

Amphetamine Induces a Calcium/Calmodulin-Dependent Protein Kinase II-Dependent Reduction in Norepinephrine Transporter Surface Expression Linked to Changes in Syntaxin 1A/Transporter Complexes

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ABSTRACT

Norepinephrine (NE) transporters (NETs) are high-affinity transport proteins that mediate the synaptic clearance of NE after vesicular release. NETs represent a major therapeutic target for antidepressants and are targets of multiple psychostimulants including amphetamine (AMPH) and cocaine. Recently, we demonstrated that syntaxin 1A (SYN1A) regulates NET surface expression and, through binding to the transporter's NH₂ terminus, regulates transporter catalytic function. AMPH induces NE efflux and may also regulate transporter trafficking. We monitored NET distribution and function in catecholaminergic cell lines (CAD) stably transfected with either full-length human NET (CAD-hNET) or with an hNET N-terminal deletion (CAD-hNET Δ_{28-47} cells). In hNET-CAD cells, AMPH causes a slow and small reduction of surface hNET with a modest increase in

hNET/SYN1A associations at the plasma membrane. In contrast, in CAD-hNET Δ_{28-47} cells, AMPH induces a rapid and substantial reduction in surface hNET Δ_{28-47} accompanied by a large increase in plasma membrane hNET Δ_{28-47} /SYN1A complexes. We also found that AMPH in CAD-hNET Δ_{28-47} cells induces a robust increase in cytosolic Ca²⁺ and concomitant activation of calcium/calmodulin-dependent protein kinase II (CaMKII). Inhibition of either the increase in intracellular Ca²⁺ or CaMKII activity blocks AMPH-stimulated hNET Δ_{28-47} trafficking and the formation of hNET Δ_{28-47} /SYN1A complexes. Here, we demonstrate that AMPH stimulation of CaMKII stabilizes an hNET/SYN1A complex. This hNET/SYN1A complex rapidly redistributes, upon AMPH treatment, when mechanisms supported by the transporter's NH₂ terminus are eliminated.

NET is responsible for the presynaptic elimination of NE after release at noradrenergic synapses (Iversen, 1971; Trendelenburg, 1991). NETs are targets for various psychostimulants, including cocaine and amphetamine (AMPH), and are antagonized by multiple antidepressants (Tatsumi et al., 1997). Topological predictions indicate that NET and its homologs bear 12 transmembrane domains with intracellular NH₂ and COOH termini. The 12 transmembrane domains topology has been supported recently by the high-resolution

structure of LeuT, a prokaryotic sodium-dependent leucine transporter with significant homology to NET and related neurotransmitter transporters (Yamashita et al., 2005).

The intracellular domains of NET have numerous putative phosphorylation sites for various protein kinases, and multiple protein kinases have been suggested to regulate NET function (Blakely et al., 2005). For example, muscarinic receptors (e.g., M3) that are able to stimulate phospholipase C and protein kinase C (PKC) can induce the loss of cell surface NETs with a consequent loss of transport activity (Apparsundaram et al., 1998). Consistent with this observation, phorbol esters trigger a loss of NET surface expression in heterologous expression systems, rat vas deferens, and in forebrain synaptosomes (Apparsundaram et al., 1998; Sung et al., 2003), and NETs, like the serotonin transporter and

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ABBREVIATIONS: NET, norepinephrine transporter; AMPH, amphetamine; NE, norepinephrine; CaMKII, calcium/calmodulin-dependent protein kinase II; SYN1A, syntaxin 1A; CAD, catecholaminergic cell line; h, human; PKC, protein kinase C; DAT, dopamine transporter; HA, hemagglutinin; His, histidine; BAPTA-AM, 1,2-bis(2-aminophenoxy)ethane-*N,N,N',N'*-tetraacetic acid-acetoxymethyl ester; PBS, phosphate-buffered saline; PMSF, phenylmethylsulfonyl fluoride; PAGE, polyacrylamide gel electrophoresis; CTR, vehicle; DMI, desipramine; IP, immunoprecipitate; ANOVA, analysis of variance; KN-93, 2-(*N*-(2-hydroxyethyl)-*N*-(4-methoxybenzenesulfonyl))amino-*N*-(4-chlorocinnamyl)-*N*-methylbenzylamine; KN-92, 2-[*N*-(4'-methoxybenzenesulfonyl)]amino-*N*-(4'-chlorophenyl)-2-propenyl-*N*-methylbenzylamine.

dopamine transporter (DAT) proteins, become phosphorylated (Jayanthi et al., 2004; Cervinski et al., 2005). Still, the mechanisms activated by transporter phosphorylation have not been clarified. In addition, several hormones and signaling pathways can positively regulate NET function, including angiotensin (Lu et al., 1996, 1998; Yang and Raizada, 1998) and insulin (Apparsundaram et al., 2001).

Recently, attention has been drawn to the physical and functional interactions of NET and related transporters with the *t*-soluble *N*-ethylmaleimide-sensitive factor attachment protein receptor protein SYN1A (Deken et al., 2000; Quick, 2003; Sung et al., 2003; Wang et al., 2003). These studies suggest that in addition to its classic role of supporting vesicular fusion, SYN1A also controls neurotransmission by regulating both plasma membrane trafficking and transporter function (Beckman and Quick, 1998; Blakely and Sung, 2000; Sung et al., 2003; Gonzalez and Robinson, 2004). With regard to NET, we have shown that 1) NET colocalizes and forms stable complexes with SYN1A; 2) NET/SYN1A interactions are direct, mediated by the cytoplasmic domain of SYN1A and the NH₂ terminus of NET; and 3) stimuli known to trigger NET redistribution, such as PKC activation, modulate NET/SYN1A interactions (Sung et al., 2003). Sung and collaborators demonstrated that deletion of the first 42 amino acids of hNET (hNET_{Δ2-42}) abolishes the NET/SYN1A interaction. However, as we demonstrate below, smaller mutations such as hNET_{Δ28-47} can preserve and/or enhance this interaction and become useful tools for studying the coordination of hNET regulation by associated proteins.

AMPH, like NE, serves as a substrate for NET (Wall et al., 1995) and promotes transport reversal, triggering vesicle-independent NE release (Wall et al., 1995; Burnette et al., 1996; Pifl and Singer, 1999). AMPH also influences biogenic amine transporters trafficking, best studied with the homologous DAT (Saunders et al., 2000; Kahlig and Galli, 2003; Gonzalez and Robinson, 2004; Johnson et al., 2005). Fleckenstein and colleagues (1999) demonstrated that a single systemic injection of AMPH induces a significant attenuation in dopamine uptake into striatal synaptosomes when prepared within 1 h after administration, effects that are reversible and seem to arise from a decrease in DAT V_{max} , suggesting that the number of DAT proteins on the plasma membrane can be down-regulated by short-term AMPH exposure. Likewise, Gulley et al. (2002) have shown that AMPH exposure to DAT-expressing oocytes or to native DAT expressed in the nucleus accumbens diminishes DAT-mediated currents and dopamine clearance, respectively. Still, it has to be determined whether similar AMPH actions apply to NET. In addition, it is unclear how psychostimulant-modulated transporter trafficking links to the emerging biology of transporter-associated proteins, such as SYN1A.

In the current report, we demonstrate that AMPH induced hNET trafficking away from the plasma membrane, a response negatively modulated by the transporter's NH₂ terminus, as inferred from the properties of a deletion, hNET_{Δ28-47}, that demonstrates more rapid and extensive AMPH-induced transporter redistribution. We propose that normally, this regulation suppresses AMPH-induced increase in intracellular Ca²⁺ and possibly CaMKII-dependent modulatory pathways that lead, among other things, to changes in NET surface expression and formation of NET/SYN1A associations. However, such protective mechanisms

also afford an opportunity for genetic or environmental modulation to disinhibit this process and greatly enhance AMPH action. We discuss our findings in terms of models of AMPH sensitization linked to Ca²⁺/CaMKII-dependent changes in monoamine signaling.

Materials and Methods

Cell Culture and Transfection. CAD cells (Qi et al., 1997) are catecholaminergic cells that express SYN1A (Sung et al., 2003) and provide an appropriate parental background for studying hNET trafficking because of their lack of NET expression, inability to uptake [³H]NE (Sung et al., 2003), and their lack of desipramine- and cocaine-sensitive whole-cell currents (Binda et al., 2005). CAD cells were maintained in Dulbecco's modified Eagle's medium/F-12 medium supplemented with 8% fetal bovine serum, 2 mM L-glutamine, 100 IU/ml penicillin, and 100 μg/ml streptomycin in a humidified incubator at 37°C and 5% CO₂. The hNET (Pacholczyk et al., 1991) and hemagglutinin (HA)-hNET_{Δ28-47} (this report) were cloned into pcDNA3, and stably transfected into CAD cells using Lipofectin (Invitrogen, San Diego, CA), and selected and maintained in 200 μg/ml G418 (Mediatech, Herndon, VA). hNET_{Δ28-47} is an hNET variant recovered during the course of expression experiments seeking to evaluate requirements for SYN1A modulation of hNET and, unlike hNET_{Δ2-42} (Sung et al., 2003), supports efficient SYN1A interactions. The deletion mutant hNET_{Δ28-47} was generated by oligonucleotide site-directed mutagenesis using QuikChange mutagenesis kit (Stratagene, La Jolla, CA) (Sung et al., 2003). Initial studies examining AMPH effects demonstrated a more robust trafficking response with this mutant compared with hNET, and thus we incorporated this mutant into our ongoing studies of hNET regulation. Transient transfections were performed with Eugene 6 (Roche, Indianapolis, IN). Typically, 1 μg of cDNA was transfected into 500,000 cells in each well of a six-well plate. Cells were transfected 48 h before transport or biochemical assays.

Antibodies and Other Reagents. Anti-HA antibody (3F10) (Boehringer Mannheim, Mannheim, Germany) and monoclonal NET17-1 (Mab Technologies, Atlanta, GA) were used at a dilution of 1:500 and 1:1000, respectively, for immunoblots and identification of NET proteins by enhanced chemiluminescence reaction. Anti-HA rat monoclonal antibody (3F10) (Boehringer Mannheim) and monoclonal anti-histidine (anti-His) antibody (Clontech, Mountain View, CA) were used (1 μg) for immunoprecipitation of hNET_{Δ28-47} and hNET, respectively. Immunoblots for SYN1A were performed by using anti-HPC-1 antibody (Sigma, St. Louis, MO) at a dilution of 1:2000. In addition, immunoblots of total and phosphorylated CaMKII were performed using anti-CaMKII (1:1000; Cell Signaling Technology, Danvers, MA) and anti-phospho-CaMKII (1:2000; Abcam, Cambridge, MA), respectively. Microcystin-LR was obtained from Alexis (San Diego, CA); BAPTA-AM and Oregon Green BAPTA-AM were purchased from Invitrogen; KN-93 and KN-92 were obtained from Calbiochem (San Diego, CA); and AMPH and desipramine were acquired from Sigma.

Cell Surface Biotinylation. Biotinylation experiments were performed on intact cells to evaluate changes of hNET and hNET_{Δ28-47} cell surface expression as described previously (Saunders et al., 2000; Sung et al., 2003; Garcia et al., 2005). In brief, 48 h before each experiment, cells were plated at a density of 1×10^6 per well in a six-well poly-(D-lysine) (Sigma)-coated plate. After each treatment, cells were washed with PBS containing Ca²⁺/Mg²⁺, and incubated with 1.0 mg/ml sulfo-succinimidyl-2-(biotinamido)ethyl-1,3-dithiopropionate-(sulfo)-NHS-SS-biotin (Pierce, Rockford, IL) for 30 min at 4°C, washed, quenched with 100 mM glycine, extracted in lysis buffer (PBS Ca²⁺/Mg²⁺, 1% Triton 100-X, and 0.5 mM PMSF), and incubated with Immunopure immobilized Streptavidin beads (Pierce) for 1 h at room temperature. Beads were washed three times in lysis buffer, and proteins bound to Streptavidin beads were eluted

in 2× Laemmli buffer containing 2-mercaptoethanol. Samples were then analyzed by SDS-PAGE (7.5% gel) and immunoblotted as described for Western blot analyses. For estimation of relative amounts of proteins, the exposed films of the immunoblots were scanned, and the captured images were processed and quantitated with Scion Image (Scion Corporation, Frederick, MD).

Coimmunoprecipitations. To examine changes in hNET $_{28-47}$ and hNET/SYN1A interactions, coimmunoprecipitation experiments were performed. CAD cells transiently transfected either with His-hNET or HA-hNET $_{28-47}$ and SYN1A were plated at a density of 1×10^5 per well in six-well poly-(D-lysine) (Sigma)-coated plates. After each treatment, cells were washed with ice-cold PBS/ Ca^{2+} / Mg^{2+} and incubated in 400 μl /well of lysis buffer containing 50 mM NaH_2PO_4 , 10 mM Tris, 100 mM NaCl, 0.5 mM PMSF, pH 8.0, plus 1% Triton X-100 for 1 h at 4°C. Cell lysates recovered by centrifugation at 20,000g for 30 min were incubated overnight at 4°C either with anti-His or with anti-HA (3F10) antibodies. Complexes were retrieved by the addition of 20 μl of protein G-Sepharose (GE Healthcare, Little Chalfont, Buckinghamshire, UK) and washed three times with lysis buffer. For the coimmunoprecipitation of surface complexes (hNET/SYN1A), cells were biotinylated with EZ-link NHS-sulfo-SS-biotin (Pierce) and lysed as described above. Monomeric avidin beads [40 μl of beads (Pierce)/1 well cell lysate] were preblocked with 10 mg/ml bovine serum albumin (30 min at 4°C) and then used to obtain biotinylated proteins. Then, avidin beads were washed five times at room temperature with lysis buffer and the bound proteins were eluted with lysis buffer containing 4 mM biotin (Sigma). Anti-His or anti-HA antibodies were added to the eluted proteins, processed for immunoprecipitation, and analyzed as described above. Multiple films were exposed for each immunoblot to ensure linearity of detection.

CaMKII Western Blot. CAD-hNET and CAD-hNET $_{28-47}$ cells, plated at a density of 1×10^6 cells/well, were treated in Krebs-Ringer-HEPES/glucose buffer in the absence or presence of 10 μM AMPH for the different time periods. The incubation was terminated on ice, and the cells were washed twice with PBS/ Ca^{2+} / Mg^{2+} and then incubated in lysis buffer containing 20 mM Tris-HCl, pH 7.5, 1 mM EDTA, 0.5 mM PMSF, 1% SDS, 1 mM sodium orthovanadate, 1 mM sodium pyrophosphate, 1 μM microcystin-LR, and 1 μM aprotinin and leupeptin for 1 h at 4°C. Cell lysates were recovered by centrifugation at 20,000g for 30 min at 4°C. Samples were then analyzed by SDS-PAGE (10% gel) followed by immunoblotting for total and activated (phospho)CaMKII.

Single-Cell Calcium Determinations. For imaging intracellular Ca^{2+} changes, hNET and hNET $_{28-47}$ cells were grown for 2 days on glass coverslips (1.5 mm diameter; MatTek Corporation, Ashland, MA). After washing the cells with an extracellular physiological solution (pH 7.34, 300 mOsm, 130 mM NaCl, 1.3 mM KH_2PO_4 , 0.5 mM MgSO_4 , 1.5 mM CaCl_2 , 10 mM HEPES, and 34 mM dextrose), cells were incubated with 5 μM Oregon Green BAPTA-AM for 20 min at room temperature in darkness and then washed three times. AMPH was added after the first 3 to 4 scanings. Images were acquired using a 488-nm excitation wavelength with a 500 long-pass filter every 10 s. To calculate $\Delta F/F$, for each time point, the background was subtracted [fluorescence measured from a confocal plane in the control condition (basal)] from the fluorescence recorded in the same z section upon the addition of AMPH. Image analysis was performed using the public domain Image J imaging program (<http://rsb.info.nih.gov/ij/>).

Results

AMPH Promotes a Reduction in hNET Surface Expression, an Effect Enhanced in the Mutant hNET $_{28-47}$. To investigate the short-term impact of AMPH on hNET trafficking, we studied stably transfected CAD-hNET cells exposed to 10 μM AMPH. Figure 1A shows immunoblots obtained from biotinylated extracts from CAD-hNET cells (top blot) and from CAD-hNET $_{28-47}$ cells (bottom blot) treated either with vehicle (CTR) or with 10 μM AMPH for the indicated time periods with normalized quantitation of multiple biotinylation experiments shown in Fig. 1B. The inset shows immunoblots for hNET proteins obtained from total extract of CAD-hNET and CAD-hNET $_{28-47}$ cells indicating that the amount of hNET proteins is similar in these two cell lines. In CAD-hNET cells, AMPH treatment triggers a gradual, time-dependent reduction in hNET cell surface expression, achieving a nearly 50% reduction after an hour of AMPH stimulation. In contrast, in CAD-hNET $_{28-47}$ cells, AMPH rapidly triggers hNET $_{28-47}$ plasma membrane reductions, achieving a level $50 \pm 2.7\%$ of control after only 1 min of AMPH treatment (Fig. 1B) followed by relatively little change in transporter surface expression with further AMPH exposure. One concern was that

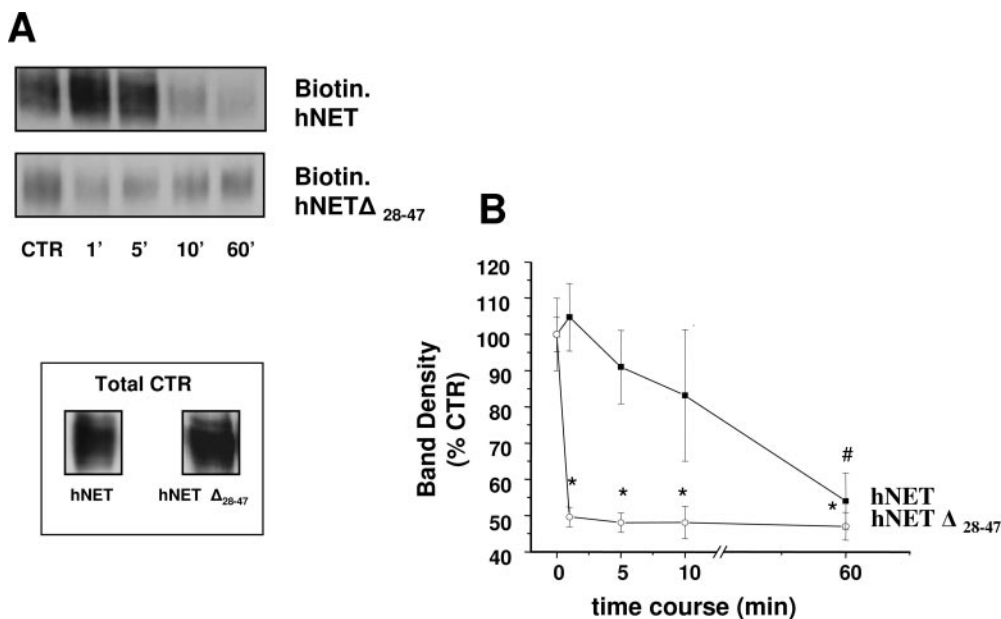


Fig. 1. A region of 20 amino acids (Δ_{28-47}) of the hNET N terminus regulates AMPH-induced hNET cell surface redistribution. **A**, representative immunoblots for hNET proteins recovered from biotinylated extracts obtained from hNET (top blot) and hNET $_{28-47}$ (bottom blot) cells treated with 10 μM AMPH for the indicated periods of time. **B**, quantification of the immunoblots using the Scion Image System. The density of the biotinylated samples was normalized to the density of the parallel total extract to correct for difference in cell seeding and hNET expression in different wells and is expressed as percentage of control. The normalized data (■, hNET; ○, hNET $_{28-47}$) are expressed as mean \pm S.E.M. and are compared with respective controls by one-way ANOVA followed by the Dunnett's test; *, #, level of significance $p < 0.001$; $n = 4$. Inset: Representative immunoblot for hNET and hNET $_{28-47}$ proteins recovered from total extract under control conditions.

this AMPH effect on hNET Δ_{28-47} may arise from nontransporter-mediated changes induced by AMPH uniquely in hNET Δ_{28-47} cells. However, pretreatment of cells with the NET antagonist desipramine (DMI) for 10 min completely blocked this AMPH effect (data not shown). To evaluate the AMPH action on hNET trafficking, NET plasma membrane proteins were assessed in preference to uptake activity due to the complex activity of AMPH pretreatment on uptake. However, to compare hNET and hNET Δ_{28-47} function, kinetic studies on [3 H]NE uptake were performed. The V_{\max} was $12.2 \pm 0.67 \times 10^{-17}$ and $9.7 \pm 1.39 \times 10^{-17}$ mol/cell/min with a K_m of 0.52 ± 0.11 and 0.6 ± 0.24 μ M for CAD-hNET and CAD-hNET Δ_{28-47} , respectively. Neither the V_{\max} nor the K_m value obtained from CAD-hNET cells were significantly different from those obtained from CAD-hNET Δ_{28-47} (Student's t test; $p > 0.05$).

AMPH Increases Levels of Intracellular Calcium. Because Ca^{2+} has been linked to support NET surface expression (Apparsundaram et al., 2001) and has been implicated in AMPH modulation of NET activity in PC-12 cells (Kantor et al., 2004), we investigated whether AMPH alters intracellular Ca^{2+} concentration in hNET stably transfected CAD cells. Ca^{2+} levels were monitored using ratiometric analysis of the cell-permeant Ca^{2+} indicator Oregon Green BAPTA-AM. Confocal microscopy images were collected at different time points, and for each time point, the background [fluorescence measured from a confocal plane in control conditions (basal)] was subtracted from the fluorescence recorded in the same z section upon the addition of AMPH. An increase in intracellular fluorescence was detected within 10 s of

AMPH application (Fig. 2A) in both CAD-hNET and CAD-hNET Δ_{28-47} cells. However, the time course and magnitude of effects was quite distinct. The relative changes ($\Delta F/F$) in Ca^{2+} -sensitive fluorescence was significantly more rapid and achieved higher levels in CAD-hNET Δ_{28-47} cells compared with CAD-hNET cells (Fig. 2B). No significant changes in intracellular fluorescence were detected either in CAD cells treated with AMPH or in vehicle-treated hNET and hNET Δ_{28-47} cells (data not shown). It is noteworthy that these increases in intracellular Ca^{2+} were blocked by pretreatment with either 50 μ M Cd^{2+} or 10 μ M DMI (data not shown), indicating, therefore, that this AMPH effect requires both Ca^{2+} -channel activation and possibly NET activity. In addition, these data suggest that the differences noticed in the AMPH-induced cell surface redistribution of hNET versus hNET Δ_{28-47} may be supported by Ca^{2+} -sensitive mechanisms.

AMPH-Induced Changes in hNET Cell Surface Redistribution are Ca^{2+} -Dependent. The ability of AMPH to promote a greater increase in intracellular Ca^{2+} in CAD-hNET Δ_{28-47} cells with respect to CAD-hNET cells that is temporally correlated with accelerated changes in transporter cell surface redistribution raises the possibility that these two phenomena are related. We therefore asked whether rapid AMPH-induced hNET Δ_{28-47} trafficking is impaired by either blocking plasma membrane Ca^{2+} -channel activity with Cd^{2+} or by buffering the increase in intracellular Ca^{2+} with BAPTA-AM. Figure 3A, top blot, shows a representative immunoblot for hNET proteins recovered from the biotinylated fraction obtained from hNET Δ_{28-47}

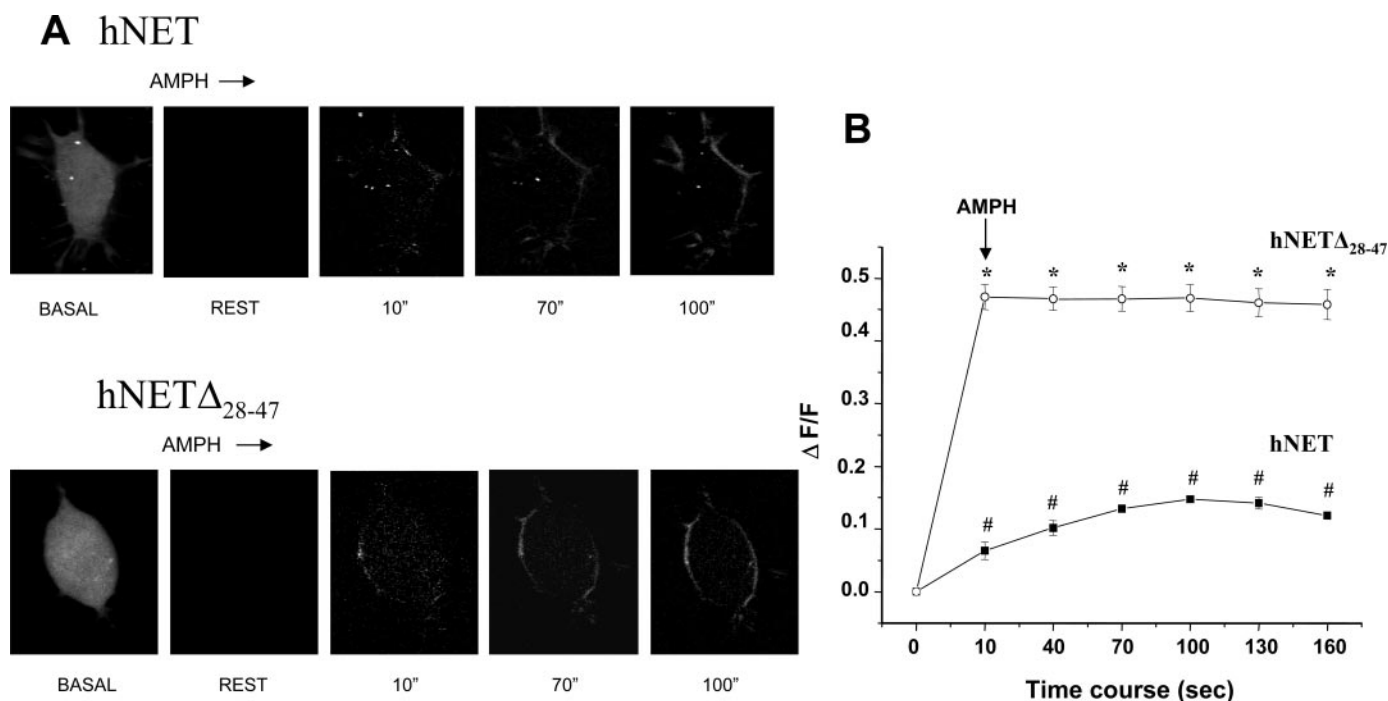


Fig. 2. AMPH induces a larger increase in intracellular Ca^{2+} in hNET Δ_{28-47} cells with respect to hNET cells. A, intracellular Ca^{2+} fluorescence was acquired using confocal imaging from hNET and hNET Δ_{28-47} cells. Ca^{2+} -green fluorescence was measured from a z section of the cell and used to monitor temporal changes of intracellular Ca^{2+} levels upon AMPH application. To determine AMPH-induced changes in fluorescence, the background fluorescence (BASAL) was subtracted from each single time point, including control conditions (REST). Upon AMPH application (AMPH), an increase of intracellular fluorescence was detected as a function of time, measured in seconds. B, the relative changes ($\Delta F/F$) in Ca^{2+} -sensitive fluorescence induced by AMPH were evaluated by Image J imaging analysis. The images were collected every 10 s for the indicated period of time. The ratio $\Delta F/F$ was measured for hNET Δ_{28-47} (\circ) and hNET cells (\blacksquare) ($n = 3$) for each time point. The normalized data are expressed as mean \pm S.E.M. and compared with respective controls by one-way ANOVA followed by Dunnett's test (*, #, level of significance $p < 0.001$).

cells treated either with vehicle (CTR), with 10 μ M AMPH for 1 min (AMPH), with 50 μ M Cd^{2+} for 30 s (Cd^{2+}), or with 50 μ M Cd^{2+} for 30 s followed by 10 μ M AMPH for 1 min in the continuous presence of Cd^{2+} (Cd^{2+} + AMPH). An immunoblot for hNET proteins recovered from total extracts is represented in Fig. 3A, bottom blot. Figure 3B, top blot, shows a representative immunoblot for hNET proteins recovered from the biotinylated fraction obtained from hNET Δ_{28-47} cells incubated in a Ca^{2+} -free buffer and treated with vehicle (CTR), with 50 μ M BAPTA-AM (BAPTA) for 40 min, or with 50 μ M BAPTA-AM for 40 min followed by 10 μ M AMPH for 1 min in the continuous presence of BAPTA-AM (BAPTA + AMPH). An immunoblot for hNET proteins recovered from total extracts is represented in Fig. 3B, bottom blot. As shown in the bar graphs in Figs. 3, C and D, both treatments completely blocked the ability of AMPH to trigger a loss of transporters from the cell surface.

AMPH Induces Rapid CaMKII Activation and, as a Consequence, Causes hNET Δ_{28-47} Cell Surface Redistribution. Next, we considered whether AMPH-induced changes in intracellular Ca^{2+} are significant enough to modify the activity of Ca^{2+} -dependent kinases. We focused on CaMKII due to studies indicating an inhibitory action of calmodulin antagonists on NET activity and suggestions that CaMKII may phosphorylate NET (Uchida et al., 1998). Using a phosphospecific antibody produced against a synthetic phosphopeptide corresponding to amino acid residues surrounding the phosphorylated Thr286 (the autophosphorylation site associated with CaMKII activation), we examined the AMPH effects on CaMKII activation. Figure 4A shows an immunoblot of Thr286 phospho-CaMKII after treatment of CAD-hNET Δ_{28-47} cells with vehicle (CTR) or with 10 μ M

AMPH (AMPH) for 1 or 10 min. Figure 4B shows quantification of the band density of three different experiments as in A, normalized to control conditions. AMPH rapidly increases the level of CaMKII phosphorylation, with significant effects observed after as little as 1 min of AMPH addition. No changes were observed in total levels of CaMKII, as assessed with a nonphosphospecific CaMKII antibody (data not shown).

It is possible that the ability of AMPH to increase levels of CaMKII phosphorylation arises from nontransporter-mediated changes induced by AMPH in hNET Δ_{28-47} cells. However, pretreatment of CAD-hNET Δ_{28-47} cells with 10 μ M DMI for 10 min completely blocked this AMPH effect. In the presence of DMI, AMPH increased the level of CaMKII phosphorylation to $105 \pm 3\%$ of control conditions ($n = 3$).

To assess a requirement for CaMKII stimulation in AMPH trigger changes in hNET Δ_{28-47} cell surface redistribution, we performed biotinylation experiments in the presence or absence of the CaMKII inhibitor KN-93, preapplied in the bath solution before AMPH application. Figure 4C shows representative immunoblots for hNET Δ_{28-47} proteins recovered from the biotinylated fraction (top blot) and total extract (bottom blot) of CAD-hNET Δ_{28-47} cells treated either with vehicle (CTR), with 10 μ M AMPH for 1 min (AMPH), with 10 μ M KN-93 for 30 min (KN93), or with 10 μ M KN93 for 30 min followed by 10 μ M AMPH for 1 min in the continuous presence of KN-93 (KN-93 + AMPH). As quantitated in Fig. 4D, preincubation of hNET Δ_{28-47} cell with KN-93 blocked the ability of AMPH to cause hNET Δ_{28-47} cell surface redistribution, supporting a role of CaMKII in this AMPH action. In contrast to KN-93, the inactive analog KN-92 had no significant effect (data not shown).

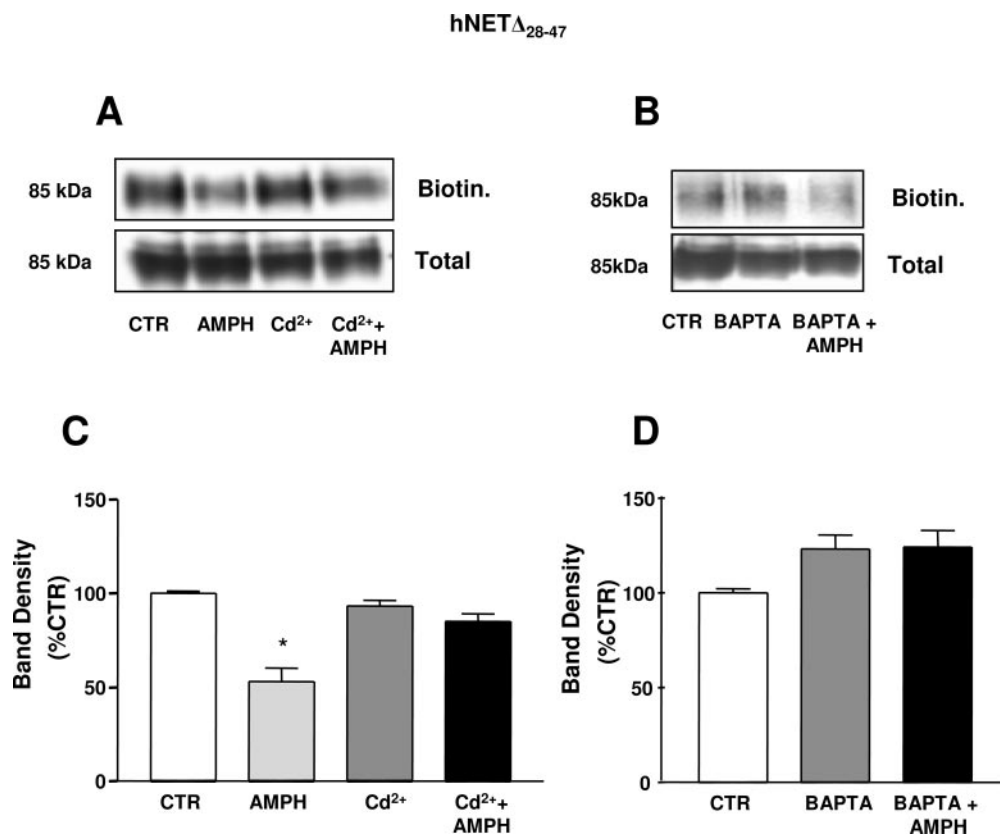


Fig. 3. Cd^{2+} and BAPTA-AM block the AMPH-induced hNET Δ_{28-47} trafficking. A, representative immunoblot for hNET proteins recovered from biotinylated fraction obtained from hNET Δ_{28-47} cells treated with vehicle (CTR), with 10 μ M AMPH for 1 min (AMPH), with 50 μ M Cd^{2+} for 30 s (Cd^{2+}), or with 50 μ M Cd^{2+} for 30 s followed by 10 μ M AMPH for 1 min in the continuous presence of Cd^{2+} (Cd^{2+} + AMPH). B, representative immunoblot for hNET proteins recovered from the biotinylated fraction obtained from hNET Δ_{28-47} cells incubated in a Ca^{2+} -free buffer and treated with vehicle (CTR), with 50 μ M BAPTA-AM (BAPTA) for 40 min, or with 50 μ M BAPTA-AM for 40 min followed by 10 μ M AMPH for 1 min in the continuous presence of BAPTA-AM (BAPTA + AMPH). C and D, quantification of the density of the immunoblots of A and B, respectively, using Scion Image system. The density of the biotinylated samples was normalized to the parallel total extracts and expressed as a percentage of vehicle-treated control. The normalized data are expressed as mean \pm S.E.M. and compared against respective controls by one-way ANOVA followed by Dunnett's test ($n = 4$; *, level of significance $p < 0.001$).

Short-Term AMPH Regulates NET/SYN1A Interaction. SYN1A colocalizes with NET at noradrenergic varicosities (Sung et al., 2003) and associates with NET in heterologous expression systems and native tissues (Sung et al., 2003). Because SYN1A supports the surface trafficking of NET proteins (Sung et al., 2003), we considered whether AMPH is able to alter NET/SYN1A associations and whether differences exist between hNET and hNET Δ_{28-47} . For these studies, we transiently transfected CAD cells either with SYN1A cDNAs with tagged hNET cDNAs, or with both and then treated these cells either with vehicle or AMPH followed by biotinylation and NET/SYN1A coimmunoprecipitation. Histidine and HA antibodies failed to immunoprecipitate SYN1A from untransfected cells. In contrast, SYN1A was detected in immunoprecipitates from total extracts of CAD cells cotransfected with SYN1A and with His-hNET cDNA (Fig. 5A). After 1-min treatment, AMPH (10 μ M) increased hNET/SYN1A interactions at the plasma membrane (Fig. 5, A and B) with respect to control conditions. In contrast, the hNET/SYN1A interactions recovered from the nonbiotinylated fractions were unaffected by AMPH treatment. AMPH increased hNET/SYN1A complexes at the plasma membrane to $130 \pm 11\%$ of vehicle-treated control. Likewise, SYN1A was detected in immunoprecipitates from total extracts of CAD cells cotransfected with SYN1A and with HA-

hNET Δ_{28-47} cDNA (Fig. 5C). Consistent with studies with hNET, AMPH (10 μ M) treatment (1 min) increased hNET Δ_{28-47} /SYN1A interactions at the plasma membrane (Fig. 5C) with respect to vehicle-treated control. Likewise, the intracellular hNET Δ_{28-47} /SYN1A interactions were slightly but not significantly affected by AMPH treatment (Fig. 5, C and D). Compared with hNET experiments, AMPH increased hNET Δ_{28-47} /SYN1A complexes at the plasma membrane to a greater extent, with an increase of $191 \pm 26\%$ of vehicle-treated control. These findings indicate that the AMPH-induced rapid hNET Δ_{28-47} trafficking correlates with more extensive NET/SYN1A interactions.

CaMKII Inhibition Attenuates Recovery of Increased Plasma Membrane SYN1A/hNET Δ_{28-47} Complexes. Although Fig. 5 demonstrates that AMPH robustly increases hNET Δ_{28-47} /SYN1A associations at the plasma membrane to a greater extent than hNET/SYN1A complexes, and this phenomenon seems to correlate with increases of intracellular Ca^{2+} , these effects could represent parallel and possibly unrelated actions of AMPH. It is interesting that the time required to demonstrate an increase in hNET Δ_{28-47} /SYN1A association is similar to the time required by AMPH to cause hNET Δ_{28-47} cell surface redistribution. Therefore, we considered that stabilization of hNET Δ_{28-47} /SYN1A complexes may be a step of the AMPH-induced NET cell surface

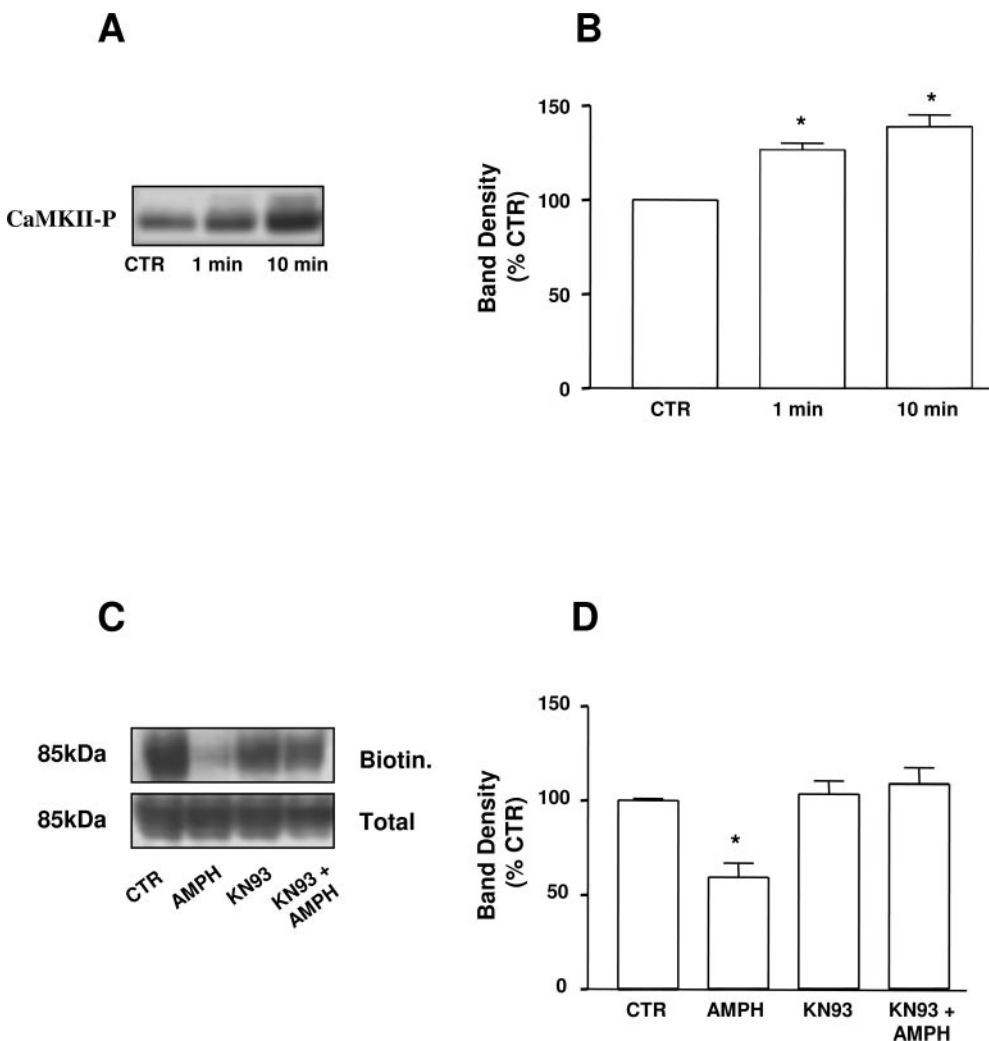


Fig. 4. AMPH and CaMKII activation induce hNET Δ_{28-47} trafficking. **A**, an immunoblot of phosphorylated CaMKII obtained from hNET Δ_{28-47} cells treated either with vehicle (CTR) or 10 μ M AMPH for the indicated periods of time. **B**, quantitation of the band density of three different experiments as in **A**, normalized to control conditions. The normalized data are expressed as mean \pm S.E.M. and are compared against respective controls by one-way ANOVA followed by Dunnett's test ($n = 3$; *, level of significance $p < 0.001$). **C**, representative immunoblot for hNET proteins recovered from biotinylated and total fraction obtained from hNET Δ_{28-47} cells treated with vehicle (CTR), with 10 μ M AMPH for 1 min (AMPH), with 10 μ M KN-93 for 30 min (KN93), or with 10 μ M KN-93 for 30 min followed by 10 μ M AMPH for 1 min in the continuous presence of KN93 (KN93 + AMPH). **D**, quantitation of the band density as in **A** using Scion Image system. The density of the biotinylated samples was normalized to the parallel total extracts and expressed as a percentage of vehicle-treated control. The normalized data are expressed as mean \pm S.E.M. and are compared against respective controls by one-way ANOVA followed by Dunnett's test ($n = 3$; *, level of significance $p < 0.001$).

redistribution pathway. Because the ability of AMPH to promote a decreased hNET Δ_{28-47} plasma membrane expression is impaired by CaMKII inhibition with KN-93 (Fig. 4), we asked whether KN-93 treatment could block the AMPH-induced increase in hNET Δ_{28-47} /SYN1A associations. CAD cells cotransfected with SYN1A and with HA-hNET Δ_{28-47} cDNA were treated either with vehicle (CTR) or with 10 μ M KN-93 for 30 min followed by 10 μ M AMPH for 1 min in the continued presence of KN-93 (KN-93 + AMPH) (Fig. 6). As before, blots of total extracts also show no impact of AMPH on SYN1A content. However, we found that KN-93 treatment blocked the ability of AMPH to increase plasma hNET Δ_{28-47} /SYN1A complexes (HA IP-surf/AMPH + KN-93) with respect to control conditions (Fig. 6A). It is interesting that because the intracellular hNET Δ_{28-47} /SYN1A interactions were unaffected by AMPH treatment (Fig. 5, C and D), these data suggest that CaMKII mechanisms target NET/SYN1A complexes in a compartmentally specific fashion.

Discussion

Neurotransmitter transporters are increasingly recognized as highly regulated components of synaptic signaling, responding to coincident neuronal activation and/or receptor activation to modulate both of the number of active carriers at the plasma membrane and the rates of transport through individual transporters (Robinson, 2001; Kahlig and Galli, 2003; Gonzalez and Robinson, 2004; Blakely et al., 2005; Torres, 2006). Multiple signaling pathways have been implicated in the regulation of catecholamine transporter trafficking and catalytic function, including pathways linked to PKC, phosphatidylinositol-3-kinase, CaMKII, p38 mitogen-activated protein kinase, and type 2 protein serine/threonine phosphatase (Bauman et al., 2000; Blakely and Sung, 2000; Robinson, 2001; Kahlig and Galli, 2003; Gonzalez and Robinson, 2004; Blakely et al., 2005; Torres, 2006). Transporter-associated proteins are believed to play an important role in the transduction of activated signaling pathways to alter

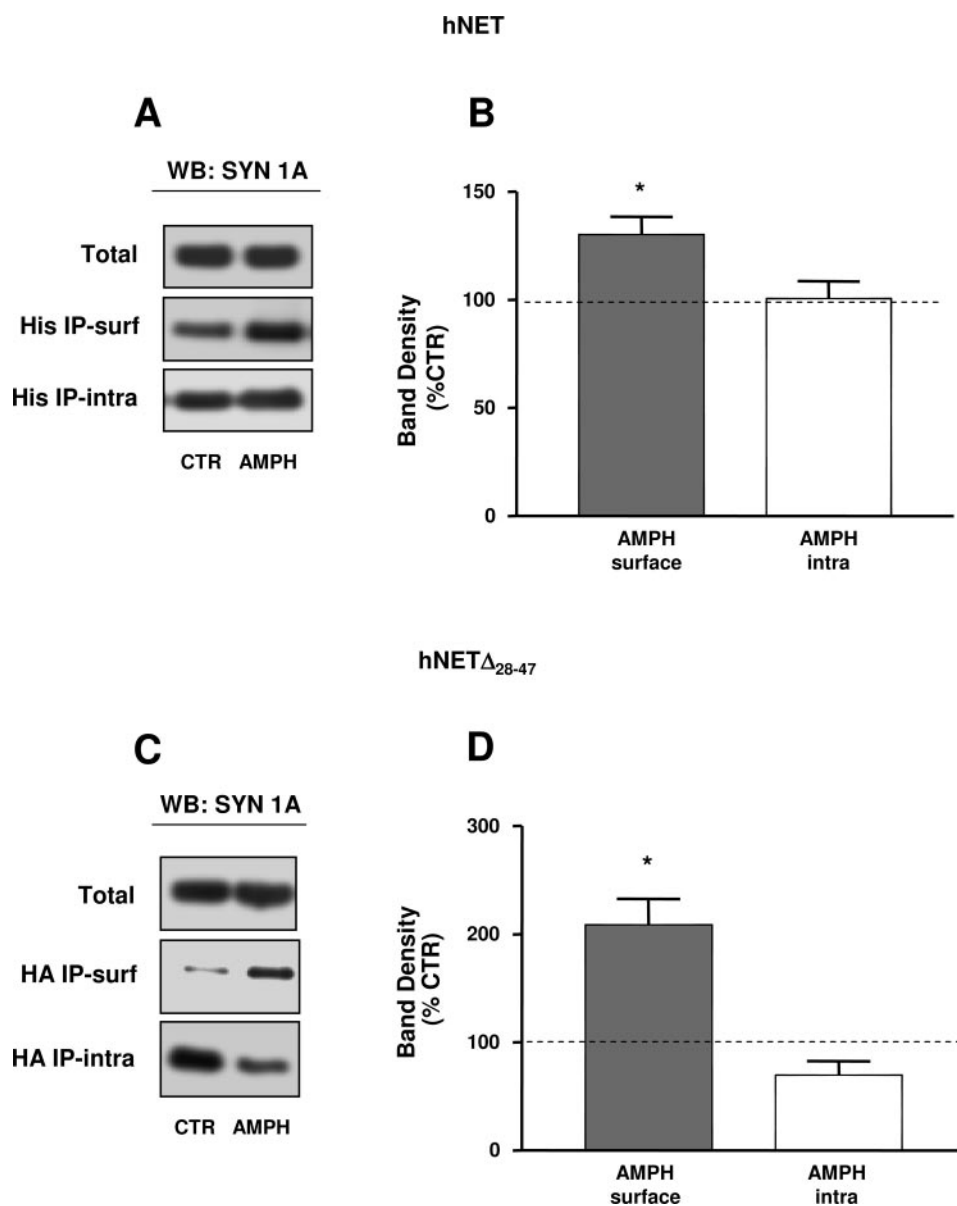


Fig. 5. AMPH-induced increase in hNET/SYN1A association occurs within plasma membrane localized complexes, and it is larger in hNET Δ_{28-47} cells with respect to hNET cells. **A**, CAD cells, cotransfected with His-hNET and SYN1A, were treated either with vehicle (CTR) or 10 μ M AMPH for 1 min. Surface proteins were labeled with NHS-sulfo-biotin at 4°C before cell lysis and then recovered by using avidin beads. Bound hNET proteins were immunoprecipitated with anti-His antibody and resolved on SDS-PAGE and immunoblotted (WB:SYN1A) for SYN1A (His IP-surf). Nonbound extracts were immunoprecipitated and blotted in parallel (His IP-intra). Blots obtained from total extracts (Total) show no impact of AMPH on SYN1A content. **B**, the density of the immunoprecipitates bands (His IP-surf and His IP-intra) was normalized to the density of the corresponding parallel total extract and expressed as a percentage of respective control. The normalized data are expressed as mean \pm S.E.M. and compared with respective controls by Student's *t* test; *, level of significance $p < 0.05$; $n = 3$. **C**, CAD cells, cotransfected with HA-hNET Δ_{28-47} and SYN1A, were treated either with vehicle (CTR) or 10 μ M AMPH for 1 min. Surface proteins were labeled as described in **A**. Surface complexes were recovered using avidin beads. Bound HA-hNET Δ_{28-47} proteins were immunoprecipitated with anti-HA and resolved on SDS-PAGE, and immunoblotted (WB:SYN1A) for SYN1A (HA IP-surf). Nonbound extracts were immunoprecipitated and blotted in parallel (HA IP-intra). Immunoblots of the total extracts (Total) show no impact of AMPH on SYN1A content. **D**, the density of the immunoprecipitate bands (HA IP-surf and HA IP-intra) was normalized to the density of the corresponding parallel total extract and expressed as a percentage of respective control. The normalized data are expressed as mean \pm S.E.M. and compared with respective controls by Student's *t* test (*, level of significance $p < 0.001$; $n = 3$).

transporter localization and function. The NET interacts, among others, with cytosolic scaffolding proteins such as the postsynaptic density 95/disc-large/zona occludens domain protein PICK1 (Torres et al., 2001) and with other intrinsic membrane proteins, most prominent of which is the *t*-soluble *N*-ethylmaleimide-sensitive factor attachment protein receptor protein SYN1A (Sung et al., 2003). In prior studies, we demonstrated that SYN1A supports cell-surface trafficking of hNET and that direct associations between NET and SYN1A influence hNET electrical activity (Sung et al., 2003). The degree to which NET substrates and antagonists influence these associations is unknown, although a precedent exists for both substrate and antagonist influences on localization and regulation of homologous DAT (Saunders et al., 2000; Daws et al., 2002; Kahlig et al., 2004) and serotonin transporter proteins (Ramamoorthy and Blakely, 1999).

In heterologous expression systems and in *ex vivo* preparations, AMPH exposure diminishes plasma membrane expression of DAT proteins (Saunders et al., 2000; Gulley et al., 2002; Chi and Reith, 2003). Moreover, AMPH, acting through either DAT or NET proteins, has been reported to promote an increase in intracellular Ca^{2+} mediated by activation of voltage-sensitive Ca^{2+} channels (Gnegy et al., 2004; Kantor et al., 2004). In the current study, we demonstrate that AMPH triggers a redistribution of hNET cell surface proteins in concert with an accumulation of plasma membrane hNET/SYN1A complexes, actions supported by an elevation of intracellular Ca^{2+} and CaMKII activation. This phenomenon seems distinct from phorbol ester or muscarinic receptor-triggered hNET internalization, in which the NET internalization is accompanied by a reduction in hNET/SYN1A associations, and it is sensitive to PKC antagonists (Apparsundaram et al., 1998; Sung et al., 2003).

To study the molecular mechanism supporting AMPH-in-

duced hNET trafficking, we took advantage of the comparatively more rapid AMPH-induced trafficking induced in hNET Δ_{28-47} compared with hNET-transfected cells. Here, we show that a deletion of a region of 20 amino acids (Δ_{28-47}) from the hNET N terminus increases the rate at which AMPH causes significant cell surface redistribution of hNET Δ_{28-47} (Fig. 1). It is noteworthy that the hNET Δ_{28-47} deletion does not disrupt hNET/SYN1A associations but may actually enhance them because we captured larger AMPH-induced changes in hNET/SYN1A complexes than could be observed with hNET. Alternatively, the initiating events leading to SYN1A/hNET associations may be enhanced in hNET Δ_{28-47} . In support of this idea, AMPH caused a significantly larger increase in intracellular Ca^{2+} in CAD-hNET Δ_{28-47} cells compared with CAD-hNET cells (Fig. 2). This was not due to higher levels of transporter expression because our stable CAD-hNET Δ_{28-47} cells express transporter proteins at the same level as our CAD-hNET cells. It is possible that hNET Δ_{28-47} is permissive for a greater degree of AMPH-induced membrane depolarization, triggering a more robust opening of Ca^{2+} channels. Substrate-induced currents through neurotransmitter transporters are known to be sufficient to depolarize cell membranes (Ingram et al., 2002; Carvelli et al., 2004; Kahlig et al., 2004). Elimination of SYN1A interactions through the mutation of a distinct area of the hNET NH2 terminus (Binda et al., 2005) generates a greatly enhanced hNET leak current, supporting contributions of this domain to transporter conductance states that may also come into play with respect to the more robust response to AMPH seen with hNET Δ_{28-47} . It is noteworthy that we found that Cd^{2+} , a nonspecific Ca^{2+} -channel blocker (Kim et al., 1998; Mesquita et al., 1998), significantly reduced the ability of AMPH to increase intracellular Ca^{2+} (data not shown) and to cause hNET Δ_{28-47} cell surface redistribution

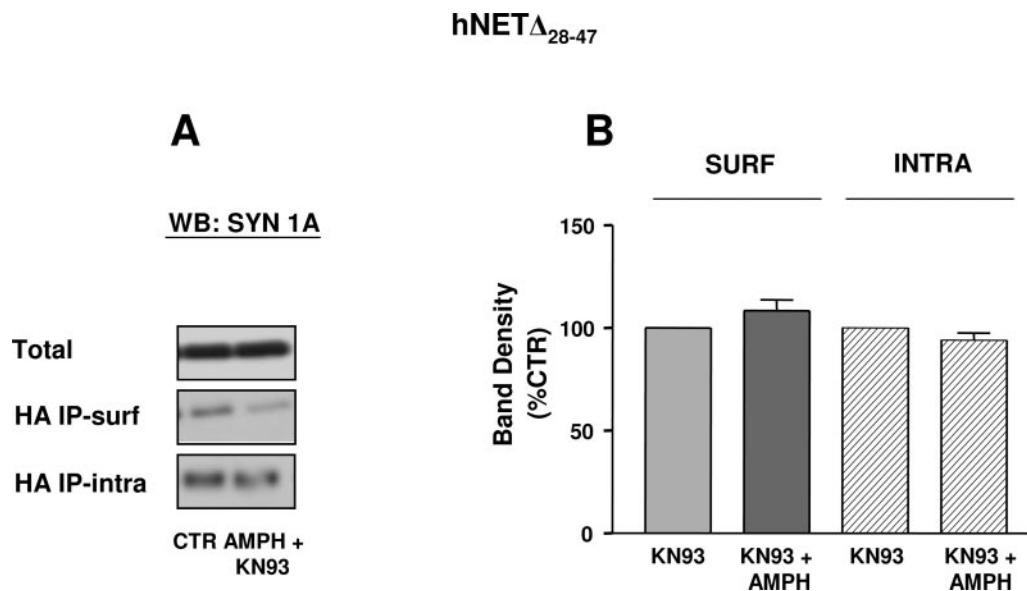


Fig. 6. KN-93 blocks AMPH induced increase in hNET Δ_{28-47} /SYN1A associations. CAD cells, cotransfected both with HA-hNET Δ_{28-47} and SYN1A, were treated either with vehicle (CTR) or with 10 μM KN93 for 30 min followed by 10 μM AMPH for 1 min in the continuous presence of KN-93 (KN93+AMPH). Surface proteins were labeled with NHS-sulfo-biotin at 4°C before cell lysis and then recovered by using avidin beads. Bound hNET Δ_{28-47} proteins were immunoprecipitated with anti-HA antibody and resolved on SDS-PAGE, and immunoblotted for SYN1A (HA IP-surf). Nonbound extracts were immunoprecipitated and blotted in parallel (HA IP-intra). Immunoblots obtained from total extracts (Total) show that AMPH has no effect on SYN1A content. B, the density of the immunoprecipitates bands (HA IP-surf and HA IP-intra) was normalized to the density of the correspondent parallel total extract and expressed as percentage of respective control. The normalized data are expressed as mean \pm S.E.M. and compared with respective controls by Student's *t* test (*, level of significance $p < 0.01$; $n = 3$).

(Fig. 3A). Moreover, chelation of intracellular Ca^{2+} with BAPTA-AM blocked AMPH-induced reduction in hNET Δ_{28-47} cell surface expression (Fig. 3), suggesting that AMPH-induced NET ion flux triggers activation of voltage-sensitive Ca^{2+} channels that in turn support changes in hNET Δ_{28-47} cell surface redistribution and SYN1A associations. A similar sequence of events is evident with hNET, although at a reduced rate and extent. Therefore, it seems likely that other cellular events could act in concert with AMPH to determine the more rapid modulation exhibited constitutively by hNET Δ_{28-47} .

Using the more robustly regulated CAD-hNET Δ_{28-47} cells, we found that AMPH increases CaMKII phosphorylation within 1 min of AMPH application. Like hNET trafficking changes, CaMKII activation was blocked by preincubation with Cd^{2+} before AMPH stimulation (data not shown), suggesting that activation of CaMKII activity is essential to the modulation of hNET by the psychostimulant. This is supported by the ability of KN-93 to block AMPH-induced hNET trafficking. That AMPH-triggered SYN1A associations are also blocked by KN-93 suggests that these associations either support internalization or represent a parallel action. For example, it is possible that CaMKII activity enhances hNET/SYN1A associations independently of its ability to cause hNET cell surface redistribution. Further studies are needed to distinguish between these possibilities.

Our findings of a role for CaMKII in AMPH-induced NET internalization are at apparent odds with studies of Uchida and coworkers (1998), who reported that elevated external Ca^{2+} elevated NET function in a KN-93-sensitive manner. Important distinctions between our studies and those of Uchida and coworkers are worth noting. For example, Uchida and coworkers used PC-12 cells for their studies that are derived from rat pheochromocytoma and, as such, are of adrenal medullary origin. Instead, CAD cells are of central nervous system origin. In addition, we used AMPH as the stimulus for NET regulation as opposed to Ca^{2+} manipulations in the medium, and, as such, binding and/or translocation of AMPH itself may place the transporter in a distinct conformation favoring internalization. As an alternative, the magnitude and timing of Ca^{2+} changes induced by these two experimental paradigms may be distinct. In neurons, for example, it is known that both exocytosis and endocytosis exhibit Ca^{2+} dependence (Kuromi et al., 2004). In parallel, NET inward and outward trafficking can both be influenced by Ca^{2+} /CaMKII-dependent mechanisms, with the final outcome determined by more subtle changes in transporter-ligand interactions, rates of rise of Ca^{2+} , and/or compartmentalization of Ca^{2+} /CaMKII. In support of multiple Ca^{2+} -mediated mechanisms regulating NET trafficking, we found that manipulations that engender elevations in internal Ca^{2+} in the absence of AMPH diminish hNET/SYN1A associations (Sung et al., manuscript in preparation). Our findings with hNET Δ_{28-47} suggest that sequences in the hNET NH_2 terminus may be responsible for a bidirectional response to changes in intracellular Ca^{2+} such that with their removal, a more profound bias toward internalization emerges. For example, it is possible that in hNET Δ_{28-47} , we deleted CaMKII phosphorylation sites regulating hNET/SYN1A associations. Indeed, it has been shown for the homologous DAT that the NH_2 terminus is a target of phosphorylation of CaMKII (Fog et al., 2006). Future studies can

target specific sequences within this domain to probe the intersecting pathways that ultimately set levels of cell surface transporter protein and NE clearance capacity.

In summary, we document that the ability of AMPH to trigger the internalization of hNET is dependent of AMPH-induced changes in intracellular Ca^{2+} and CaMKII activation. The differences that we observe in rate and magnitude of responses between hNET and hNET Δ_{28-47} reveal how changes in transporter sequence, as might arise through naturally occurring transporter gene variants, can influence transporter regulation in response to identical regulatory contexts (Hahn et al., 2005; Mazei-Robison and Blakely, 2005; Mazei-Robison et al., 2005; Prasad et al., 2005). It also seems reasonable to speculate that alterations in levels or activity of transporter regulatory proteins or their upstream modulators that ultimately impact the hNET NH_2 terminus could mimic these differences. Thus, knowledge of these regulatory mechanisms could provide new insights for understanding altered responsiveness of catecholamine transporters after repeated AMPH administration (Iwata et al., 1997; Kantor et al., 2004).

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