nahid Seyedi contributed equally to this work.

This work was supported by the National Institutes of Health National Heart Lung and Blood Institute [Grant HL034215]; an American Heart Association Grant-in-Aid; Caja Madrid Foundation; and a Pharmaceutical Research Manufacturers Association of America Foundation predoctoral fellowship.
Figure Legends

Figure 1. Release of NE from cardiac synaptosomes during 30-min hypoxia. Bars (means ± S.E.M.) represent the hypoxia-induced increase in NE release above the normoxic basal level of 273 ± 11.5 pmol/mg protein (n = 49). A: Activation of ALDH2 with Alda-1 (20 μM; 12 min) reduces hypoxia-induced NE release. Desensitization of ALDH2 with GTN (2 μM; 30 min) prevents the effect of Alda-1 (n = 7-12). *, P < 0.05 vs. hypoxia; #, P < 0.05 vs. Alda-1 by unpaired t test. B: PKCε activation with ΨεRACK (PKCε activator; 500 nM; 12 min) reduces hypoxia-induced NE release. ALDH2 desensitization with GTN (2 μM; 30 min) prevents the effect of ΨεRACK (n = 7-8). *, P < 0.05 vs. hypoxia; #, P < 0.05 vs. ΨεRACK by unpaired t test. C: Activation of adenosine A1-receptor with 2' -MeCCPA (A1R agonist; 10 nM; 12 min) diminishes hypoxia-induced NE release. ALDH2 desensitization with GTN (2 μM; 30 min) and PKCε blockade with εV1-2 (PKCε inhibitor; 1 μM; 20 min) each prevents the effect of 2'-MeCCPA (n = 7-10). **, P < 0.005 vs. hypoxia; #, P < 0.05 vs. 2'-MeCCPA by unpaired t test. D: Blockade of adenosine A1-receptor with DPCPX (A1R antagonist; 300 nM; 12 min) enhances hypoxia-induced NE release (n = 15-17). *, P < 0.05 vs. hypoxia by unpaired t test. E: Selective activation of adenosine A3-receptor with IB-MECA (A3R agonist; 50 nM; 12 min) reduces hypoxia-induced NE release. ALDH2 desensitization with GTN (2 μM; 30 min) and PKCε blockade with εV1-2 (1 μM; 20 min) each prevents the effect of IB-MECA (n = 7-11). **, P < 0.01 vs. hypoxia; ##, P < 0.005 vs. IB-MECA; ###, P < 0.001 vs. IB-MECA by unpaired t test. F:
Blockade of adenosine A$_3$-receptor with MRS1523 (A$_3$R antagonist; 100 nM; 12 min) enhances hypoxia-induced NE (n = 7-9). *, P < 0.05 vs. hypoxia by unpaired t test.

**Figure 2.** Incubation of isolated cardiac synaptosomes with acetaldehyde elicits a concentration-dependent increase in NE release which is inhibited by activation of either ALDH2 or PKCε. Points (means ± S.E.M.; n = 4-46 and 12-24 in A and B, respectively) represent percent increases in NE release above a mean basal control level of 205 ± 7.4 pmol/mg protein (n = 92). A: ALDH2 activation with Alda-1 (20 µM; 10 min) attenuates the acetaldehyde-induced release of NE. ALDH2 desensitization with GTN (2 µM; 30 min) prevents the effect of Alda-1. B: PKCε activation with ΨεRACK (500 nM, 10 min) attenuates the release of NE. ALDH2 desensitization with GTN (2 µM; 30 min) prevents the effect of ΨεRACK. ***, P < 0.0001 from control and GTN + Alda-1 in A, and from control and GTN + ΨεRACK in B, by unpaired t test.

**Figure 3.** Activation of adenosine A$_1$- and A$_3$-receptors inhibits the acetaldehyde-induced NE release from isolated cardiac synaptosomes: prevention by either PKCε inhibition or ALDH2 desensitization. Points (means ± S.E.M.; n = 8-42) represent percent increases in NE release above a mean basal control level of 267 ± 6.6 pmol/mg protein (n = 124). A: Selective activation of A$_1$-receptors with 2'-MeCCPA (10 nM; 10 min) attenuates NE release by acetaldehyde, an action which is prevented by A$_1$-receptor blockade with DPCPX (300 nM; 10 min). B and
C: The A₁-receptor-induced attenuation of NE release is prevented either by PKCε inhibition with εV₁₂ (1 µM; 10 min) or by ALDH2 desensitization with GTN (2 µM; 30 min). D: Selective activation of A₃-receptors with IB-MECA (50 nM; 10 min) attenuates NE release by acetaldehyde, an action which is prevented by A₃-receptor blockade with MRS1523 (100 nM; 10 min). E and F: The A₃-receptor-induced attenuation of NE release is prevented either by PKCε inhibition with εV₁₂ (1 µM; 10 min) or by ALDH2 desensitization with GTN (2 µM; 30 min). ** and ***, P < 0.01 and 0.001 from control and A₁-receptor and A₃-receptor agonists in combination with respective antagonists, or in combination with εV₁₂ or GTN, by unpaired t test.

**Figure 4.** ALDH2 activation inhibits the positive chronotropic effect of acetaldehyde and associated increase in NE overflow in guinea pig hearts ex vivo. A, time course of the increase in spontaneous heart rate during perfusion with acetaldehyde (500 µM). Pretreatment with the ALDH2 activator Alda-1 (20 µM; 10 min) inhibits the acetaldehyde-induced tachycardia and attenuates the associated increase in NE overflow. Points are heart rates recorded at the corresponding times on the abscissa (means ± S.E.M.; n = 5 and 6 for control and Alda-1, respectively). † and ††, P < 0.05 and 0.01, respectively, from control by one-way ANOVA + Bonferroni’s test. ** and ***, P < 0.01 and 0.001, respectively, from acetaldehyde, by two-way ANOVA + Bonferroni’s test. B, time course of the increase in NE overflow (measured in 5-min intervals) in the same hearts as in A. Bars are means (means ± S.E.M.; n = 5 and 6 for control and
Alda-1, respectively). † and ††, $P < 0.05$ and 0.01, respectively, from control by one-way ANOVA + Bonferroni’s test. **, $P < 0.01$ from acetaldehyde, by two-way ANOVA + Bonferroni’s test.

**Figure 5.** Incubation of isolated cardiac synaptosomes with acetaldehyde elicits a concentration-dependent increase in NE release which is potentiated by the NE transporter inhibitor DMI (300 nM; 10 min). A selective N-type $\text{Ca}^{2+}$ channel blocker, $\omega$-conotoxin GVIA ($\omega$-CTX; 100 nM; 10 min) markedly reduces the acetaldehyde-induced NE release. Points (means ± S.E.M.; $n = 8-32$) represent percent increases in NE release above a mean basal control level of $246 \pm 6.80$ pmol/mg protein ($n = 32$). ***, $P < 0.001$ from acetaldehyde control by unpaired $t$ test.

**Figure 6.** Release of NE from cardiac synaptosomes during 30-min hypoxia. Bars (means ± S.E.M.) represent the hypoxia-induced increase in NE release above the normoxic basal level of $291 \pm 24$ pmol/mg protein ($n = 14$). Treatment with the selective histamine $\text{H}_3$-receptor agonist methimepip (1 nM; 12 min) reduces hypoxia-induced NE release and this effect is blocked by a previous addition of the selective histamine $\text{H}_3$-receptor antagonist JNJ5207852 (30 nM; 12 min). PKCε blockade with εV1-2 (1 μM; 20 min) and ALDH2 desensitization with GTN (2 μM; 30 min) each prevents the effect of methimepip ($n = 5-16$). ***, $P < 0.001$ vs. hypoxia; ##, $P < 0.005$ vs. methimepip; ###, $P < 0.0005$ vs. methimepip by unpaired $t$ test.
**Figure 7.** Activation of histamine $H_3$-receptors inhibits the acetaldehyde-induced NE release from isolated cardiac synaptosomes: prevention by either PKCε inhibition or ALDH2 desensitization. Points (means ± S.E.M.; $n = 12-28$) represent percent increases in NE release above a mean basal control level of 268 ± 9.2 pmol/mg protein ($n = 96$). A: Selective activation of $H_3$-receptors with methimepip (1 nM; 10 min) attenuates NE release by acetaldehyde, an action which is prevented by $H_3$-receptor blockade with JNJ5207852 (30 nM; 10 min). B and C: The $H_3$-receptor-induced attenuation of NE release is prevented either by PKCε inhibition with εV1-2 (1 µM; 10 min) or by ALDH2 desensitization with GTN (2 µM; 30 min). ***, P < 0.0001 from control and $H_3$-receptor agonists with respective antagonists or εV1-2 and GTN, by unpaired $t$ test.

**Figure 8.** Activation of adenosine $A_1$-receptors, $A_3$-receptors or histamine $H_3$-receptors increases ALDH2 activity in PC12-$H_3$ cells. Incubation of PC12-$H_3$ cells with the selective ALDH2 activator Alda-1 (100 µM; 20 min) increases ALDH2 activity (measured by the rate of NADH production at 340 nm). A, Incubation of PC12-$H_3$ cells with the $A_1$-receptor agonist 2′-MeCCPA (10 nM; 20 min) increases ALDH2 activity. Selective desensitization of ALDH2 with GTN (2 µM; 30 min) each prevents the effects of Alda-1 and $A_1$-receptor agonist. Pretreatment of PC12-$H_3$ cells with the selective $A_1$-receptor antagonist DPCPX (300 nM; 30 min) or with the selective PKCε inhibitor εV1-2 (1 µM; 30 min) prevents the effects of $A_1$-receptor activation. B, Incubation of PC12-$H_3$ cells with
the A3-receptor agonist IB-MECA (50 nM; 20 min) increases ALDH2 activity. Selective desensitization of ALDH2 with GTN (2 µM; 30 min) prevents the effects of Alda-1 and IB-MECA. Pretreatment of PC12-H3 cells with the selective A3-receptor antagonist MRS1523 (100 nM; 30 min) or with the selective PKCε inhibitor εV1.2 (1 µM; 30 min) prevents the effects of A3-receptor activation. C, Incubation of PC12-H3 cells with the H3-receptor agonist methimepip (1 nM; 20 min) increases ALDH2 activity. Selective desensitization of ALDH2 with GTN (2 µM; 30 min) prevents the effects of Alda-1 and methimepip. Pretreatment of PC12-H3 cells with the selective H3-receptor antagonist JNJ5207852 (30 nM; 30 min) or with the selective PKCε inhibitor εV1.2 (1 µM; 30 min) prevents the effects of H3-receptor activation. Bars are mean percent increases from control (±S.E.M.; n = 4-16). Basal NADH production was 7.47 ± 0.13 µmol/min/mg protein. ***, P < 0.0001 from control; †††, P < 0.0001 from Alda-1; ***, P < 0.0001 from A1R agonist, ‡‡‡, P < 0.001 from A3R agonist, ###, P < 0.0001 from methimepip by unpaired t test.

**Figure 9.** Proposed pathway for the inhibition of NE release from cardiac sympathetic neurons upon activation of mitochondrial ALDH2. This involves the pivotal phosphorylation/activation of mitochondrial ALDH2 by PKCε, which is translocated/activated when Gαi/o-coupled receptors, such as A1-, A3- and H3-receptors are activated by adenosine and histamine released in ischemic conditions in close proximity to sympathetic nerve endings.
Figure 1

NE release (% increase)

A. Alda-1

B. PKCε activator

C. A1R agonist

D. A1R antagonist

E. A3R agonist

F. A3R antagonist
Figure 2

Graph A: NE release (% increase) vs. Acetaldehyde (µM) for Control, Alda-1, and Alda-1 + GTN.

Graph B: NE release (% increase) vs. Acetaldehyde (µM) for Control, PKC ε activator, and PKC ε activator + GTN.

*** indicates a statistically significant difference.
Figure 4
Figure 5
Figure 7
Figure 8