MicroRNA-205 Inhibits Src-Mediated Oncogenic Pathways in Renal Cancer

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Abstract

The Src family of protein kinases (SFK) plays key roles in regulating fundamental cellular processes, including cell growth, differentiation, cell shape, migration, and survival, and specialized cell signals in various malignancies. The pleiotropic functions of SFKs in cancer make them promising targets for intervention. Here, we sought to investigate the role of microRNA-205 (miR-205) in inhibition of Src-mediated oncogenic pathways in renal cancer. We report that expression of miR-205 was significantly suppressed in renal cancer cell lines and tumors when compared with normal tissues and a nonmalignant cell line and is correlated inversely with the expression of SFKs. miR-205 significantly suppressed the luciferase activity of reporter plasmids containing the 3′-UTR (untranslated region) sequences complementary to either Src, Lyn, or Yes, which was abolished by mutations in these 3′-UTR regions. Overexpression of miR-205 in A498 cells reduced Src, Lyn, and Yes expression, both at mRNA and protein levels. Proliferation of renal cancer cells was suppressed by miR-205, mediated by the phospho-Src–regulated ERK1/2 pathway. Cell motility factor FAK (focal adhesion kinase) and STAT3 activation were also inhibited by miR-205. Transient and stable overexpression of miR-205 in A498 cells resulted in induction of G0/G1 cell-cycle arrest and apoptosis, as indicated by decreased levels of cyclin D1 and c-Myc, suppressed cell proliferation, colony formation, migration, and invasion in renal cancer cells. miR-205 also inhibited tumor cell growth in vivo. This is the first study showing that miR-205 inhibits proto-oncogenic SFKs, indicating a therapeutic potential of miR-205 in the treatment of renal cancer. Cancer Res; 71(7): 1–11. ©2011 AACR.

Introduction

The Src family of kinases (SFK) are prototypical modular signaling proteins and the largest family of nonreceptor protein tyrosine kinases (1–3). They have been shown to be upregulated in multiple types of human tumors, with Src activity increasing proportionally to the progressive stages of the disease (1, 4). Of the 9 family members, c-Src, Fyn, and Yes are widely expressed in tissues and seem to play an important role in the regulation of cell adhesion, cell growth, and differentiation (5). Among the SFKs, Src itself is most frequently implicated in human cancer, and previous studies have shown that in mouse models, Src activation is associated with progression and metastasis in pancreatic (6) and colorectal (7) carcinomas. In prostate cancer cells in vitro, inhibition of SFKs decreases proliferation (8) and, more profoundly, invasion and migration (9); the latter through selective inhibition of phosphorylation of Src substrates such as focal adhesion kinase (FAK) and Crk-associated substrate (10). In renal cancer, Src has been shown to contribute to the appearance of malignant phenotypes, particularly due to the resistance against apoptosis by Bcl-xl and angiogenesis stimulated by Src-STAT3-VEGF signaling (11). The pleiotropic effects of Src activity are due to the multiple signal pathways engaged by Src and its accompanying kinases. Src can channel phosphorylation signals through Ras/Raf/extracellular signal-regulated kinase 1/2 (ERK1/2) and in certain cells, phosphatidylinositol 3-kinase (PI3K)/AKT, pathways. Somewhat selective to SFKs is the activation of phosphorylation of Src substrates such as focal adhesion kinase (FAK) and Crk-associated substrate (10). In renal cancer, Src has been shown to contribute to the appearance of malignant phenotypes, particularly due to the resistance against apoptosis by Bcl-xl and angiogenesis stimulated by Src-STAT3-VEGF signaling (11). The pleiotropic effects of Src activity are due to the multiple signal pathways engaged by Src and its accompanying kinases. Src can channel phosphorylation signals through Ras/Raf/extracellular signal-regulated kinase 1/2 (ERK1/2) and in certain cells, phosphatidylinositol 3-kinase (PI3K)/AKT, pathways. Somewhat selective to SFKs is their ability to activate STAT3 and β-catenin, which leads to the activation of c-Myc (12, 13) and, consequently, cyclin D1 (14, 15). Overall, these studies suggest that Src plays pleiotropic roles in cancer, often in a cell-dependent manner, and that Src is a promising target for intervention. Here, we provide the first demonstration that inhibition of SFKs can be effectively achieved by microRNA-205 (miR-205) in renal cancer.

Renal cell carcinoma (RCC) is the seventh most common cancer in the United States and was predicted to result in nearly 13,000 deaths in 2009 (16). Surgery is the first line of treatment with successful resection, often resulting in...
long-term disease-free status. Although the overall survival rate is more than 60% over 5 years (16), approximately 30% of patients who have a diagnosis of localized RCC develop metastatic recurrence (17). These patients have a very poor prognosis because of the refractory nature of RCC to current treatment regimens. Therefore, there has been much interest in the identification of biomarkers for RCC to better predict cancer development and prognosis.

miRNAs are small, noncoding RNAs that have been found to regulate expression through targeted repression of gene transcription and translation. These endogenous silencing RNAs have been shown to play important roles in development and differentiation (18, 19), cellular stress responses (20), and cancer (21). Specific subsets of miRNAs have also been shown to be dysregulated in various solid tumors (22, 23). Because of their tremendous regulatory potential and tissue- and disease-specific expression patterns (24, 25), there is increasing evidence that miRNA expression profiles could be indicative of disease risk and burden. Thus, miRNAs are being assessed as possible biomarkers to aid in the diagnosis and prognosis of different cancers (26, 27). Here, we report that miR-205 is significantly downregulated in renal cancer tissue samples and cell lines. In addition, we examined the consequences of miR-205 overexpression and identified the SFKs as direct targets of miR-205 in renal cancer.

Materials and Methods

Cell culture, plasmids, and transfection

Human RCC cell lines A498, ACHN, Caki-1, and 769-P and a nonmalignant renal cell line HK-2 were obtained from the American Type Culture Collection (ATCC) and grown according to the ATCC protocol (28). Plasmids pEZxmRNA 3'UTR (untranslated region) target expression clones for Src (HmiT017696-MT01), Lyn (HmiT010935-MT01), Yes (HmiT018569-MT01), and miRNASelect pEP-miR Null control vector (pEP Null), and miRNASelect pEP-hsa-miR-205 expression vector (pEP miR-205; Cell Bioscience) were purchased. TaqMan probes for hsa-miR-205 and miRNASelect pEP-hsa-miR-205 expression vector (pEP miR-205; Cell Biosciences Inc.) were purchased.免疫

Quantitative real-time PCR

Tissue samples from radical nephrectomy were obtained from the Veterans Affairs Medical Center, San Francisco, CA. Total RNA was extracted and assayed for mature miRNAs and miRNAs, using the TaqMan MicroRNA Assays and Gene Expression Assays, respectively, in accordance with the manufacturer's instructions (Applied Biosystems). All real time reactions were run in a 7500 Fast Real Time PCR System (Applied Biosystems). Relative expression was calculated using the comparative Ct.

Flow cytometry, cell viability, migratory, clonability, and invasion assays

Fluorescence-activated cell-sorting (FACS) analysis for cell cycle and apoptosis was done 72 hours posttransfection, using nuclear stain DAPI (4',6-diamidino-2-phenylindole) for cell-cycle analysis or Annexin V-FITC/7-AAD Kit (Beckman Coulter, Inc.) for apoptosis analysis, according to the manufacturer's protocol. Cell viability was determined at 24, 48, and 72 hours by using the CellTiter 96 AQueous One Solution Cell Proliferation Assay Kit (Promega), according to the manufacturer's protocol. For colony formation assay, cells were seeded at low density (1,000 cells/plate or 200 cells/plate) and allowed to grow till visible colonies appeared. Then, cells were stained with Giemsa, and colonies were counted. An artificial "wound" was created on a confluent cell monolayer, and photographs were taken after 24 hours for migration assay. Also, a cytoselect 24-well cell migration and invasion assay kit (Cell Biolabs, Inc.) was used for migration and invasion assays, according to manufacturer's protocol.

Immunoblotting

Immunoblotting was done as described previously (29). Briefly, protein was isolated from 70% to 80% confluent cultured cells, using the M-PERMammalian Protein Extraction Reagent (Pierce Biotechnology), following the manufacturer's directions. Equal amounts of protein were resolved on 4% to 20% SDS polyacrylamide gels and transferred to nitrocellulose membrane. The resulting blots were blocked with 5% nonfat dry milk and probed with antibodies. All antibodies were obtained from Cell Signaling Technology, Inc., except c-Myc and cyclin D1, which were purchased from BD Pharmingen (BD Biosciences). Blots were visualized using enhanced cheluminescence (Pierce Biotechnology).

Luciferase assays

The Src, Lyn, Yes, Lck, and control vectors were purchased from GeneCopoeia and named as Src-3'UTR, Lyn-3'UTR, Yes-3'UTR, Lck-3'UTR, and empty vector, respectively. Mutated 3'UTR sequences of Src, Lyn, and Yes complementary to miR-205 were cloned and named Src-Mut, Lyn-Mut, and Yes-Mut, respectively. For reporter assays, cells were transiently transfected with wild-type or mutant reporter plasmid and miR-205 or control-miR. Firefly luciferase activities were measured by using the Dual Luciferase Assay (Promega) 24 hours after transfection and the results were normalized with Renilla luciferase. Each reporter plasmid was transfected at least 3 times (on different days), and each sample was assayed in triplicate.

Stable cell generation and in vivo study

A498 cells were transfected with pEP Null vector and pEP miR-205 vector (Cell Biolabs) and selected with puromycin (1 μg/mL). pEP miR-205 vector was labeled with red fluorescent protein. After transfection, cells were observed under a microscope to check for red fluorescence and then selected with a
cell sorter (BD FACSaria II; BD Biosciences). The sorted cells were grown in puromycin and real-time quantitative PCR (qRT-PCR) was done to check the expression of miR-205. For in vivo studies, $5 \times 10^6$ cells were injected into nude mice subcutaneously and tumor growth was followed for 28 days. We also looked at the antitumor effects of miR-205 by local administration in established tumors. Each mouse was injected with $7.5 \times 10^6$ cancer cells. Once palpable tumors developed (average volume = 80 mm$^3$), 6.25 μg of synthetic miRNA complexed with 1.6 μL siPORT Amine transfection reagent (Ambion) in 50 μL PBS was delivered 7 times intratumorally in 3-day intervals. Tumor growth was followed for 21 days from first injection. All animal care was in accordance with the institutional guidelines.

**Statistical analysis**

All quantified data represent an average of at least triplicate samples or as indicated. Error bars represent SD of the mean. Statistical significance was determined by the Student’s t test and 2-tailed $P$ values less than 0.05 were considered significant.

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**Results**

**miR-205 is downregulated in renal carcinoma, and its expression is inversely correlated with that of SFKs**

Preliminary microarray data revealed that miR-205 was highly downregulated in renal cancer cell lines compared with the nonmalignant HK-2 cell line (data not shown). We validated the microarray data by miRNA qRT-PCR (miR qRT-PCR) analysis and results confirmed that miR-205 was downregulated in all the cancer cell lines (Fig. 1A). To examine the clinical relevance of miR-205, its expression was analyzed in carcinoma and normal renal tissue samples. Patients and tumor characteristics are summarized in Supplementary Table S1. Almost all carcinoma samples showed significant downregulation of miR-205 expression with respect to the normal samples, and an overall lower relative average expression was observed in carcinoma than in normal samples (Fig. 1B). These results suggest a potential tumor suppressor role for miR-205 in renal carcinoma. To identify the potential targets of miR-205, we used different algorithms that predict the mRNA targets of a miRNA: miRanda (30), miRNA target Figure 1. miR-205 expression is downregulated in renal cancer and inversely correlated with expression of Src, Lyn, and Yes. A, qRT-PCR analysis of miR-205 expression levels in renal cancer and nonmalignant cell lines. B, miR-205 expression in a cohort of renal cancer and normal tissue samples. C, the miR-205 seed sequence is complementary to the 3'-UTR of Src, Lyn, and Yes. D and E, Src, Lyn, and Yes mRNA and protein expression in human renal cancer and nonmalignant cell lines. GAPDH, glyceraldehyde 3-phosphate dehydrogenase; *, $P < 0.05$.

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predictions (31), TargetScan (32), and PicTar (33). Among the list of potential targets of miR-205 were mRNAs encoding the SFKs Src, Lyn, Yes, and Lck. The seed sequence of miR-205 was complementary to the 3′-UTR of these genes (Fig. 1C). To investigate the correlation between expression of miR-205 and that of Src, Lyn, and Yes, we measured expression of Src, Lyn, and Yes at the mRNA and protein levels in the same panel of cell lines and in individual sets of 12 pairs of tissue samples (Supplementary Fig. S1). The mRNA and protein expression levels of these genes were higher than the nonmalignant cell line (Fig. 1D and E), although the absolute level of expression varied among different cell lines. The relative miR-205 expression was higher in the normal tissue samples than in paired tumor samples, whereas the mRNA expression of Src, Lyn, and Yes was higher in tumors than in their normal samples (Supplementary Fig. S1). These data clearly showed an inverse correlation between the expression of miR-205 and that of Src, Lyn, and Yes in renal cancer, suggesting that these genes are targets of miR-205.

**The Src family members are direct targets of miR-205**

We investigated whether the 3′-UTR of Src, Lyn, Yes, and Lck are functional targets of miR-205 in renal cancer. Transient transfection of human A498 cancer cells with Src, Lyn, and Yes 3′-UTR plasmids along with miR-205 led to a significant decrease in relative luciferase units when compared with empty vector and Cont-miR or empty vector and miR-205 (Fig. 2A–D). No significant difference was observed in the case of Lck-3′-UTR (data not shown). The luciferase activity of the reporter vectors containing a mutated 3′-UTR of the respective genes was unaffected by miR-205 (Fig. 2A–D). These results indicate that members of the SFKs Src, Lyn, and Yes (but not Lck) are direct targets of miR-205 in renal cancer.

**miR-205 suppresses Src family members and negatively regulates the Ras/Raf/ERK1/2 pathway in renal carcinoma**

We then determined whether the overexpression of miR-205 could regulate the levels of Src, Lyn, and Yes mRNA or protein and alter downstream signaling events. A498 cells were transfected with miR-205, resulting in miR-205 overexpression as determined by miR qRT-PCR analysis (Fig. 3A). miR-205 transient transfection significantly downregulated Src, Lyn, and Yes at the mRNA level (Fig. 3B). Western blot analysis also confirmed the downregulation of these genes at the protein level with miR-205 overexpression (Fig. 3C). These results support the notion that miR-205 binds to the 3′-UTR of these genes and regulates their expression. Src family kinases have been shown to be upregulated in multiple types of human tumors. c-Src itself is widely expressed in tissues and plays an important role in the regulation of cell adhesion, cell growth, and differentiation (5). It is frequently implicated in human cancer, and previous studies have shown that, in mouse models, Src activation is associated with pancreatic cancer progression and metastasis (6, 34). Therefore, we analyzed its role in response to miR-205 overexpression. Src has been reported to channel phosphorylation signals through the Ras/Raf/ERK1/2 (35). Src also activates STAT3, a Src target and key transcriptional factors of c-Myc and cyclin D1 (36, 37), which leads to their activation (12, 13, 38). Inhibition of Src has...
been found to inhibit cancer cell proliferation (8), invasion, and migration (9); the latter through selective inhibition of phosphorylation of Src substrates such as FAK and Crk-associated substrate (10). To determine whether these effectors are affected by miR-205–mediated suppression of Src, A498 cells were transfected with miR-205 or Cont-miR. Western blot analysis showed reduced levels of the members of the phospho-ERK1/2 pathway, phospho-STAT3, phospho-FAK, c-Myc and a decrease in phospho-FAK in miR-205–transfected A498 cells. E, relative miR-205 expression in anti–miR-205 transiently transfected A498 cells. F, Western blot and qRT-PCR analysis showing that Src, Lyn, and Yes expression was rescued in cells transfected with anti–miR-205. MAPK, mitogen activated protein kinase; MEK, MAP/ERK kinase; GAPDH, glyceraldehyde 3-phosphate dehydrogenase.

Figure 3. miR-205 suppresses Src, Lyn, and Yes expression and regulates the ERK1/2 pathway. A, relative miR-205 expression level. B and C, qRT-PCR and Western blot analysis showing decreased Src, Lyn, and Yes expression. D, Western analysis showing a decrease in the ERK1/2 pathway, cyclin D1, and c-Myc and a decrease in phospho-STAT3 and FAK in miR-205–transfected A498 cells. E, relative miR-205 expression in anti–miR-205 transiently transfected A498 cells. F, Western blot and qRT-PCR analysis showing that Src, Lyn, and Yes expression was rescued in cells transfected with anti–miR-205.

miR-205 induces apoptosis, cell-cycle arrest, impairs cell viability, migratory, clonability, and invasive properties of renal cancer cells

Because Src has been reported to be involved in cancer cell proliferation (8), invasion, and migration (9), we sought to determine whether downregulation of Src by miR-205 has effect on the cell cycle, viability, migratory, or invasion properties of A498 cancer cells. A significant decrease in cell proliferation was observed over time in A498 cells expressing miR-205 (Fig. 4A) as compared with cells expressing Cont-miR. The miR-205–transfected cells also had low colony formation ability, as both the size and number of foci in miR-205–expressing cells were suppressed when compared with Cont-miR–expressing cells (Fig. 4B). To determine whether miR-205 affects renal cancer cell migration or invasiveness, wound healing, migration, and invasion assays were conducted. miR-205–overexpressing A498 cells were less proficient than Cont-miR–transfected cells in closing an artificial wound created over a confluent monolayer (Fig. 4C). Less absorbance was observed at 560 nm with miR-205–transfected cells.
cells than Cont-miR–transfected cells in the migration assay (Fig. 4C). miR-205 overexpression also significantly reduced the invasiveness of A498 cells (Fig. 4D). FACS analysis revealed that reexpression of miR-205 leads to a significant increase (10% ± 3%) in the number of cells in the G0/G1 phase of the cell cycle whereas the S-phase population decreased from 15% ± 4% to 5% ± 3%, suggesting that miR-205 causes a G0/G1 arrest in miR-205–transfected A498 cells compared with a nonspecific miRNA control (Cont-miR; Fig. 4E). FACS analysis for apoptosis was conducted using Annexin V-FITC–7-AAD dye. The percentage of total apoptotic cells (early apoptotic + apoptotic) was significantly increased (14% ± 3%) in response to miR-205 transfection compared with Cont-miR (4% ± 2%), with a corresponding 10% ± 4% decrease in the viable cell population (Fig. 4F). All the functional assays were confirmed in the 769-P cell line, which is from the same tumor type as A498 cells, and the results were consistent (Supplementary Fig. S2). These results indicate that suppression of phospho-Src by miR-205 inhibits renal cell proliferation, invasion, and migration by inhibiting phosphorylation of FAK, a Src substrate, c-Myc, a Src target gene (39), and cyclin D1, the rate limiting factor for cellular proliferation (40, 41).

**Src inhibition by siRNA mimics miR-205 reconstitution in renal cancer and attenuation of miR-205 in nonmalignant cells increases proliferation, migration, and invasion**

Phenocopy experiments inhibiting Src expression by siRNA were also conducted (Fig. 5). We initially tested 3 siRNAs to achieve 80% to 90% Src gene knockdown and confirmed the results at the mRNA and protein levels (Fig. 5A). Then we selected one siRNA (S-1) for further experiments. Our results showed that siRNA inhibition of Src caused decreased cell viability (Fig. 5B), migratory, and invasive (Fig. 5C) capability of A498 cancer cells. We also observed a G0/G1 cell-cycle arrest (14%), whereas there was a decrease of 11% in S-phase cell population (Fig. 5D). Almost 5% of the cells were in the apoptotic fraction in Src siRNA–transfected cells compared with the control. These results are consistent with previous findings that Src expression in nonmalignant cells increases proliferation, migration, and invasion.

**Figure 4.** Transient transfection of miR-205 inhibits renal cancer cell proliferation, colony formation, migration, and invasion and induces apoptosis and cell-cycle arrest in A498 cells. A, proliferation of A498 cells after miR-205 transfection was significantly reduced compared with Cont-miR. B, miR-205 overexpression significantly inhibits colony formation of A498 cells. C, wound healing and migration assays of A498 cells transfected with miR-205. D, invasion assay shows a significant decrease in the number of invading A498 cells transfected with miR-205. E, cell-cycle analysis showing an increase in the G0/G1 phase of A498 cells overexpressing miR-205. F, apoptosis assay showing induction of apoptosis by miR-205. *, *P < 0.05.
with nonspecific control (Fig. 5D). These results provide evidence that inhibition of Src by miR-205 reconstitution is responsible for the observed phenotype in renal cancer cells. We also knocked down the expression of miR-205 in HK-2 cells that expressed high levels of miR-205 (Fig. 6A) and determined its effect on cell growth, migration, and invasion. Our results showed that cells transfected with anti-miR-205 showed increased proliferation (Fig. 6B), migration (Fig. 6C), and invasion (Fig. 6D) compared with control anti-miRNA. These results show that miR-205 is an important tumor suppressor...
miRNA in renal cancer and attenuation of this miRNA in overexpressing nonmalignant renal cells increases their proliferative, migratory, and invasive capability.

**miR-205 inhibits tumor growth in vivo**

The antitumor effect of miR-205 stably transfected in A498 cells was determined by carrying out phenocopy experiments *in vitro* (Supplementary Fig. S3) and confirmed by *in vivo* experiments. Stable overexpression of miR-205 dramatically suppressed tumor growth *in vivo* on subcutaneous injection into nude mice when compared with cells expressing control vector (Fig. 7A). We further checked the expression of miR-205 or Src, Lyn, and Yes in 8 harvested tumors, 4 from pEP Null control group, and 4 from pEP miR-205 group. Our results showed that miR-205 expression was significantly high, with a corresponding significant decrease in the target gene expression in tumors that had pEP miR-205 compared with the pEP Null control (Supplementary Fig. S4A and B). Because over-expression of miR-205 inhibited cell growth *in vitro*, we conducted an additional experiment to check the antitumor effect of miR-205 after local administration in established A498 tumors. Indeed, the tumor volume regressed from 81 to 5 mm³ with miR-205 compared with Cont-miR, in which tumor volume increased from 80 to 306 mm³ (Fig. 7B). These results show that miR-205 suppressed cancer growth both *in vitro* and *in vivo*.

**Discussion**

In this study, we provide evidence that miR-205 interdicts SFK pathways by inhibiting their expression at both the mRNA and protein levels. Our results show that Src inhibition by miR-205 leads to growth suppression and cell-cycle arrest in renal cancer and are accompanied by inactivation of ERK1/2 and downregulation of c-Myc and cyclin D1. FAK and STAT3 phosphorylation were also decreased by diminished Src...
activity, leading to significantly reduced cell migration and invasion.

Expression of miR-205 in cancer is controversial because it has been found to be either upregulated (42) or downregulated (43) in tumors. In this study, we examined the expression pattern and functional significance of miR-205 in renal cancer. We found miR-205 to be significantly downregulated in tumor samples when compared with adjacent normal samples. The downregulation of miR-205 expression was also observed in RCC cell lines when compared with a nonmalignant cell line. This is consistent with a previous microarray analysis of 27 samples of kidney cancer tissues that showed downregulation of miR-205 (42). The significant suppression of miR-205 expression in tumors and cancer cell lines suggests a tumor suppressor role in renal carcinoma. However, neither the functional role nor the targets of miR-205 in renal cancer have been previously defined.

An obstacle to understanding miRNA function has been the relative lack of experimentally validated targets. To determine potential targets of miR-205 action, several in silico algorithms were utilized to identify SFKs as putative targets of miR-205. The SFKs play an important role in the regulation of cellular proliferation and cell-cycle progression (5). Our results indicate an inverse correlation between expression of miR-205 and that of phospho-Src, Lyn, and Yes in cell lines and tissues samples. We showed that miR-205 directly targets the 3′-UTR of phospho-Src, Lyn, and Yes, as its overexpression was associated with suppression of luciferase activity. In addition, a significant downregulation of phospho-Src, Lyn, and Yes protein and miRNA levels was observed after miR-205 overexpression, indicating that phospho-Src, Lyn, and Yes mRNAs are targets of miR-205.

Because of the reported importance of phospho-Src in renal cancer (11), we further characterized its role in response to miR-205. It has been reported that Src is involved in multiple signaling pathways including Ras/Raf/ERK1/2, PI3K/AKT, β-catenin/c-Myc/cyclin D1, and FAK/p130CAS/MMP-9 that induce growth, survival, and migration in various types of cancer cells (35). We observed that inhibition of phospho-Src by miR-205 overexpression reduced signaling via the ERK1/2 pathway. A previous study by Chang and colleagues (35) and others (44) have shown that Src inhibition by small molecule inhibitors induced apoptosis and cell-cycle arrest at the G0/G1 phase of the cell cycle in prostate cancer cell lines. Our results revealed that inhibition of phospho-Src by miR-205 overexpression induced apoptosis and G0/G1 arrest in renal cancer cells. This effect on the cell cycle prompted us to study the effect on c-Myc, a Src target gene (39), cyclin D1, the rate limiting factor for cellular proliferation (41), and phospho-STAT3, a Src target and key transcriptional factor for c-Myc and cyclin D1 (37). We found that all these genes were downregulated at the protein level. Our results indicate that miR-205 inhibited renal cell migration and invasion and also downregulated phospho-FAK, a Src substrate in renal cancer.

Figure 7. miR-205 inhibits tumor growth in vivo. A, tumor volume following subcutaneous injection of stable A498 cells expressing miR-205 was significantly reduced. B, tumor volume following intratumoral injection of Cont-miR or miR-205 precursor into established tumors. *, P < 0.05.
cells. Inhibition of Src has been found to decrease the invasion and migration of prostate cancer cells (9) through selective inhibition of phosphorylation of Src substrates, such as FAK. To determine whether Src inhibition is responsible for the phenotype observed after miR-205 reconstitution, we conducted phenocopy experiments inhibiting Src expression by siRNA. Our results showed that inhibition of Src was responsible for decreased cell viability, migratory, and invasive capability of A498 cancer cells. We also observed a G0/G1 cell-cycle arrest (14%) whereas there was a decrease of 11% in S-phase cell population. Almost 5% apoptotic cells were observed in Src siRNA-transfected cells compared with nonspecific control. These results prove that tumor-suppressive effect of miR-205 is mediated by Src inhibition in renal cancer.

The antiproliferative effects of miR-205 observed in this study, mediated by suppression of phospho-Src and downstream target genes, were confirmed following stable overexpression of miR-205 in A498 cells. In vivo studies showed a striking reduction in subcutaneous tumor cell growth in mice injected with stable A498 cancer cells overexpressing miR-205. Furthermore, results from local administration of miR-205 in established tumors revealed a dramatic regression of tumor growth compared with the Cont-miR. In conclusion, our study shows an important tumor suppressor role for miR-205 in renal cancer.

The SFKs are essential for many important tumorigenic phenotypes, including proliferation, invasion, migration, epithelial-to-mesenchymal transition (5, 45), apoptosis, survival, angiogenesis, etc. Thus, the activity of SFKs increase in progressive stages of tumors, with the highest activity observed in metastatic lesions (46). Increasing evidence from molecular and pharmacologic studies suggests that inhibition of Src, the prototype SFK member, inhibits tumor function associated with metastasis, including migration, invasion, and expression of the proangiogenic molecules, such as interleukin-8 and VEGF (47). In addition, recent studies indicate that Src plays critical roles in host cells in the tumor microenvironment and the tumor cells that contribute to metastasis (4). Several studies have shown that Src-mediated phosphorylation of VE-cadherin, a cell adhesion molecule that is essential to vascular cell-to-cell junctional integrity, directly leads to increased vascular permeability, thus facilitating intravasation and extravasation of migratory tumor cells (48). Thus, Src plays pleiotropic roles in cancer, making it a promising therapeutic target for intervention. Our study is the first report showing that miR-205 inhibits the proto-oncogenic SFKs, indicating the therapeutic potential of miR-205 in the treatment of renal cancer.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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