Pancreatic Cancer Cells and Normal Pancreatic Duct Epithelial Cells Express an Autocrine Catecholamine Loop that Is Activated by Nicotinic Acetylcholine Receptors α3, α5, and α7

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Abstract

Pancreatic cancer is the fourth leading cause of cancer deaths in developed countries. Smoking is an established risk factor for this malignancy but the underlying mechanisms are poorly understood. Previous reports have provided evidence that nicotinic acetylcholine receptors (nAChR) and beta adrenergic receptors (β-AR) stimulate the growth and migration of pancreatic cancer cells. However, a potential cooperation of these two receptor families in the regulation of pancreatic cancer has not been studied to date. Using two pancreatic cancer cell lines and immortalized pancreatic duct epithelia in vitro, our current data show that all three cell lines synthesized and released the catecholamine neurotransmitters noradrenaline and adrenaline upon exposure to nicotine and that this activity was regulated by α3, α5, and α7-nAChRs. In accordance with the established function of these catecholamines as β-AR agonists, nicotine-induced cell proliferation was blocked by the β-AR antagonist propranolol. Nicotine-induced proliferation was also abolished by the α7-nAChR antagonist α-bungarotoxin, whereas catecholamine production in response to nicotine was blocked by gene knockdown of the α3, α5, and α7-nAChRs. The nicotinic agonists acetylcholine, nicotine, and its nitrosated carcinogenic derivative NNK induced the phosphorylation of CREB, ERK, Src, and AKT and these responses were inhibited by propranolol. Our findings identify this hitherto unknown autocrine catecholamine loop as an important regulatory cascade in pancreatic cancer that may prove a promising new target for cancer intervention.

Introduction

Pancreatic cancer is the fourth leading cause of cancer deaths with a morality rate near 100% within 2 years of diagnosis (1). The major impediment to effective clinical outcomes for this malignancy is its delayed diagnosis and resistance to existing cancer therapeutics (2, 3). Novel strategies for more successful prevention and therapy of pancreatic cancer are therefore urgently needed.

Pancreatic ductal adenocarcinoma (PDAC) accounts for the majority of pancreatic cancer cases and is thought to arise from pancreatic duct epithelia (3). Smoking is a documented risk factor for pancreatic cancer (4), with smokers showing a 2-fold increase in the risk of developing PDAC (5). Tobacco smoke is composed of more than 4,000 chemicals, including the nicotine-derived carcinogenic nitrosamine 4-(methylnitrosamo)-1-(3-pyridyl)-1-butanone (NNK; ref. 6). It has been shown that NNK causes PDAC in rats (7) and hamsters (8). Although nicotine acts as the primary psychoactive component responsible for smoke addiction, it is thought to be noncarcinogenic. However, several laboratories have reported that nicotine activates numerous cellular signaling pathways downstream of nicotinic acetylcholine receptors (nAChR), resulting in the stimulation of cell proliferation, angiogenesis, and metastasis of several cancers, including PDAC (9–12).

The nAChRs constitute a heterogeneous family of ion channels that were initially thought to be restricted to the central and peripheral nervous system. However, recent studies have identified the expression of this receptor family in numerous non-neuronal cells, including the pancreas (13). In the nervous system and adrenal glands, nAChRs regulate the synthesis of the catecholamine neurotransmitters noradrenaline and adrenaline and their release into the extracellular environment and systemic circulation (14, 15). Both catecholamines are agonists for beta adrenergic receptors (β-AR). Binding of adrenaline or noradrenaline to these receptors activates the stimulatory G protein (Gαs) which in turn activates adenyl cyclase, the single rate-limiting step for the formation of intracellular cyclic AMP (cAMP;
ref. 16, 17). Moreover, studies by our laboratory have shown that PDAC cells express β-ARs with β2-ARs predominating and that cAMP signaling downstream of these receptors stimulates the proliferation and migration of these cells (18–20).

In the current experiments, we have tested the hypothesis that analogous to their function in the central nervous system, nAChRs regulate the synthesis and release of noradrenaline and adrenaline in PDAC cells and pancreatic duct epithelial cells and that this autocrine catecholamine loop activates multiple cellular pathways that are overexpressed in pancreatic cancer.

Materials and Methods

Chemicals, primers, and antibodies

Lipofectamine 2000 reagent, stealth-183 for the CHRNA7 gene, stealth-1079 for the CHRNA3 gene, stealth-873 for the CHRNA5 gene, stealth-1973 for the CHRNA4 gene, stealth RNAi Negative Control Low GC Duplex, and Opti-MEM I reduced serum medium 1 × were all purchased from Invitrogen Corporation. The primer used to interfere with the α7 subunit mRNA was sense, GGA AGC UUU ACA AGG AGC UGG UCA A and antisense, UUG ACC AGC UCC UUG UAA AGC UUC C. The primer used to interfere with the α3 subunit mRNA was sense, GCU CUU CCA UGA ACC UCA AGG ACU A and antisense, UAG UCC UUG AGG UUC AUG GAA GAC A. The primer used to interfere with the α5 subunit mRNA was sense, GGG AGC AAA GGA AAC AGA ACC GAC A and antisense, UGU CGG ACC UCA AGG ACU A. The primer used to interfere with the α4 subunit mRNA was sense, GAC CGC AUC UUC CUC UGG AUG UUC A and antisense, UGA CGG UUC UGU UUC CUU UGC UCC C. The primer used to interfere with the α7 subunit mRNA was sense, GGA AGC UUU ACA AGG AGC UGG UCA A and antisense, UUG ACC AGC UCC UUG UAA AGC UUC C. The primer used to interfere with the α3 subunit mRNA was sense, GCU CUU CCA UGA ACC UCA AGG ACU A and antisense, UAG UCC UUG AGG UUC AUG GAA GAC A. The primer used to interfere with the α5 subunit mRNA was sense, GGG AGC AAA GGA AAC AGA ACC GAC A and antisense, UGU CGG ACC UCA AGG ACU A and antisense, UGA CGG UUC UGU UUC CUU UGC UCC C. The primer used to interfere with the α4 subunit mRNA was sense, GAC CGC AUC UUC CUC UGG AUG UUC A and antisense, UGA CGA AGA AGG UGC GGU C.

The TE buffer 1 × was purchased from Promega Corporation. The 2-Cat ELISA Kits were purchased from Rocky Mountain Diagnostics Incorporation. ELISA kits for AKT (pS473), ERK1/2 (pTpY185/187), and CREB (pS133) were purchased from Invitrogen Corporation. The c-Src Kinase assay was purchased from MBL International.

The antibodies AKT (60 kDa), p-AKT (60 kDa), Src (60 kDa), p-Src (60 kDa), ERK1/2 (44/42 kDa), p-ERK1/2 (44/42 kDa), p-CREB (43 kDa), anti-rabbit, and anti-mouse were all purchased from Cell Signaling. The primary antibodies anti-CREB (43 kDa) and anti-nicotinic acetylcholine receptor alpha 4 (55 kDa) were purchased from Millipore. The nAChR subunits α7 (56 kDa), α3 (57 kDa), α5 (53 kDa), and β-actin (42 kDa) antibodies were purchased from Abcam. Nicotine and propranolol were both purchased from Sigma-Aldrich. The site-selective α7-nAChR antagonist, α7-bungarotoxin, was purchased from Calbiochem. The lysis buffer used to extract proteins along with Pierce ECL Western blotting substrate was purchased from Thermo Scientific.

Cell culture

The human PDAC lines Panc-1 and BxPC-3 were purchased from the American Type Culture Collection. The immortalized human pancreatic duct epithelial cell line, HPDE6-C7, was cloned established after transduction of the HPV16-E6E7 genes into primary cultures of pancreatic duct epithelial cells and was a kind gift from Dr. Tsao (Division of Cellular and Molecular Biology, Department of Pathology, Ontario Cancer Institute/Princess Margaret Hospital, University of Toronto, Toronto, ON, Canada). All cell lines have been authenticated at the beginning of the current study by Research Animal Diagnostic Laboratory (RADIL) by species-specific PCR evaluation.

The Panc-1 cell line was maintained in Dulbecco’s Modified Eagle’s Medium supplemented with 10% FBS. BxPC-3 cells were maintained in RPMI-1640 medium supplemented with 10% FBS. HPDE6-C7 cells were maintained in keratinocyte serum-free medium (KSFPM) supplemented with 25 mg/500 mL bovine pituitary extract (BPE) and 2.5 μg/500 mL epidermal growth factor (EGF; Gibco Invitrogen Corporation). All cell lines were grown without antibiotics in an atmosphere of 5% CO2, 99% relative humidity, and 37°C.

Analysis of intracellular and secreted adrenaline and noradrenaline

All 3 cell lines were maintained in their respective complete medium until reaching 65% confluence, at which time they were switched to basal medium for 24 hours starvation. Cells were then switched into fresh basal media and were divided into 2 groups. The first groups of cells were either untreated or treated with 1 μmol/L nicotine for 1, 5, 15, or 30 minutes. The second groups of cells were either untreated or treated with 10 pmol/L, 500 pmol/L, 1 nmol/L, 500 nmol/L, 1 μmol/L, or 10 μmol/L nicotine for 30 minutes. The culture media, containing secreted catecholamines, were then collected in 15 mL test tubes. The cells which contained synthesized intracellular catecholamines were lysed and harvested into 1.5 mL Eppendorf tubes after a one-time wash with warm 1 × PBS. Quantitative analyses of intracellular and secreted adrenaline and noradrenaline of 5 samples per treatment group were conducted using 2-Cat ELISA kits following the vendor’s recommendations. Absorbance of samples was read using an uQuant Bio-Tek Instrument ELISA reader at 450 nm primary wavelength with a 630 nm reference wavelength.

Gene knockdown of the α3, 4, 5, and 7-nAChRs

Cells from all 3 cell lines were grown for 24 hours in their respective complete media. At that time, cells were switched to Opti-MEM I media and were divided into several groups. Groups 1 and 2 from each cell line were left untreated in Opti-MEM I media for 24 hours. Group 3 was transfected for 24 hours with stealth RNAi Negative Control Low GC Duplex. Groups 4 and 5 were transfected with either stealth-183, 1079, 873, or 1973 for the CHRNA7, 3, 5, and 4 genes, respectively, for 24 hours in Opti-MEM I media. Once the 24-hour transfection was complete, all cells were switched into their respective basal media. Groups 1, 3, and 4 were left untreated for 30 minutes in basal media, whereas groups 2 and 5 were treated with 1 μmol/L nicotine for 30 minutes in
basal media. All transfections were done using Lipofectamine 2000 reagent following the instructions of the manufacturer. Cell lysates were then harvested and collected in 1.5 mL Eppendorf tubes after one time wash with warm 1× PBS for adrenaline and noradrenaline analyses by immunoassays as described above. The transfection efficiency was monitored by Western blot analyses using α3, 4, 5, and 7-nAChRs as primary antibodies and actin as a loading control following the procedure outlined below. Following background subtraction, mean densities of 2 rectangular areas of standard size per band from 3 independent Western blot analyses were determined and mean values and SDs (n = 6) of protein expression were calculated.

**Assessment of cell proliferation by MTT assay**

Cells from the 3 cell lines were seeded in 6-well plates at a density of 50,000 cells per well in their respective phenol red–free complete media. Cells were then left untreated or treated with 1 μmol/L nicotine for 72 hours, 200 nmol/L α-bungarotoxin for 72 hours, 1 μmol/L propranolol for 72 hours, 200 nmol/L α-bungarotoxin for 10 minutes followed by 1 μmol/L nicotine for 72 hours, or 1 μmol/L propranolol for 10 minutes followed by 1 μmol/L nicotine for 72 hours. The MTT colorimetric assay (Sigma-Aldrich) was used to assess cell proliferation following instructions by the vendor. The MTT assay is based on the NAD-dependent enzymatic reduction of the tetrazolium salt MTT to form formazan in metabolically active viable cells. Absorbance of samples was read using an uQuant Bio-Tek Instrument ELISA reader at 570 nm primary and 650 nm reference wavelengths.

**Quantitative assessment of phosphorylation of signaling proteins by ELISA assays**

Cells from the 3 cell lines were left to grow in their respective complete media until reaching 65% confluence. Cells were then left untreated or treated with 1 μmol/L nicotine for 72 hours, 1 μmol/L propranolol for 72 hours, or 1 μmol/L propranolol for 10 minutes followed by 1 μmol/L nicotine for 72 hours in complete media. The cells were then lysed and harvested into 1.5 mL Eppendorf tubes after a one time wash with warm 1× PBS. Quantitative analyses of AKT, CREB, Src, and ERK1/2 phosphorylation of 5 samples per treatment group were conducted using AKT, CREB, c-Src, and ERK1/2 ELISA kits, respectively, following the vendors’ recommendations. Absorbance of samples was read using an uQuant Bio-Tek Instrument ELISA reader at 450 nm primary wavelength with a 630 nm reference wavelength.

**Western blot analysis**

Cells from HPDE6-C7, BxPC-3, and Panc-1 were grown in their respective complete medium until reaching 65% confluence. Cells were then switched to their respective basal media without any supplements or antibiotics for 24 hours starvation. The cells were then switched to fresh basal media and were divided into 3 groups. Group 1 was either untreated or treated with 1 μmol/L nicotine for 10, 15, 30, or 60 minutes. Group 2 was either untreated or treated with 1 nmol/L NNK for 10, 15, 30, or 60 minutes. Group 3 was either untreated or treated with 10 μmol/L acetylcholine for 10, 15, 30, or 60 minutes. Protein samples were prepared...
using lysis buffer (50 mmol/L Tris-HCl, 1% NP-40, 150 mmol/L NaCl, 1 mmol/L phenylmethylsulfonylfluoride, 1 mmol/L Na3VO4, 1 mmol/L NaF, and 1 µg/mL of aprotinin, leupeptin, and pepstatin). After heat denaturation, protein samples were electrophoresed using 12% SDS gels (Invitrogen) and blotted onto membranes. The membranes were blocked (5% nonfat dry milk solution) for 1 hour at room temperature. Membranes were then incubated (0.5% Tween 20/TBS) and incubated with their respective antibodies: AKT, p-AKT, Src, p-Src, CREB, p-CREB, ERK1/2, and p-ERK1/2. The membranes were then washed (0.5% Tween 20/TBS) and incubated with their respective fluorescent secondary antibodies for 2 hours. Protein bands were then visualized with enhanced chemiluminescence reagent (Pierce ECL Western Blotting Detection Substrate).

Statistical analysis of data

GraphPad Instat 3 software (GraphPad Instant biostatistics) was used to test significant differences between different treatment groups. Statistical tests used included nonparametric one-way ANOVA and Tukey–Kramer multiple comparison tests. In addition, ImageJ from NIH (Bethesda, MD) was used for mean density determination of bands. Data of the immunoassays and MTT assays are expressed as mean density determination of bands. Statistical tests used included nonparametric one-way ANOVA and Tukey–Kramer multiple comparison tests. In addition, ImageJ from NIH (Bethesda, MD) was used to test significant differences between different treatment groups. The EC50 values were as follows: HPDE6-C7 intracellular adrenaline, 100 nmol/L; secreted adrenaline, 98 nmol/L; intracellular noradrenaline, 14 nmol/L; secreted noradrenaline, 250 nmol/L; Panc-1 intracellular adrenaline, 460 pmol/L; secreted adrenaline, 350 pmol/L; intracellular noradrenaline, 7.3 nmol/L; secreted noradrenaline, 214 pmol/L; BXPC-3 intracellular adrenaline, 469 pmol/L; secreted adrenaline, 3.24 nmol/L; intracellular noradrenaline, 2.6 nmol/L; secreted noradrenaline, 6.7 nmol/L. Representative data points are mean ± SD from 5 samples per treatment group.

Results

Effects of nicotine on catecholamine neurotransmitter levels

One important role of the α7-nAChR in the nervous system is the regulation of the synthesis and release of neurotransmitters, including adrenaline and noradrenaline (14, 21). Although our laboratory has previously shown that β-ARs regulate the proliferation and migration of pancreatic cancer cells in vitro (18–20), the function of nAChRs expressed in these cells is poorly understood. We therefore tested the hypothesis that PDAC cells and normal pancreatic duct epithelial cells synthesize and release their own catecholamine neurotransmitters and that this activity is regulated by nAChRs. In support of this hypothesis, our immunoassays detected noradrenaline and adrenaline in cell lysates as well as culture media of both pancreatic cancer cell lines and the immortalized pancreatic duct epithelial cells. The intracellular as well as secreted levels of noradrenaline and adrenaline increased significantly (P < 0.0001) in a time-dependent manner when the cells were exposed to nicotine (1 µmol/L) for 1 to 30 minutes (Fig. 1). The immortalized duct epithelial cell line HPDE6-C7 was less responsive to nicotine than the cancer cells (P < 0.0001 at the 30-minute time point) as indicated by lower levels of intracellular and secreted (A) adrenaline levels and secreted (C) and intracellular (D) noradrenaline levels in HPDE6-C7, BXPC-3, and Panc-1 cells treated with nicotine concentrations from 10 pmol/L through 10 µmol/L for 30 minutes. The EC50 values were as follows: HPDE6-C7 intracellular adrenaline, 100 nmol/L; secreted adrenaline, 98 nmol/L; intracellular noradrenaline, 14 nmol/L; secreted noradrenaline, 250 nmol/L; Panc-1 intracellular adrenaline, 460 pmol/L; secreted adrenaline, 350 pmol/L; intracellular noradrenaline, 7.3 nmol/L; secreted noradrenaline, 214 pmol/L; BXPC-3 intracellular adrenaline, 469 pmol/L; secreted adrenaline, 3.24 nmol/L; intracellular noradrenaline, 2.6 nmol/L; secreted noradrenaline, 6.7 nmol/L. Representative data points are mean ± SD from 5 samples per treatment group.

Figure 2. Secreted (A) and intracellular (B) adrenaline levels and secreted (C) and intracellular (D) noradrenaline levels in HPDE6-C7, BXPC-3, and Panc-1 cells treated with nicotine concentrations from 10 pmol/L through 10 µmol/L for 30 minutes. The EC50 values were as follows: HPDE6-C7 intracellular adrenaline, 100 nmol/L; secreted adrenaline, 98 nmol/L; intracellular noradrenaline, 14 nmol/L; secreted noradrenaline, 250 nmol/L; Panc-1 intracellular adrenaline, 460 pmol/L; secreted adrenaline, 350 pmol/L; intracellular noradrenaline, 7.3 nmol/L; secreted noradrenaline, 214 pmol/L; BXPC-3 intracellular adrenaline, 469 pmol/L; secreted adrenaline, 3.24 nmol/L; intracellular noradrenaline, 2.6 nmol/L; secreted noradrenaline, 6.7 nmol/L. Representative data points are mean ± SD from 5 samples per treatment group.
secreted catecholamines at all time points investigated (Fig. 1). Exposure of the cells for 30 minutes to nicotine at concentrations from 10 pmol/L through 10 μmol/L additionally revealed concentration-dependent increases in intracellular and secreted catecholamines in all 3 cell lines (Fig. 2). In accordance with the differences in responsiveness observed in the time courses (Fig. 1), the EC_{50} values of nicotine for intracellular and secreted noradrenaline and adrenaline were in the nanomolar range for the 2 cancer cell lines whereas they were in the 10 to 100 nanomolar range for HPDE6-C7 cells (Fig. 2).

**Effects of nAChR knockdown on neurotransmitter levels and nAChR protein**

To assess the potential regulatory role of the α3, α4, α5, and α7-nAChRs for catecholamine synthesis in pancreatic cancer and pancreatic duct epithelial cells, the 3 cell lines were transfected with stealth α3, α4, α5, or α7 RNA interference (RNAi) constructs. Immunoblot analyses showed that transfections with the α3, α5, and α7 RNAi constructs significantly inhibited (P < 0.0001) the stimulatory effect of nicotine on adrenaline and noradrenaline synthesis in each of the 3 cell lines and reduced catecholamine synthesis below base levels in control cells (Fig. 3). These findings confirm regulatory roles of the α3, α5, and α7-nAChRs for catecholamine production by these cells. In contrast, gene knockdown of the α4-nAChR did not significantly reduce catecholamine synthesis in either cell line (Fig. 3). As no reduction in catecholamine synthesis was observed in the cells transfected with the negative control RNAIs, these findings indicate that the cells also produce one or both of the physiologic agonists for these nAChRs (acetylcholine, choline) that continuously stimulated base level catecholamine synthesis.

Results of Western blot analyses showed significant increases (P < 0.0001) in the expression of all investigated nAChR proteins in all 3 cell lines exposed for 30 minutes to 1 μmol/L nicotine (Fig. 4). Furthermore, transfection of these cells with stealth RNAi for each of the investigated nAChR constructs significantly decreased (P < 0.0001) their protein expression in cells with and without nicotine exposure (Fig. 4). In contrast, transfection of cells with stealth RNAi negative control low GC showed no significant change in the protein expression of this receptor (Fig. 4), confirming the specificity of the observed gene knockdowns.

**Activation of multiple signaling proteins by nAChR agonists and inhibition by the beta blocker propranolol**

Binding of an agonist to β-ARs activates adenylyl cyclase, leading to the formation of cAMP and phosphorylation of the transcription factor CREB by activated protein kinase A (17). In addition, activated protein kinase A transactivates the EGF receptor (EGFR) pathway in pancreatic cancer cells and pancreatic duct epithelia, leading to the phosphorylation

![Figure 3](image-url)
of the extracellular signal–regulated kinases (ERK1/2; ref. 19). We therefore assessed the phosphorylation of CREB and ERK by Western blot analyses in our 3 cell lines after exposures from 10 to 60 minutes to nicotine (1 μmol/L), NNK (1 nmol/L), or acetylcholine (10 μmol/L). We also monitored the phosphorylation of Src family tyrosine kinases and of the serine/threonine protein kinase B, AKT, because both are frequently overexpressed in pancreatic cancer (22, 23). As Fig. 5 shows, 1 μmol/L nicotine induced the phosphorylation of all 4 signaling proteins in both pancreatic cancer cell lines and immortalized pancreatic duct epithelial cells. In accordance with findings that the affinity of NNK to the α7-nAChR is about 1,000 times greater than that of nicotine (24), similar responses of the 4 investigated signaling proteins were observed when the cells were exposed to 1 nmol/L NNK (Fig. 5). The physiologic nAChR agonist, acetylcholine, binds to these receptors at a significantly lower affinity than nicotine (14). We therefore used acetylcholine at a 10 μmol/L concentration when assessing its effects on the phosphorylation status of the signaling proteins under investigation. As shown in Fig. 5, at this concentration, acetylcholine had similar inducing effects on all 4 signaling proteins as nicotine and NNK. The quantitative assessment of nicotine-induced activation of these signaling proteins and the inhibitory effects of propranolol were achieved by immunoassays. As Fig. 6 shows, the phosphorylation of ERK, CREB, Src, and AKT were each significantly (P < 0.001) induced by nicotine and these responses were completely blocked by propranolol (P < 0.0001). Propranolol also significantly (P < 0.01) reduced base level phosphorylation of these signaling proteins in cells not exposed to nicotine (Fig. 6).

Regulation of cell proliferation by neurotransmitter receptors

MTT assays were conducted to evaluate cell proliferation of HPDE6-C7, BxPC-3, and Panc-1 cells induced by nicotine (1 μmol/L) in the presence and absence of the general β-AR antagonist, propranolol (1 μmol/L) or the site-selective α7-nAChR antagonist, α-bungarotoxin (200 nmol/L). Cells from each of the 3 investigated cell lines exposed to nicotine for 72 hours showed significant increases (P < 0.0001) in cell proliferation. This response to nicotine was reduced below base levels (P < 0.0001) by preexposure of cells to either α-bungarotoxin or propranolol (Fig. 7A), indicating that the α7-nAChR as well as β-ARs were involved in the observed nicotine-induced cell proliferation. In addition, base level cell proliferation in the absence of nicotine was significantly (P < 0.0001) reduced by α-bungarotoxin or propranolol (Fig. 7A), suggesting regulatory functions of both receptor types in nonexogenously stimulated cells.
Autocrine Mitogenic Catecholamine Loop in Pancreatic Cancer Cells

Discussion

Our data show, for the first time, that pancreatic cancer cells and normal pancreatic duct epithelia express an autocrine catecholamine loop that stimulates their proliferation and are jointly regulated by the nAChRs α3, α5, α7, and by β-ARs. The catecholamines noradrenaline and adrenaline that were synthesized and released by 2 investigated pancreatic cancer cell lines and a cell line of immortalized pancreatic duct epithelia are commonly known as stress neurotransmitters because they are synthesized in the adrenal medulla and released into the systemic blood circulation in response to psychologic stress (15). In addition, both of these neurotransmitters are synthesized and released from nerves of the sympathicus (25), thus regulating vital functions in multiple organs. Furthermore, noradrenaline and adrenaline have excitatory and anti-inflammatory functions in the brain where they are synthesized and released by neurons (21). It is well documented that nicotine increases catecholamine production at these neuroendocrine sites, thus increasing the systemic levels of noradrenaline and adrenaline (26, 27). Accordingly, a previous study by our laboratory showed a significant nicotine-induced growth promotion of pancreatic cancer xenografts associated with increased levels of noradrenaline, adrenaline, and cAMP in blood and xenograft tissues as well as an induction of p-CREB and p-ERK in xenograft tissues. These changes were interpreted as indirect effects of such systemic neuroendocrine responses (28). Our current in vitro experiments are not influenced by this systemic neuroendocrine effect of nicotine and unequivocally show that 2 pancreatic cancer cell lines as well as immortalized pancreatic duct epithelia synthesized and released their own noradrenaline and adrenaline in response to nicotine. The important role of the catecholamine neurotransmitters in the observed nicotine-induced stimulation of cell proliferation was confirmed by abolishment of this response by propranolol, an antagonist for β1- as well as β2-ARs. As assessed by both gene knockdown and pharmacologic blockage with α-bungarotoxin the α7-nAChR regulated catecholamine production as well as cell proliferation in response to nicotine. Interestingly, gene knockdown of the α3 and α5-nAChRs also significantly reduced catecholamine production in all 3 cell lines, indicating cooperative function of these 2 nAChRs with the α7-nAChR. In contrast, the α4-nAChR did not appear to participate in the regulation of catecholamine production. These findings are in accordance with reports that the α3, α5, and α7-nAChRs cooperate in regulating the proliferation of oral keratinocytes (29), whereas the α4-nAChR regulates the production of γ-aminobutyric acid (GABA) in human small airway epithelial cells (30). The α3, α5, and α7-nAChRs thus function as the upstream regulator of this novel autocrine regulatory loop with β-ARs as the effectors of released noradrenaline and adrenaline (Fig. 7B). Our

Figure 5. Western blot analyses assessing phosphorylation of AKT, Src, CREB, and ERK1/2 in HPDE6-C7 (A), BxPC-3 (B), and Panc-1 (C) cells treated with 10 μmol/L acetylcholine, 1 μmol/L nicotine, and 1 nmol/L NNK at different time exposures. All agents increased phosphorylation of all 4 proteins as compared with the untreated groups. The unphosphorylated proteins AKT, Src, CREB, and ERK1/2 were used as controls (C) to ensure equal loading of proteins.
Findings are in accord with recent observations that the α7-nAChR regulates the synthesis and release of noradrenaline and adrenaline in small airway epithelial cells (30) and colon cancer cells (31) and suggest this autocrine catecholamine loop as a novel target for pancreatic cancer intervention. This interpretation is supported by our findings that multiple phosphorylated signaling proteins that are frequently overexpressed in pancreatic cancer were simultaneously induced in each of the investigated cell lines by exposure to nicotine whereas the beta blocker propranolol reversed these responses and additionally reduced the phosphorylation of all investigated signaling protein levels below base levels. These findings indicate that the observed phosphorylation of signaling proteins were events downstream of β-ARs. Inhibitors of ERK, Src, AKT, and EGFR tyrosine kinases alone or in combination are currently being explored as "targeted therapeutics" for pancreatic cancer, an approach that necessitates treatment of the patient with multiple inhibitors (2, 3). Our current data suggest single agent therapy with the beta blocker propranolol as a novel alternative to this strategy.

Although CREB, Src, and AKT are traditionally considered downstream effectors of the EGFR pathway in pancreatic cancer (3), in vitro studies with pancreatic cancer cell lines and immortalized pancreatic duct epithelia have shown that ERK is also phosphorylated simultaneously with CREB in response to β-adrenergic agonists following the PKA-dependent transactivation of the EGFR (19). In addition, studies in ovarian cancer cells have identified the phosphorylation of Src in these cells as a cAMP-dependent event in response to stress neurotransmitters (32).

The nitrosated carcinogenic nitrosamine NNK is an nAChR agonist with a 1,000-fold higher affinity to the α7-nAChR than nicotine (24, 29). In the current experiments, exposures of the cells to NNK were therefore conducted at a 1 nmol/L concentration as opposed to 1 μmol/L nicotine used in the accompanying experiments. In turn, the documented lower affinity of acetylcholine to nAChRs than nicotine (14) was the reason why we exposed our cell lines to 10 μmol/L acetylcholine. As our Western blot analyses show that the induction of the investigated signaling proteins was similar with all 3 agents at the concentrations used. Exposure

Figure 6. ELISA assays showing phosphorylation levels of Src (A), ERK1/2 (B), AKT (C), and CREB (D) for HPDE6-C7, BxPC-3, and Panc-1. Nicotine significantly (P < 0.001) induced the phosphorylation of all signaling proteins investigated. Propranolol, a beta blocker significantly (P < 0.001) reduced base level and nicotine induced phosphorylation of all 4 proteins. Representative data points are mean ± SD from 5 samples per treatment group.
of the cells to 1 μmol/L nicotine for 30 minutes additionally upregulated the protein expression of nAChRs in the investigated 3 cell lines. This response is in accordance with the reported rapid increase of nAChR numbers in response to nicotine or other agonists (33). Similar effects of nicotine on the α7-nAChR have been described in the brain and are thought to be caused by posttranslational and posttranscriptional mechanisms (34).

Smoking is a documented risk factor for the development of pancreatic cancer (4). However, this malignancy also develops in a significant number of nonsmokers. Although some of these cases are preceded by diabetes or pancreatitis, 2 additional known risk factors for pancreatic cancer (4, 35), our current findings suggest that psychologic stress may also contribute to the development and progression of this disease. Whereas in our experiments, the production of catecholamines and resulting induction of multiple signaling proteins that regulate cell proliferation, migration, and apoptosis was induced by the exogenous addition of nAChR agonists to the cells, psychologic stress triggers a systemic increase in noradrenaline and adrenaline via activation of the pituitary/adrenal system (15). In analogy to reports that experimentally induced psychologic stress promotes the growth and metastasis of ovarian cancer via β-adrenergic, cAMP-dependent signaling (36), psychologic stress may therefore also facilitate the development of pancreatic cancer and promote the progression of this malignancy, thus impairing therapeutic outcomes (37, 38). However, further studies are needed to address this potential aspect of pancreatic cancer regulation.

In summary, our data suggest that the autocrine catecholamine loop expressed in pancreatic cancer cells and in normal pancreatic duct epithelial cells that is jointly governed by the α3, α5, and α7-nAChRs and β-ARs as an important regulatory network that controls multiple signal transduction pathways known to be hyperactive in pancreatic cancer. As shown in Fig. 7, this entire cascade could theoretically be inhibited by beta blockers or by agents that inhibit the activation of adenylyl cyclase and associated formation of cAMP. Although the α7-nAChR has been suggested as a drug target for the therapy of non–small cell lung cancer (39), the vital functions of this receptor in the nervous system renders the use of α7-nAChR antagonists for cancer therapy problematic. On the other hand, beta blockers have
been safely used for decades as cardiovascular therapeutics and the beta blocker propranolol prevented the development of NNK-induced pancreatic cancer in hamsters (38). A recent report has also identified significantly better clinical outcomes in patients with breast cancer treated with beta blockers (40). These findings are in accordance with data that have shown stimulation of breast cancer cell proliferation by β-adrenergic agonists in vitro (41, 42). In addition, it has been shown that GABA inhibited the proliferation and migration of pancreatic cancer cells in vitro via GABA-B receptor-mediated inhibition of adenylyl cyclase (20). GABA also reversed the growth-promoting effects of nicotine on pancreatic cancer xenografts by reducing tumor cAMP levels (28). GABA has been safely used as a nutritional supplement for many years and selective GABA-B receptor agonists are widely used for the pharmacologic management of spastic pain after spinal injuries and spinal surgery. Further studies are now warranted to explore the potential usefulness of these agents for the improvement of clinical outcomes in pancreatic cancer therapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Pancreatic Cancer Cells and Normal Pancreatic Duct Epithelial Cells Express an Autocrine Catecholamine Loop that Is Activated by Nicotinic Acetylcholine Receptors $\alpha_3$, $\alpha_5$, and $\alpha_7$

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