Inhibiting the Cyclin-Dependent Kinase CDK5 Blocks Pancreatic Cancer Formation and Progression through the Suppression of Ras-Ral Signaling

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Abstract

Cyclin-dependent kinase 5 (CDK5), a neuronal kinase that functions in migration, has been found to be activated in some human cancers in which it has been implicated in promoting metastasis. In this study, we investigated the role of CDK5 in pancreatic cancers in which metastatic disease is most common at diagnosis. CDK5 was widely active in pancreatic cancer cells. Functional ablation significantly inhibited invasion, migration, and anchorage-independent growth in vitro, and orthotopic tumor formation and systemic metastases in vivo. CDK5 blockade resulted in the profound inhibition of Ras signaling through its critical effectors RalA and RalB. Conversely, restoring Ral function rescued the effects of CDK5 inhibition in pancreatic cancer cells. Our findings identify CDK5 as a pharmacologically tractable target to degrade Ras signaling in pancreatic cancer. Cancer Res; 70(11): 4460–9. ©2010 AACR.

Introduction

Pancreatic cancer is one of the most lethal human malignancies, with an estimated 34,290 deaths in the United States in 2008 (1). Despite extensive efforts aimed at developing improved therapeutic strategies, the dismal 5-year overall survival rate of ~4% has not significantly improved over the last five decades. Therefore, the quest for potent targeted therapeutic approaches for pancreatic cancer remains an imperative clinical issue.

Cyclin-dependent kinase 5 (CDK5) has ~60% structural identity with cyclin-dependent kinases. Nevertheless, its moniker as a "cyclin-dependent kinase" is somewhat misleading; CDK5 has no known cell cycle or mitotic function, and it is not activated by cyclins (2). Instead, CDK5 is activated by the association with either of the two obligate CDK5-specific activator proteins, p35 (CDK5R1) or p39 (CDK5R2; refs. 3, 4). Thus, although CDK5 is ubiquitously expressed, the restricted expression pattern of the obligate activator proteins confines physiologic CDK5 function to a limited repertoire of tissues, most prominently in cells of neuronal origin; expression of either p35 or p39 is synonymous with CDK5 kinase activity. Homozygous deletion of the Cdk5 gene in mice has shed light on the critical functions of CDK5 in brain development (5). Specifically, Cdk5−/− mice die perinatally, with a remarkable inversion of the six layers of the cerebral cortex, suggesting a global abnormality of neuronal migration. Mis-expression of the CDK5 activator p35 (and more specifically, its proteolytic COOH-terminal fragment p25) leads to the deregulation of CDK5 function and promotes neurofibrillary tangles and plaque formation, both hallmarks of Alzheimer disease (6, 7).

Given the numerous parallels between neuronal migration during embryogenesis and the migration of cancer cells from their primary site during metastasis (8, 9), a requirement for CDK5 in the latter phenomenon might be envisioned. Over the past decade, the compendium of extraneuronal functions of CDK5 has expanded (10). We previously identified an association between CDK5 and human cancer, with the demonstration that inhibition of CDK5 activity inhibits prostate cancer metastases in experimental models (11). These observations were predominantly empirical and the intracellular mechanisms linking CDK5 activity to cancer progression remained essentially unknown. Here, we show that CDK5 blockade not only inhibited pancreatic cancer migration in vitro and metastases in vivo but also downregulated anchorage-independent growth and primary tumor engraftment in xenograft models, suggesting a more pervasive requirement for sustained CDK5 signaling on pancreatic tumorigenesis. We identify a novel Ras-CDK5-Ral signaling axis...
in pancreatic cancer that provides a unique therapeutic opportunity to target mutant Ras in cancer cells through the inhibition of a key downstream effector pathway. Given the central role of Ras GTPases in tumor initiation and tumor progression in Ras-driven neoplasia (12, 13), this study establishes CDK5 as a bona fide therapeutic target in pancreatic cancer, a malignancy with >90% frequency of KRAS2 gene mutations (14–16).

Materials and Methods

Cell lines and constructs
Pancreatic cancer cell lines (PK-9, SW1990, Su86.86, BxPC-3, MIAPaCa-2, PANC-1, AsPc-1, and CFPAC-1) were obtained from the American Type Culture Collection, whereas the low-passage cell lines (Pa16C, Pa03C, Pa20C, Pa18C, and Pa04C) were generated at our institution, as recently described (14). All cancer cell lines were cultured as previously described (17). The generation and culture of hTERT-immortalized human pancreatic nestin-expressing (HPNE) cells has previously been described (18).

RNA extraction, reverse transcription, and quantitative real-time PCR
RNA extraction from tissue samples or cultured cells was done as previously described (19).

Migration and wound healing assays
In vitro wound healing and migration assays were performed as previously described (11, 19).

Soft agar assays
Soft agar assays were performed as previously described (19).

Western blotting
Western blot analyses were performed as previously described (11).

Kinase assays
CDK5 in vitro kinase activity was determined as previously described (11).

Immunofluorescence analysis
Immunofluorescence analysis was performed as previously described (20) with minor modifications.

Raf, Rho, and Rac activation assays
RafA-GTP, RafB-GTP, RhoA-GTP, and Rac-GTP levels were determined using the respective activation assay kits (both Upstate) following the standard procedure recommended by the manufacturer.

Subcutaneous and orthotopic xenografts
Generation of subcutaneous and orthotopic xenografts of pancreatic cancer has been previously described (19, 21–24).

Statistical analysis
Kruskal-Wallace analysis and $\chi^2$ test were performed using SPSS version 15.0.1.1 (SPSS, Inc.) for Microsoft Windows. Two-tailed $t$ test and Mann-Whitney $U$ test were performed using Prism (GraphPad Software, Inc.) version 5.01. $P < 0.05$ was regarded to be statistically significant. Bar diagrams were generated using Prism version 5.01 and show means and SEMs if not otherwise indicated.

Additional, more detailed descriptions of experimental procedures used in this work are provided as supporting online material.

Results

The CDK5 obligate activator p35 is commonly expressed in human pancreatic cancer cells
Western blot analysis showed p35 protein expression in all 13 tested pancreatic cancer cell lines as well as in the non-neoplastic human pancreatic hTERT-HPNE cells. Higher expression of p35 was observed in 9 of 13 pancreatic cancer cell lines, whereas the remaining four cell lines showed similar basal expression compared with hTERT-HPNE (Fig. 1A). Expression of p35 transcripts was confirmed at the mRNA level in eight of eight pancreatic cell lines tested (Fig. 1B).

Blockade of endogenous CDK5 function inhibits pancreatic cancer cell migration and anchorage-independent growth

To determine the phenotypic effect of CDK5 blockade in pancreatic cancer, we generated MIAPaCa-2 cells with enforced expression of a dominant-negative CDK5 (dnCDK5) protein. The dnCDK5 construct is a D144N kinase–dead mutant that is expressed in a bidirectional vector, pBl-EGFP, which also expresses enhanced green fluorescent protein (EGFP; ref. 11). The pBl-EGFP dnCDK5 and pBl-EGFP empty vectors were stably selected in MIAPaCa-2 cells and two independent clones ("CDK5-dn1" and "CDK5-dn2") with a high level of expression were picked (Fig. 2A and B). Blockade of endogenous CDK5 had little to no effect on cell number over 96 hours, as assessed by the MTT assay (Fig. 2C). In contrast, there was a profound inhibition of cell migration at 48 and 72 hours, as assessed by an in vitro modified Boyden chamber assay, in the two dnCDK5 clones (Fig. 2D). Wound healing assays performed in vector versus dnCDK5-expressing MIAPaCa-2 cells confirmed the inhibitory effects of CDK5 blockade on cell motility (Supplementary Fig. S1A and B). Of note, small interfering RNA–mediated CDK5 knockdown also significantly reduced the migration of BxPC-3 cells (data not shown). These results were similar to those observed in prostate cancer cells with knockdown of endogenous CDK5 function (11). Remarkably, we additionally observed a dramatic inhibition of anchorage-independent growth in the MIAPaCa-CDK5dn clones compared with the vector-only clones (Fig. 2F). This inhibition of anchorage-independent growth suggested that CDK5 might play a role in pancreatic tumorigenesis beyond what has been reported in the context of prostate cancer, in which no significant effects on clonogenicity or tumor formation were observed. Abrogation of CDK5 function by expression of the dnCDK5 allele caused significant changes in cell morphology as shown by immunofluorescence labeling of the cell skeleton (Fig. 2E).
vector-transfected cells mostly showed an almost spindle-like shape with a clearly defined leading edge and microtubule-organizing centers between the leading edge and nucleus. MIAPaCa-2 cells stably expressing the CDK5-dn allele were more round in shape and mostly lacked a clearly defined leading edge and microtubule-organizing center.

To corroborate these observations in additional pancreatic cancer models, we used five pancreatic cancer cell lines with activating KRAS2 mutations (CFPAC1, PANC-1, Pa16C, Pa03C, and Pa20C), besides MIAPaCa-2 cells. Further, we used a complementary genetic strategy for antagonizing CDK5 function: RNA interference (RNAi) by enforced expression of a lentiviral complementary genetic strategy for antagonizing CDK5 function: RNA interference (RNAi) by enforced expression of a lentiviral shRNA directed against CDK5.

In parental MIAPaCa-2 cells, immunoprecipitation-kinase assays served as negative controls. RT-PCR analysis in human pancreatic cancer cell lines revealed expression of p35 mRNA transcripts in 8 of 8 tested cell lines (Supplementary Fig. S2B). Consistent with the effects observed with the genetic inhibition of CDK5 function, roscovitine treatment decreased the number of migrating cells in an in vitro Boyden chamber assay (Supplementary Fig. S5).

Inhibition of CDK5 function inhibits tumor growth and metastasis in an orthotopic xenograft model of human pancreatic cancer

Having established a role for sustained CDK5 activity on cell motility and anchorage-independent growth of pancreatic cancer cells, we next examined the effects of CDK5 inhibition in an in vivo orthotopic xenograft model. Two-independent MIAPaCa-2 clones expressing a dominant-negative allele of CDK5 ("dn1" and "dn2") were used for these studies and four mice were injected per group. At 6 weeks postinjection, the mice were euthanized and a comprehensive necropsy was performed for assessment of primary and metastatic tumor load. The orthotopic primary xenografts established from both independent dnCDK5 clones were significantly smaller compared with the vector-transfected MIAPaCa-2 xenografts (Fig. 4A and B). Other than a reduction in overall viable cell density, there were no histologic differences in the tumor microarchitecture between xenografts from vector- versus CDK5-dn—transfected MIAPaCa-2 cells (Fig. 4C). Further, necropsy confirmed a significant reduction in the frequency of metastases to regional lymph nodes, spleen, liver, kidneys, lungs, or intestine in sets of mice harboring dnCDK5 clones, compared with vector-transfected MIAPaCa-2 xenografts [Supplementary Fig. S5D; Fig. 4D; 8 of 48 (17%) versus 11 of 24 (46%) affected organ sites; P = 0.008]. Ascites was observed in 4 of 4 (100%) of mice in the control group, but only in 2 of 8 (25%) of mice carrying dnCDK5 xenografts (not significant; P = 0.061). Similar results were obtained when shRNA-mediated knockdown of CDK5 in Pa20C cells was used as a complementary orthotopic xenograft model system (Supplementary Table S1; Supplementary Fig. S6).
Figure 2. Dominant-negative form of CDK5 inhibits migration and anchorage-independent growth of pancreatic cancer cells. A and B, cells expressing the pBII-EGFP vector (either empty or expressing D144N dnCDK5) were confirmed by (A) EGFP expression and (B) Western blot analysis for CDK5 levels in MIAPaCa-2 cells. C, inhibition of CDK5 activity had no effect on MIAPaCa-2 cell growth on plastic, as assessed by MTS assay in empty versus the two dnCDK5-expressing clones (CDK5-dn1 and CDK5-dn2). D, in contrast, modified Boyden chamber assays showed marked reduction of in vitro migration in both dnCDK5 clones compared with vector-transfected cells at 48 and 72 h, respectively. E, immunofluorescence staining showed striking differences in cell morphology in the dnCDK5 versus vector-transfected MIAPaCa-2 cells. Although vector-transfected cells exhibit clear polarity with microtubule-organizing centers (MTOC; arrows) between the nucleus and leading edge of the cell, dnCDK5-expressing MIAPaCa-2 cells lack polarity and exhibit a rounded cell shape. F, colony formation in soft agar was also significantly reduced in both dnCDK5 clones compared with vector-transfected cells. Columns, mean of the respective colony counts; bars, SEM; *, \( P < 0.05 \) compared with vector-transfected controls.
Thus, consistent with the phenotypes observed in vivo, loss of CDK5 function in pancreatic cancer cells is associated with significantly decreased tumorigenicity and systemic metastases in vivo.

**CDK5 blockade inhibits the Ral effector pathway central to oncogenic Ras signaling**

These data showed that in pancreatic cancer, loss of CDK5 function interferes with the malignant phenotype, affecting both tumor formation (anchorage-independent growth in vitro and orthotopic engraftment in vivo) and tumor progression (cell migration in vitro and systemic metastases in vivo). It was important to begin to identify the signal transduction pathways underlying this reduced tumorigenicity. Previously, Counter and colleagues (12, 13) have shown the critical and divergent roles of the Ral effector pathway in oncogenic Ras–induced neoplasia, using pancreatic cancer as a prototype. Specifically, these investigators showed that the loss of RalA function can inhibit tumorigenicity across a spectrum of KRAS2-mutant pancreatic cancer cell lines, whereas sustained RalB activity seemed to be a critical determinant of tumor progression and metastasis. Those studies showed that the Ral pathway is a central effector of Ras-mediated malignant properties in pancreatic cancer. Therefore, we explored whether CDK5 function might be important for the activity of the Ras-Ral effector pathway axis in pancreatic cancer.

**Figure 3.** Knockdown of CDK5 expression by RNA-mediated interference in KRAS2 mutant pancreatic cancer cells blocks migration and inhibits anchorage-independent growth. A, Western blot analysis confirmed successful knockdown of CDK5 expression in CFPAC-1, PANC-1, MIAPaCa-2, Pa03C, Pa16C, and Pa20C cells transfected with lentiviral CDK5-shRNA (c) compared with lentiviral vector-transfected cells (v). B, modified Boyden chamber assays confirmed variable decrease of in vitro migration upon CDK5 downregulation, with the most pronounced effects observed in CFPAC-1 and MIAPaCa-2 cells. C, CDK5 RNAi also significantly inhibited colony formation in soft agar in all four KRAS2 mutant cell lines. Columns, mean of the respective colony counts; bars, SEM; *, P < 0.05 compared with empty vector–transfected controls.
cancer, as a basis for the observed phenotypes in our model system. Indeed, we found that the activated forms of both Ral proteins, RalA-GTP and RalB-GTP, were profoundly reduced in the dnCDK5-expressing MIAPaCa-2 clones, across multiple independent experiments (Fig. 5A). Rho-GTP and Rac-GTP levels were also found to be decreased in the CDK5-dn clones. Similarly, striking downregulation of the activated Ral-GTP moieties was seen upon the RNAi knockdown of CDK5 in five of the six tested KRAS2-mutant pancreatic cancer cell lines (Fig. 5B). Of note, Pa03C, which showed neither loss of anchorage-independent growth nor decrease in migration, retained activation of both Ral proteins, underscoring the importance of this effector pathway in the observed phenotype(s). We also examined the effects of roscovitine on Ral-GTP levels, and marked reduction of activated RalA-GTP was observed in all three examined KRAS2-mutant lines (MIA-

PaCa-2, CFPAC-1, and Panc-1), whereas RalB-GTP was down-regulated in all but MIAPaCa-2 cells (Fig. 5C). Thus, these experiments confirmed that in the majority of pancreatic cancer cells with constitutively activated Ras signaling, CDK5 inhibition can block the activation of a critical effector pathway implicated in tumor initiation and progression.

To further corroborate that downregulation of Ral signaling is indeed an underlying cause of the phenotypic changes in pancreatic cancer cells observed upon inhibition of endogenous CDK5 function, we attempted to rescue the malignant phenotype by constitutively activating RalA and RalB in pancreatic cancer cells expressing dnCDK5. Therefore, we generated dnCDK5 MIAPaca-2 clones with enforced expression of a constitutively active form (Rlf-CAAX) of the Ral guanine exchange factor (RalGEF), Rg12 (25). This RalGEF can activate RalA and RalB, independent of signaling from oncogenic Ras.

Figure 4. CDK5 inhibition inhibits primary tumor growth and systemic metastases in an orthotopic xenograft model of pancreatic cancer. A, orthotopic xenografts were generated in athymic mice by intrapancreatic injection of MIAPaCa-2 cells expressing empty pBl-EGFP vector, or dnCDK5 (clones dn1 and dn2). The resulting primary tumors were universally smaller in both dnCDK5 clones compared with vector-transfected cells. B, the average primary tumor mass was significantly lower in the two cohorts with loss of CDK5 function compared with vector-transfected cells. C, other than a decrease in viable cell density, the reduction in primary tumor mass was not accompanied by any obvious changes in the tumor architecture or extent of differentiation, as assessed by H&E staining on light microscopy. D, reduction in primary tumor mass in the dnCDK5 clones was accompanied by inhibition of systemic metastases compared with vector-transfected cells. White arrows, metastatic foci; *, \( p < 0.05 \) compared with vector-transfected controls.
Rlf-CAAX expression restored RalA-GTP and RalB-GTP levels in multiple independent dnCDK5 MIAPaCa-2 clones (Fig. 6A) and significantly “rescued” the phenotype of anchorage-independent growth, compared with vector-transfected dnCDK5 clones (Fig. 6B and C). Of note, in vivo tumorigenicity was also partially rescued, as shown using subcutaneous xenografts. Although vector-transfected CDK5dn-expressing MIAPaCa-2 cells (“MIAPaCa-2-CDK5dn1-control”) formed xenografts in only 2 of 7 (29%) mice, MIAPaCa-2-CDK5dn1-Rgl2-CAAX cells formed xenografts in 7 of 7 (100%) mice (Fig. 6). Thus, our results place CDK5 as an essential signaling intermediate in the Ral effector pathway, downstream of oncogenic Ras. The precise mechanism by which CDK5 modulates Ral activation remains a matter of investigation; nonetheless, this result indicates that CDK5 inhibition blocks the malignant properties of pancreatic cancer cells by disrupting an obligate Ras-CDK5-Ral signaling axis.

Figure 5. Genetic or pharmacologic blockade of CDK5 function is associated with Ral pathway inhibition in multiple KRAS2 mutant pancreatic cancer cells. A, reduction in the endogenous level of activated RalA-GTP, RalB-GTP, Rho-GTP, and Rac-GTP was observed in MIAPaCa-2 cells expressing dnCDK5 compared with vector-transfected cells. B, RalA and RalB activation assays of six KRAS2 mutant pancreatic cancer cell lines transfected with CDK5shRNA (c) compared with vector-only transfected controls (v) confirms the downregulation of the active GTP-bound protein in five of six cell lines, with Pa03C being the exception. C, RalA and RalB activation assays in a subset of three pancreatic cancer cell lines treated with roscovitine in vitro for 30 min compared with DMSO-treated cells shows the reduction of GTP-bound RalA in all three cell lines and the reduction of GTP-bound RalB in two of three cell lines.

Blockade of Ral effector function through CDK5 inhibition cooperates with inhibition of RAF/mitogen-activated protein/extracellular signal-regulated kinase kinase/extracellular signal-regulated kinase and phosphoinositide 3-kinase/Akt pathways in limiting pancreatic cancer growth

Although the Ral signaling pathway is critical for Ras-driven human tumorigenesis, other Ras effector pathways, including the RAF/mitogen-activated protein/extracellular signal-regulated kinase (ERK) kinase (MEK)/ERK and phosphoinositide 3-kinase (PI3K)/Akt pathways, also are important in human cancer (Supplementary Fig. S7A; ref. 26). In pancreatic cancer cells, it has been shown that inhibitors of the Ras effector pathways RAF/MEK/ERK and PI3K/Akt could induce G0-G1 cell cycle arrest and, in some instances, apoptosis (27, 28). Therefore, we reasoned that inhibition of the Ral pathway, through the blockage of CDK5 activity, in combination with inhibition of either the RAF/MEK/ERK or PI3K/Akt pathway, might result in a more pronounced effect on the transformed properties of Ras-driven pancreatic cancer cells. To test this possibility, we compared the effect of the MEK inhibitor U0126 and the PI3K inhibitor LY294002 in MIAPaCa-2 cells containing the previously described dnCDK5 for inhibition of CDK5, or vector-only control cells. The combination of either small-molecule antagonist at 10 μmol/L concentration with CDK5 inhibition resulted in marked decrease in anchorage-independent growth compared with blockade of any one Ras effector pathway alone. This effect was even more accentuated when all three major downstream effectors of Ras were inhibited simultaneously, with essentially no visible colony formation in soft agar (Supplementary Fig. S7B and C). Similar results were obtained when the Raf inhibitor sorafenib was used instead of U0126 to block signaling through the RAF/MEK/ERK axis (Supplementary Fig. S8). Thus, Raf inhibition mediated by CDK5 blockage seems to cooperate with blockade of other Ras effector pathways, further reiterating its potential as a bona fide therapeutic target in pancreatic cancer.

Discussion

In the current study, we show that inhibition of CDK5 results in the suppression of cancer growth and metastatic
progression in preclinical models of pancreatic cancer. It is noteworthy that the levels of p35 in pancreatic cancer are not uniformly higher than those in nonneoplastic pancreatic epithelial cells. In addition, enforced overexpression of p35 above the observed endogenous levels in MIAPaCa-2 cells led to slightly increased \textit{in vitro} cell migration but did not further enhance colony formation in soft agar of xenograft growth in athymic mice (data not shown). This suggests that the relative level of CDK5 activity, over some threshold, may not further increase tumorigenicity and that CDK5 activity is necessary, although not sufficient, for pancreatic tumor growth and progression.

These results have significant therapeutic implications for this almost uniformly lethal disease. The potential for therapeutic application is especially relevant to pancreatic cancer because our data indicate that CDK5 signaling is critical for Ras signaling through the Ral pathway, which has emerged as an important determinant of the malignant phenotype in pancreatic cancer cells (12, 13). The Ras pathway is activated by \textit{KRAS2} gene mutations in >90% of cases of pancreatic cancer (14) and \textit{KRAS2} mutations are among the earliest genetic aberrations observed in low-grade PanIN lesions during the multistep progression model leading to fully invasive pancreatic cancer (29). The striking frequency and early onset of this mutation strongly indicate that Ras signaling is central to the malignant phenotype in pancreatic cancer and identify Ras as a prime therapeutic target in this disease. Indeed, in preclinical studies, disruption of \textit{KRAS2} function through RNAi, antisense DNA, or expression of dominant-negative \textit{KRAS}N17 attenuates the tumorigenicity of PDAC cell lines (30–32). Unfortunately, strategies to inhibit the Ras pathway directly in patients have been largely unsuccessful, as exemplified by the lack of clinical activity of farnesyltransferase inhibitors, which interfere with critical posttranslational modification of RAS proteins (33). Similarly, targeting downstream effectors of the Ras pathway has not yet been therapeutically effective (reviewed in ref. 34). In this context, one may speculate that inhibition of specific Ras effector pathways may

**Figure 6.** Overexpression of Rgl2-CAAX partially rescues the phenotype of anchorage-independent growth and tumorigenicity in CDK5-dn MIAPaCa-2 cells. A, enforced expression of Rgl2-CAAX restored GTP-bound RalA protein levels in MIAPaCa-2 clones with blockade of endogenous CDK5 function (dn1 and dn2). B and C, restoration of RalA activity was associated with rescue of the anchorage-independent growth phenotype in both dnCDK5 clones, compared with vector-transfected cells. D, \textit{in vivo} tumorigenicity was also partially rescued as observed in murine xenograft experiments.
be ineffective because either (a) the specific targeted pathways are not critical for pancreatic cancer or (b) the multiple signal transduction pathways activated by Ras provide some redundancy, necessitating simultaneous inhibition of more than one effector pathway.

Given the impediments in therapeutic targeting of Ras effector pathways, our finding that CDK5 activity is required for Ral activation may be quite significant for pancreatic cancer. In prior reports by Counter and colleagues (12, 13), inhibition of RalA signaling resulted in the abrogation of the malignant phenotype in KRAS2-mutant pancreatic cancer cell lines, whereas downregulation of RalB inhibited experimental (tail vein injection) metastasis. These findings underscore the Ral pathway as an important therapeutic target for pancreatic cancer. Nevertheless, like other GTP-binding proteins in the Ras family, Ral has been difficult to inhibit, although there has been recent progress in use of a geranylgeranyltransferase inhibitor in vitro for blocking Ral membrane localization (35). Our data, showing that CDK5 inactivation results in the inhibition of Ral activation, identify a facile, druggable kinase target to access this important effector arm of the Ras signal transduction pathway. Inhibition of CDK5 function alone in pancreatic cancer cells is sufficient to abrogate the activation of both Ral proteins, which may account for the observed phenotype of decreased tumorigenicity (through RalA inhibition) as well as reduced systemic metastases (through the RalB effector). Further, our experiments using CDK5 inactivation in combination with the inhibition of other Ras effector pathways (Supplementary Figs. S7 and S8) suggest that such a combination strategy may be especially effective in pancreatic cancer. It is significant that CDK5 inhibitors are already in pharmaceutical development (36, 37), in part because CDK5 has been considered a potential therapeutic target for neurodegenerative diseases (reviewed in refs. 38, 39); therefore, development of CDK5 as a therapeutic target for pancreatic cancer could be relatively rapid.

The molecular mechanism by which CDK5 activity regulates Ral activation will be a fascinating focus of future study. As is the case for other GTP-binding proteins in the Ras superfamily, the level of Ral activation corresponds to the level of GTP occupancy of the Ral proteins, which is proximally controlled by the action of guanine nucleotide exchange factors (RalGEFs, which load GTP) and GTPase-activating proteins (RalGAPs, which promote GTP hydrolysis to GDP). There are five known RalGEFs; in contrast, although RalGAP activity has been detected in cells (40, 41), a specific RalGAP has only recently been identified (42). Activated Ras can activate Ral by recruiting RalGEFs to the cell membrane, where their nucleotide exchange function is activated allosterically (43). One may envision, for example, that CDK5 may participate in the activation of Ral by direct phosphorylation of Ral or a RalGEF, or indirectly, by phosphorylating an interacting protein, thus promoting guanine nucleotide exchange or inhibiting GTPase activity. Alternatively, CDK5 may phosphorylate or otherwise deactivate a RalGAP or interacting protein, inhibiting Ral GTPase activity and increasing GTP occupancy. Control of other GEFs and GAPs by such phosphorylation events has been extensively documented (reviewed in ref. 44). CDK5 itself has been reported to regulate the activity of modulating factors for other GTP-binding proteins by direct phosphorylation of the GEF RasGRF2 (45), release from sequestration of RhoGDI (46), or increased expression of RhoGAP (47), further suggesting that such mechanisms may underlie CDK5 regulation of Ral.

In summary, we show that the inhibition of CDK5 activity antagonizes tumorigenic and metastatic properties of pancreatic cancer cells. CDK5 seems to inhibit Ras signaling in these cells, blocking the critical Ral effector arm of the Ras signal transduction pathway. Mutated Ras is central to tumorigenesis in the overwhelming majority of cases of pancreatic cancer and, therefore, has been considered a prime therapeutic target for this disease. Unfortunately, both Ras and Ral have been virtually intractable therapeutically. Our demonstration that CDK5 activity is necessary for Ras pathway signaling and tumorigenic behavior in pancreatic cancer provides optimism that selective kinase inhibitors of CDK5 may finally allow us to successfully address Ras as a therapeutic target in pancreatic cancer.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Grant Support

NIH R01CA134767 (B.D. Nelkin and A. Mishra); NIH R01 CA085567 and grants from the Flight Attendant Medical Research Foundation and the National Pancreas Foundation (B.D. Nelkin); the Sol Goldman Pancreatic Cancer Research Center, the Michael Rolfe Foundation for Pancreatic Cancer Research, and NIH R01CA13669 (A. Maitra); and in part by BONFOR grant number 0-111.0001.2 (G. Feldmann).

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Received 03/25/2009; revised 03/30/2010; accepted 03/30/2010; published OnlineFirst 05/18/2010.

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Cancer Res 2010;70:4460-4469. Published OnlineFirst May 18, 2010.

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