Neuronal Pentraxin 2 Supports Clear Cell Renal Cell Carcinoma by Activating the AMPA-Selective Glutamate Receptor-4

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Abstract

Clear cell renal cell carcinoma (ccRCC) is the most common subtype of kidney cancer and has the highest propensity to manifest as metastatic disease. Recent characterizations of the genetic signature of ccRCC have revealed several factors correlated with tumor cell migration and invasion; however, the specific events driving malignancy are not well defined. Furthermore, there remains a lack of targeted therapies that result in long-term, sustainable response in patients with metastatic disease. We show here that neuronal pentraxin 2 (NPTX2) is overexpressed specifically in ccRCC primary tumors and metastases, and that it contributes to tumor cell viability and promotes cell migration through its interaction with the α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor subunit GluR4. We propose NPTX2 as a novel molecular target for therapy for patients with ccRCC diagnosed with or at risk of developing metastatic disease.

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Introduction

Renal cell carcinoma (RCC) is one of the most common solid tumors in the United States, responsible for more than 13,000 deaths annually (1). The clear cell variant (ccRCC) is the most common subtype of RCC, accounting for an estimated 80% of all patients (2). The prognosis for patients diagnosed with early-stage disease is comparatively good, with stage I patients demonstrating more than 90% and stage II patients demonstrating 63% to 95% overall survival of 5 or more years (3). Regrettably, up to 30% of early-stage cases of ccRCC treated surgically will relapse with metastatic disease likely because of the presence of undetectable micrometastases (4). In addition, 20% to 30% of all patients with ccRCC present with advanced or metastatic disease upon initial diagnosis oftentimes because of the asymptomatic nature of early-stage disease (5).

Metastatic ccRCC renders a bleak prognosis, with an estimated 5-year overall survival of less than 10% because of lack of remedial therapies that produce significant disease regression or attenuation of disease progression (6). Drug resistance is a hallmark of ccRCC and is thought to be a culmination of several intrinsic and acquired tumorigenic properties linked to cancer cell heterogeneity, including a lack of known molecular factors that can be targeted pharmacologically (7, 8). ccRCC rarely responds to chemotherapy and radiation therapies, and drug resistance develops rapidly with application of targeted therapies (8). It is also apparent that ccRCC tumor cells demonstrate a disposition for increased migratory capacity, likely a major contributing factor to the development of tumor metastasis and disease relapse. A focus on identification of therapeutically targetable molecular factors for ccRCC is paramount.

Neuronal pentraxins belong to a class of secreted proteins characterized by their pentraxin protein domain. They are related to C-reactive protein (CRP), which is a serum protein that contributes to host defense and is expressed during acute phase inflammatory responses in mammals (9). NPTX2 is homologous to neuronal pentraxin 1 (NPTX1, NP1) and neuronal pentraxin receptor (NPTXR, NPR), both of which have been characterized in nervous system tissues (10). NPTX2 has a broader expression pattern, and is observed in nervous, testicular, pancreatic, skeletal muscle, heart, and hepatic tissues (11). NPTX1 and NPTX12 form homomeric or heteromeric multimers with NPTXR, which may function to bind the pentraxins to cell membrane surfaces (12). Previous research has identified a role for neuronal pentraxin molecules in neurite outgrowth and in synaptic plasticity of neuronal cells (13). This is thought to be mediated through clustering of the AMPA family of ionotropic glutamate receptors that form ion permeable channels during the development of excitatory synapses in neuronal cells (14–17) or by facilitating uptake of synaptic material during synapse remodeling (12, 18).
Here we demonstrate an essential tumor-promoting role for NPTX2 in ccRCC. We establish NPTX2 as a stimulatory ligand that binds to the AMPA receptor subunit GluR4, which we find also to be overexpressed in ccRCC, leading to Ca\(^{2+}\) influx, actin cytoskeletal remodeling, and increased tumor cell migration. Inhibition of NPTX2 expression in ccRCC cells leads to decreased tumor cell proliferation, decreased tumor cell invasion, and induction of programmed cell death. Our results substantiate that NPTX2/GluR4 is a critical survival pathway for ccRCC and is a therapeutic candidate for patients with or at risk of developing metastatic ccRCC.

Materials and Methods

Cell lines and reagents

Human ccRCC cell lines A498, Caki1, and Caki2 were purchased from ATCC. KJ265T and RWV366T were established in the Copland laboratory as previously described (19). UMRC2 and UMRC6 cells were a kind gift from Dr. Bart Grossman (20). STR validation of all tumor cell lines was performed as previously described (19). Normal renal epithelial (NRE) cells include K347, K355, K359, RC58N, K366N, HRE152 (Copland Lab), and HK2 (ATCC). All cell lines were cultured in DMEM medium (Cellgro) containing 5% FBS (Hyclone) and 1% penicillin–streptomycin (Invitrogen) at 37°C in humidified conditions with 5% CO\(_2\). VHL mutational and deletional status were examined via DNA sequencing and multiplex ligation-dependent probe amplification, respectively. Human recombinant NPTX2 (R-NPTX2) generated in HEK293 cells was purchased from OriGene. CFM-2 was purchased from Tocris Bioscience.

Lentivirus

MISSION shRNA pLKO constructs (Sigma-Aldrich) were used to make self-inactivating shRNA lentiviruses for NPTX2 (NM_002523.1-1316s1c1, NM_002523.1-1623s1c1, NM_002523.1-804s1c1, NM_002523.1-855s1c1), GluR4 (NM_008291.1-1676s1c1, NM_008291.1-2145s1c1, NM_008291.1-2285s1c1, NM_008291.1-925s1c1), and a nontarget (NT) random scrambled sequence construct (SHC002). Lentivirus was prepared as previously described (19).

Transfections

The following plasmids were used: HA epitope-tagged human NPTX2 (pPM-hNPTX2-HA; Applied Biosystems), and Flag epitope-tagged human GluR4 (Flag-GluR4-Flip-HispcDNA3.1)—a generous gift from Dr. Kari Keinanen at the University of Helsinki, Helsinki, Finland (21).

RNA isolation and qPCR

RNA extraction was performed as previously described (22). cDNA was prepared from purified RNA samples using the High Capacity cDNA Reverse Transcriptase Kit (Applied Biosystems) per manufacturer’s instruction. TaqMan Fast Universal PCR Master Mix (Applied Biosystems) and TaqMan FAM dye-labeled probes, including NPTX2 [Hs00195591_m1], SNAI1 [Hs00195591_m1], SNAI2 [Hs00161904_m1], CTNNB1 [Hs00355049_m1], TGFbeta1 [Hs00171257_m1], SPARC [Hs00234160_m1], VIM [Hs00185584_m1], and EN1 [Hs00415006_m1] were used to perform qPCR analysis. Fold change values were compared between normal and tumor samples, NT scrambled and target lentiviral infected samples, and transfected versus empty vector (EV) controls using the ΔΔCT method (23).

Gene array analysis, pathway analysis, and database meta-analysis

GSEA was done using IPA (Ingenuity Systems). Meta-analysis was performed as previously described using NextBio data mining platform (24).

Western blot analysis

Cell protein extracts were prepared using RIPA lysis buffer containing 50 mmol/L Tris, 5 mmol/L EDTA, 150 mmol/L NaCl, 0.1% SDS, 0.5% deoxycholate, 1% NP40, protease inhibitor cocktail (Roche), and phosphatase inhibitor (Pierce). Tissue protein extracts were prepared from frozen samples using 1% SDS (Invitrogen) in 50 mmol/L pH 8.0 Tris buffer containing protease inhibitor cocktail (Roche) and phosphatase inhibitor (Pierce) with brief sonication on ice. Electrophoresis, transfer, blocking, and antibody preparations were performed as previously described (19). The following primary antibodies were included: NPTX2 (Sigma-Aldrich), PAR5 (Abcam), and β-actin (Sigma-Aldrich; A5441). GluR1 (Santa Cruz; sc-55509), GluR2 (Santa Cruz; sc-7601), p-CAMK1 (Santa Cruz; sc-373853), total CAMK1 (Abnova; AB2769), GluR3 (Cell Signaling; D47E3), PARP (Cell Signaling; 9542), HA-tag (Cell Signaling; 3272) and Flag-tag (Cell Signaling; 8146), GluR4 (Millipore; AB1508), total AKT (Cell Signaling; 2972), and p-AKT (R&D Systems; AF887). Secondary species-specific horseradish peroxidase–labeled antibodies (Jackson Immunoresearch) were applied, and Super signal Chemiluminescent Kit (Pierce) was used to perform detection.

Immunoprecipitation assay

Immunoprecipitation assay was performed using Protein G Mag Sepharose beads (GE Healthcare) according to manufacturer’s protocol using the cross-linking method. Antibodies include anti-HA (Cell Signaling; 3272) and anti-Flag (Cell Signaling; 8146). Cell protein extracts were prepared using 1% Triton X-100 (Sigma-Aldrich) in 50 mmol/L Tris pH 7.4 containing 150 mmol/L NaCl, 1 mmol/L EDTA (Promega), protease inhibitor cocktail (Roche), and phosphatase inhibitor (Pierce) on ice. Sample protein concentrations were diluted to 1 μg/mL in lysis buffer. Gel electrophoresis, membrane...
transfer, and antibody detection techniques applied are those as described in protein expression analysis above.

Immunohistochemistry and immunofluorescence
Tissue microarrays (TMA) were prepared using formalin-fixed paraffin-embedded tissue samples procured from de-identified patients. This study was approved by the Mayo Institutional Review Board. All IHC scores are reported as H scores. Imaging, staining, and analysis were performed as previously described (19) using the primary antibodies: NPTX2 (Sigma-Aldrich: PRS4573), NPTXR (R&D Systems: AF4114), and GluR4 (Millipore: AB1508). Cells were plated and fixed for immunofluorescence as previously described (19). The following primary antibodies were included: NPTX2 (Pierce; PA512289), GluR4 (Millipore; AB1508), HA-tag (Cell Signaling; 3724), and Flag-tag (Cell Signaling; 8146). Fibronectin (BD Biosciences; 610077). Fluorescently labeled, species-specific secondary antibodies (Sigma-Aldrich) were applied. Fluorescent images (×20 to ×60) were obtained using an Olympus microscope (Olympus IX71).

Cell death analysis via flow cytometry
ccRCC cell lines were infected with NT versus target NPTX2 or GluR4 shRNA lentiviral constructs overnight. Cells were selected using puromycin (Sigma) for 72 hours. Seven days after selection, both adhered and floating cells were collected with Accutase (Innovative Cell Technologies, Inc.), washed with DPBS, and suspended in 1× cold binding buffer (BD Pharmingen) at 1 × 10⁶ cells/mL. Cells were stained with propidium iodide (BD Pharmingen), and cell death analysis was performed using an Accuri C6 flow cytometer (Accuri). Unstained NT control cells were used to set population parameters.

Calcium Green-1 AM staining
ccRCC cells were plated at 1,000 cells/well in 96-well clear-bottom black plates (Corning, Inc.). Cells were washed 3× with DPBS, and Calcium Green-1 AM stain (Invitrogen) was applied at 5 μmol/L in 5% CS-FBS DPBS for 45 minutes, protected from light. Cells were washed 3× with PBS and Ca²⁺/Mg²⁺ buffer containing 135 mmol/L NaCl, 5 mmol/L KCl, 1 mmol/L each CaCl₂ and MgCl₂, 5.6 mmol/L glucose, 10 mmol/L Heps, and 0.1% BSA at pH 7.4 (25) was added with/without specified concentrations of CEM-2 and/or R-NPTX2. Fₘₐₓ: Ca²⁺/Mg²⁺ buffer with 2 μmol/L ionomycin (LC Labs) and 10 mmol/L CaCl₂, Fₘᵦ: 10 mmol/L EGTA and 10 mmol/L MgCl₂ in Ca²⁺/Mg²⁺ buffer without CaCl₂ (26). A SpectraMax M5 (Molecular Devices), set at 531 nmol/L emission and 506 nmol/L excitation at 37°C, was used to measure fluorescence at specified time points. The following formula was used to determine the free calcium concentration in each population of cells: [Ca²⁺]free = K₅₋₁(Fₘₐₓ − F)/Fₘᵦ, where the dissociation constant (K₅₋₁) for Calcium Green-1 AM is 190 nmol/L (26).

Invasion assay
Cells were starved overnight in 0.2% FBS DMEM. A total of 5,000 cells were plated (in triplicate) with 0.25% BSA in the upper chamber and 5% FBS was the attractant in the lower chamber. BD Biocat Matrigel Invasion Chambers (8-μm pore; BD Biosciences) were prepared per manufacturer’s protocol. After 20 hours, transwell inserts were fixed in 100% methanol and stained with 0.2% crystal violet/2% ethanol. Invasive cells were counted and ×10 images were obtained using an Olympus microscope (Olympus IX71).

Statistical analysis
Experimental values are presented as either percentage or fold change ± SD unless otherwise specified. Group comparisons (normal vs. tumor, NT vs. shRNA, control vs. treated, EV vs. expression vector) were analyzed using a 2-tailed paired Student t test with changes greater than 20%, where *P < 0.05 was considered statistically significant.

Results
NPTX2 expression is tumor specific and is required for ccRCC viability
Patient gene array examining normal matched ccRCC patient mRNA from stage I, II, III, and IV revealed that NPTX2 expression was significantly increased in diseased samples at every stage (n = 72 tumor and matched normal samples; GSE53757). To confirm these observations at the protein level, patient TMAs were prepared from matched normal and ccRCC tissue samples from stage I, II, III, IV (primary tumor site), and tumor metastases. Immunohistochemistry (IHC) staining for NPTX2 confirmed significantly elevated protein levels in ccRCC samples at all stages as indicated by H scores (Fig. 1A). Normal renal epithelial samples (NRE) and established ccRCC cell lines were examined for NPTX2 expression via qPCR and Western blot analysis in order to establish working models. The majority of ccRCC cell lines demonstrate elevated NPTX2 at the mRNA level (5/7) when compared with normal samples (1/4; Supplementary Fig. S1A). Western blot analysis revealed high NPTX2 protein expression in A498, Caki2, and KIJ265T, lower NPTX2 expression in RWV366T, whereas A498 and Caki1 are VHL wild type (Supplementary Fig. S1B). The data suggest that NPTX2 expression in ccRCC is not related to von Hippel Lindau (VHL) gene status.

To examine the role of NPTX2 expression in ccRCC cell proliferation and viability, four lentiviral constructs designed to target NPTX2 were prepared (sh804, sh855, sh1316, and sh1623). A498 cells infected with each construct were evaluated by qPCR and Western blot analysis for lentiviral efficacy when compared with a nontarget (NT) control (Supplementary Fig. S1C and S1D). The NPTX2 shRNA-1316 (sh1316) construct demonstrated the highest knockdown, producing an 80% decrease in mRNA levels and resultant 60% decrease in protein levels (Supplementary Fig. S1C and S1D). To validate lentiviral specificity for NPTX2, a rescue assay measuring proliferation was performed. A498 cells were transfected with an EV or a human NPTX2 expression plasmid (+NPTX2), and were subsequently infected with either the NT or sh1316
Figure 1. NPTX2 expression profile in clear cell renal cell carcinoma. A, TMA IHC of patient with ccRCC versus matched normal tissue for NPTX2 expression in stage I, II, III, IV (primary), and IV (metastatic; normal n = 44, 32, 35, 7, and 6 and tumor n = 41, 26, 33, 10, and 17, respectively). Cytoplasmic and membranous staining pattern observed. H-score ± standard deviation from the mean is shown. B, Western blot of protein lysates prepared from NRE cells and ccRCC cell lines for NPTX2 expression. Protein expression level quantitation is normalized to β-actin, and total human brain tissue lysate was used as a positive control. C, NPTX2 knockdown was evaluated in A498, KIJ265T, and Caki2 ccRCC cell lines infected with the sh1316 lentiviral construct as compared with NT controls via QPCR. D, 7-day proliferation assay of ccRCC sh1316 clones versus NT controls. E, cell death of A498, KIJ265T, and Caki2 NT versus sh1316 cell populations analyzed via flow cytometry. F, Western blot analysis for total and cleaved PARP in NT versus NPTX2 knockdown cells. Cells collected for cell death analysis (E and F) correspond to day 7 of proliferation assay (D).
lentiviral construct. sh1316 targets an intronic coding region of endogenous NPTX2 and thus does not affect recombinant NPTX2 plasmid overexpression in cells. NPTX2 overexpression was able to fully recover the proliferative capacity of A498 sh1316 cells (Supplementary Fig. S1E).

A498, KIJ265T, and Caki2 cell lines, which express high endogenous NPTX2 (Fig. 1B), were infected with the NPTX2 sh1316 construct. More than an 80% decrease in mRNA (Fig. 1C) and 60% decrease in proliferation was observed 7 days after selection in all three cell lines (Fig. 1D). To evaluate the mechanism of decreased proliferation in ccRCC sh1316 cells, cell death was examined by flow cytometry. Results yielded a significant increase in cell death of A498, KIJ265T, and Caki2 sh1316 cell populations respectively when compared with NT controls (Fig. 1E). Apoptosis was confirmed via Western blot analysis for PARP cleavage in NPTX2 knockdown cells (Fig. 1F).

We used Nextbio (24) to assess publically available gene expression datasets (Table 1), and found that NPTX2 was consistently upregulated in nine comparisons of ccRCC versus normal kidney tissue (27–35), and that NPTX2 was correlated specifically with the clear cell subtype of RCC as compared with other subtypes of RCC, including granular, papillary, and chromophobe (Table 1; refs. 36–38). We also found that NPTX2 was overexpressed in comparisons of more advanced ccRCC versus less advanced disease, including stage IV versus stage I, distant metastasis versus no metastasis, metastasis versus primary tumor, and stage II versus stage I (Table 1; refs. 35, 36, 38, and 39). We performed a gene expression meta-analysis of the 13 top ccRCC experiments (27–30, 32, 33, 36, 37, 39–41) using Nextbio and found that NPTX2 was the most consistently differentially expressed gene (Table 2), being significantly upregulated in all datasets. These data support that NPTX2 overexpression is a prevalent feature of the ccRCC genetic profile, and is the most frequently dysregulated gene in patient tumor tissues.

### NPTX2 promotes invasive phenotype in ccRCC cells

Immunofluorescence for NPTX2 demonstrates a specific protein expression pattern in which it is most abundant at the leading cell edges and protrusions of the cell membrane as seen in KIJ265T cells, which have high endogenous NPTX2 expression (Supplementary Fig. S2A; Fig. 1B). Overexpression of NPTX2 in RWV366T and Caki1 cells (+NPTX2), which have low endogenous NPTX2 (Fig. 1B) induced morphological changes consistent with reduced cell–cell adhesion and increased cell migration, including the development of membrane protrusions as compared with EV control cells (Fig. 2A). To evaluate whether NPTX2 expression is associated with actin cytoskeletal remodeling, immunofluorescence for vasodilator-stimulated phosphoprotein (VASP), an actin nucleation factor

| Table 1. Expression analysis of NPTX2 in published microarray datasets |
|------------------|------------------|------------------|------------------|
| ccRCC vs. normal kidney | Difference | Significance | Reference |
| Set 1 | 41.2 | 8.50E–05 | (27) |
| Set 2 | 33.6 | 1.10E–05 | (28) |
| Set 3 | 26.4 | 9.30E–05 | (29) |
| Set 4 | 39.2 | 0.0043 | (30) |
| Set 5 | 25.3 | 8.50E–12 | (31) |
| Set 6 | 11 | 1.60E–08 | (32) |
| Set 7 | 21 | 0.0002 | (33) |
| Set 8 | 9.35 | 0.037 | (34) |
| Set 9 | 104.8 | 0.0013 | (35) |

Specificity for NPTX2 in ccRCC vs. other RCC subtypes

| ccRCC vs. granular RCC | 8.42 | 0.0007 | (36) |
| ccRCC vs. granular RCC | 31.8 | 2.00E–09 | (37) |
| ccRCC vs. papillary RCC | 12.3 | <1.0E–323 | (36) |
| ccRCC vs. papillary RCC | 30.6 | 3.90E–10 | (37) |
| ccRCC vs. papillary RCC | 9.09 | 6.00E–19 | (38) |
| ccRCC vs. chromophobe RCC | 4.64 | 8.00E–04 | (36) |

Increased NPTX2 in more advanced ccRCC

| ccRCC stage IV vs. stage I | 6.98 | 8.00E–04 | (36) |
| ccRCC distant met vs. no met | 6.41 | 1.20E–03 | (36) |
| ccRCC met vs. primary tumor | 2 | 4.09E–02 | (39) |
| ccRCC stage II vs. stage I | 7.88 | 4.83E–01 | (35) |
| ccRCC stage II vs. stage I | 1.68 | 4.70E–03 | (38) |

NOTE: NPTX2 expression was evaluated in 9 datasets comparing normal versus ccRCC expression; datasets comparing expression of NPTX2 in the clear cell variant of RCC versus granular, papillary, and chromophobe RCC; and NPTX2 expression in various degrees of ccRCC disease progression (P < 0.05).
## Table 2. Meta-analysis of microarray data identifying commonly co-regulated genes in RCC

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**NOTE:** The following comparisons were evaluated: A, ccRCC vs. normal B, ccRCC vs. chromophobe RCC; C, ccRCC vs. granular RCC; D, ccRCC vs. papillary RCC. The top 10 most consistently differentially expressed genes in ccRCC are listed and are significantly upregulated in all datasets evaluated (P < 0.05).
Figure 2. NPTX2 modulates actin cytoskeletal remodeling and promotes invasion. A, phase-contrast microscopy of EV versus NPTX2-transfected (+ NPTX2) RWV366T and Caki1 cells, taken at ×20 magnification. Arrows highlight select membranous protrusions. Immunofluorescence of EV versus NPTX2 (HA tagged)-transfected (+NPTX2) RWV366T cells (B) and A498 cells stained for NPTX2 (left) and VASP (center; C). Images are merged in the right. Magnification (×60) of regions highlighted in ×20 images is shown. D, pathway signature of EMT/cell migration in high-NPTX2 expressing tumors identified using Ingenuity Software Analysis. (Continued on the following page.)
that localizes to areas of dynamic actin reorganization (42) was performed. In RWV366T EV control cells, VASP localizes along cell–cell boundaries (Fig. 2B). In NPTX2 overexpressing RWV366T cells, VASP demonstrates a punctate expression pattern along the cell periphery (Fig. 2B), where it colocalizes with ectopically expressed NPTX2. A498 ccRCC cells, which have high endogenous NPTX2 expression (Fig. 1B), replicate the VASP staining pattern observed in 366T NPTX2-HA cells (Fig. 2C). These results suggest that NPTX2 expression could alter actin dynamics and impair cell–cell adhesion in ccRCC cells.

Previous studies by our group have revealed that the genetic signature of ccRCC is associated with a loss of renal epithelial differentiation and increased expression of mesenchymal molecular markers (22), many of which have been previously implicated in tumor cell invasion (43). To examine the potential role of NPTX2 in ccRCC mesenchymal transformation and tumorigenesis, we initially performed pathway signature analysis. Using our ccRCC patient gene array (GSE53757), samples were sorted into high or low NPTX2 priority (Supplementary Fig. S2B) and genes whose relative transcript expression was significantly altered (where fold change expression was $\leq 0.5$ or $\geq 2$) in the high NPTX2 group as compared with the low NPTX2 group were identified. Ingenuity software was used to perform pathway analysis. The results revealed NPTX2 coregulation with a substantial number of genes associated with epithelial-to-mesenchymal transition (EMT) and cell migration (Fig. 2D). To determine whether NPTX2 regulates the expression of these genes, QPCR for several EMT markers, including CDH1, SNAIL1, SNAIL2, TGFBI, CTNNB1, SPARC, VIM, and FN1 (43), was performed in A498, KIJ265T, and Caki2 infected with either NT or sh1316 NPTX2 lentiviruses. All 3 cell lines demonstrated increased CDH1—a marker of epithelial differentiation (Fig. 2E–G), and significant decreases in the expression of mesenchymal genes, including SNAIL1, SNAIL2, TGFBI, CTNNB1, SPARC, VIM, and FN1 in A498 cells (Fig. 2E); SNAIL2 and FN1 in KIJ265T cells (Fig. 2F); and TGFBI, SPARC, VIM, and FN1 and Caki2 cells (Fig. 2G), as a result of decreased NPTX2. Immunofluorescence for fibronectin (FN1), an EMT-associated extracellular matrix protein that was previously reported to contribute to tumor cell invasiveness (44) and that also correlates with an increased mortality rate in patients with ccRCC (45), showed that A498 NT control cells exhibited high levels of both cytoplasmic and membranous fibronectin expression, and displayed numerous filopodia-like protrusions at the plasma membrane (Supplementary Fig. S2C). Fibronectin expression at the cell periphery was significantly decreased in response to NPTX2 depletion, and the number of filopodia was greatly reduced (Supplementary Fig. S2C). To test the effects of NPTX2 on invasive capabilities of ccRCC cells, invasion assays were performed. Caki1 EV cells exhibited little invasion, however when NPTX2 was overexpressed these cells demonstrated over a 10-fold increase in invasive potential (Fig. 2H). Similarly, RWV366T NPTX2 cells displayed over a 2.5-fold increase in invasive potential as compared with EV control cells (Fig. 2H). Conversely, KIJ265T and A498 sh1316 NPTX2 knockdown cells were considerably restricted in their ability to invade through the transwell inserts, with approximately a 70% decrease in KIJ265T and an 80% decrease in A498 sh1316 cells observed as compared with controls (Fig. 2I). Of note, RWV366T and Caki1 control cells demonstrated lower overall invasion when compared with KIJ265T and A498 control cells (Fig. 2H and I). Collectively, these results depict a correlation between NPTX2 expression and a migratory phenotype as well as implicate a role for NPTX2 in promoting ccRCC cell invasive capacity.

NPTX2 functions in ccRCC by binding to the AMPA receptor subunit GluR4

As NPTX2 is a secreted protein, we examined expression of the canonical receptor for NPTX2, neuronal pentraxin receptor (NPTXR) by IHC analysis, finding that ccRCC tissues demonstrate a loss of NPTXR expression when compared with matched normal kidney tissue, with very low detectable levels observed in ccRCC at any stage of disease (Fig. 3A). We then evaluated expression of the α-amino-3-hydroxy-5-methyl-4-isoxazolopropionic acid (AMPA) receptor subunits GluR1 to GluR4, as neuronal pentraxins have been previously reported to interact with this receptor complex, where it mediates clustering of AMPAR during synaptogenesis in excitatory neurons (15–17).

Gene array revealed no change in GluR1 expression between normal and ccRCC, a decrease in GluR2 and GluR3 in ccRCC samples, and a 3-fold increase in GluR4 mRNA expression in ccRCC (GSE53757). Western blot analysis of normal matched ccRCC metastatic tissue for GluR2 and GluR3 protein revealed no detectable levels in either matched normal or diseased tissue, and very low levels of GluR1 (data not shown). GluR4 demonstrated a clear pattern of elevated tumor protein expression in four of five ccRCC samples via Western blot analysis (data not shown). IHC of patient ccRCC tumor tissue stage I to IV and tumor metastasis revealed elevated GluR4 expression in ccRCC tissues as compared with normal kidney, with the highest expression observed in metastatic tissues (Fig. 3B). To establish working cell models, NRE and ccRCC cells were evaluated by QPCR and Western blot analysis for GluR4 expression. QPCR of normal and ccRCC cell lines demonstrated a similar pattern of AMPA receptor subunit expression observed in the patient gene array, with decreased expression of GluR2 and GluR3, no change in GluR1, and elevated GluR4 detected in tumor samples as compared with normal levels (Fig. 3C). Three NRE samples and four ccRCC cell lines probed for...
GluR4 expression via Western blot analysis revealed no detectable protein expression in normal cells and high expression in tumor samples with high endogenous NPTX2 expression-Ki67-positive, A498, and Caki2 (Fig. 3D). Caki1 cells that have low endogenous NPTX2 also exhibit lower GluR4 expression (Fig. 3D).

We next investigated whether GluR4 interacts directly with NPTX2 in ccRCC. Four lentiviral constructs targeting GluR4 were generated (sh925, sh1676, sh2145, sh2285), and efficacy was screened in A498 cells. The sh1676 construct yielded the most significant decrease in GluR4 mRNA and protein (Supplementary Fig. S3A and S3B), and was therefore...
used in further experimentation. Caki2 cells, which express high levels of both NPTX2 and GluR4 (Figs. 1B and 3D) were examined for the ability of NPTX2 to adhere to the cell membrane in the presence or absence of GluR4. NT control cells exhibited a distinct pattern of NPTX2 clustering at the cell membrane (Fig. 4A). In contrast, the sh1676 GluR4 knockdown cells demonstrated a similar pattern to that of sh1316 NPTX2 knockdown cells, with little to no NPTX2 binding observed at the cell membrane (Fig. 4A). These results suggest that GluR4 is necessary for NPTX2 membrane adhesion in ccRCC cells. We also evaluated the interaction of NPTX2 and GluR4 via immunoprecipitation. KIJ265T and Caki2 cells were transfected with epitope-tagged human NPTX2-HA and GluR4-Flag expression vectors (HA-Flag). Immunoprecipitation was performed using an HA-tag-specific antibody, and the resulting pull-downs were probed for GluR4 via Western blot analysis using a Flag-tag-specific antibody. NPTX2 successfully bound GluR4 in both cell lines (Fig. 4B). The reciprocal was also performed: pull-downs using a Flag-tag-specific antibody followed by evaluation of associated NPTX2 expression using an HA-tag-specific antibody demonstrated that GluR4 was able to coprecipitate NPTX2 in both cell lines (Fig. 4C). These results confirm the interaction of NPTX2 and GluR4 in ccRCC.

Using the sh1676 lentiviral construct, GluR4 expression was knocked down in A498, KIJ265T, and Caki2 cells (Fig. 4D), and resulting effects on proliferation and cell viability were evaluated. A significant reduction in proliferation (Fig. 4E) and viability (Fig. 4F and G) was observed as a result of GluR4 knockdown in all 3 ccRCC cell lines, demonstrating that loss of GluR4 in ccRCC phenocopied loss of NPTX2.

NPTX2-GluR4 mediates influx of intracellular calcium in ccRCC cells

AMPA receptors belong to the non–NMDA-type of ionotropic-glutamate (iGluR) transmembrane receptors, which form homomeric or heterotrimeric calcium permeable ligand-gated ion channels composed of 4 subunits (46, 47). To evaluate whether NPTX2 plays a role in AMPA receptor-mediated intracellular calcium influx, the allosteric AMPA antagonist CFM-2 (48) was tested in ccRCC cell lines to assess its effect on cell proliferation. Exposure to CFM-2 caused a dose-dependent antiproliferative effect in ccRCC cell lines, with IC50 values in the low μmol/L range (3–5 μmol/L) for Caki2, A498, and KIJ265T (Fig. 5A).

To evaluate the effect of NPTX2 on ccRCC intracellular calcium levels, A498 cells, which have high endogenous NPTX2 and GluR4 (Figs. 1B and 3D), were stained with Calcium Green-1, treated with CFM-2, and fluorescence relative to intracellular Ca2+ content was measured. CFM-2 induced a dose-dependent decrease in intracellular Ca2+ in A498 cells (Fig. 5B). We also examined the effects of exogenous application of recombinant human NPTX2 protein (R-NPTX2) on Caki1 intracellular Ca2+ influx. Treatment of EV-transfected Caki1 cells with R-NPTX2 (1 ng/μL) increased intracellular Ca2+ influx by approximately 6-fold at 1 minute, and this was partially blocked by CFM-2 (10 μmol/L; Supplementary Fig. 5A). These effects were greatly enhanced in GluR4 transfected Caki1 cells (Supplementary Fig. 5B). Similarly, cotransfection of NPTX2 and GluR4 into Caki1 cells further demonstrate sustained elevated Ca2+ as compared with the EV control or NPTX2 alone (Supplementary Fig. 5C). CFM-2 treatment resulted in a dose-dependent decrease of intracellular Ca2+ in both NPTX2 and NPTX2-GluR4 transfected Caki1 cells, with the most significant reductions observed at 10 μmol/L (Supplementary Fig. 5C).

The phosphorylation of CAMK1 and AKT kinases and subsequent activation are modulated by intracellular calcium, and both kinases are involved in AMPAR signaling and regulation (49, 50). Phosphorylation of CAMK1 at Thr177 (51) and AKT at Ser473 (52) are reported to represent full activation of each kinases. KIJ265T and A498 cells were treated with a 10 μmol/L dose of CFM-2 for 1 hour, and CAMK1 and AKT phosphorylation was evaluated via Western blot analysis. CAMK1 and AKT phosphorylation was significantly reduced in response to CFM-2 treatment in both cell lines (Fig. 5C). Caki1 cells treated with 1 ng/μL of R-NPTX2 were probed for phosphorylation of CAMK1 and AKT over a time course. Increases in CAMK1 and AKT phosphorylation were observed at 1 minute and peaked at 5 minutes after R-NPTX2 treatment (Fig. 5D). R-NPTX2–mediated downstream phosphorylation was completely blocked by CFM-2 treatment (Fig. 5D). These data demonstrate a role for NPTX2 in mediating activation of downstream calcium-dependent kinases such as CAMK1 and AKT, likely by facilitating calcium influx through AMPA receptor complexes.

As our data suggest a role for NPTX2 in ccRCC cell invasiveness, we also tested the effects of CFM-2 treatment on KIJ265T and A498 in vitro invasion. Cells were plated in invasion chambers with or without CFM-2 treatment (10 μmol/L), and invading cells were stained and counted after 20 hours. CFM-2 treatment reduced both KIJ265T and A498 cell invasive capacity by approximately 50% (Fig. 5E). These data show that AMPA receptor activity influences ccRCC cell invasion, and that this may be abrogated with treatment using an AMPAR antagonist such as CFM-2.

Discussion

Here we identify overexpression of NPTX2 as a novel feature of ccRCC, with elevated transcript and protein expression detected at all stages of disease in the majority of samples examined (Fig. 1). Meta-analysis of public datasets revealed that NPTX2 is consistently upregulated at the transcript level in ccRCC, and that NPTX2 expression is more strongly correlated with advanced ccRCC lesions versus low grade lesions (Table 1). Interestingly, of the other top 10 coregulated genes significantly altered in ccRCC (Table 2), each of them have been associated with roles in cell migration, inflammation, angiogenesis, and metabolism pathways implicated in oncogenesis. Several have been identified as protumorigenic, including ANGPT2 (53), STC2 (54), CLEC2B (55), GBP1 (56), and PLXND1 (57). Previous studies in pancreatic cancer have implicated NPTX2 as having tumor suppressor activity (58). We show here that in the context of ccRCC NPTX2 supports tumor cell viability, correlates
Figure 4. GluR4 binds NPTX2 and promotes ccRCC cell viability. A, confocal immunofluorescence of nonpermeabilized Caki2 NT, sh1316, and sh1676 clones for NPTX2 binding to the cell membrane. Each cell is outlined, and cross-sections are displayed on the top and right plots for each image. Relative fluorescence corresponding to NPTX2 expression is quantitated. Immunoprecipitation (IP) of KIJ265T and Caki2 cells transfected with both HA epitope-tagged human NPTX2 and Flag epitope-tagged human GluR4 (HA-Flag) versus EV for HA (NPTX2)-mediated Flag (GluR4) pulldown (B) and Flag (GluR4)-mediated HA (NPTX2) pulldown (C). Western blot analysis of total lysate (Total) confirms expression of epitope-tagged proteins. D, QPCR for GluR4 expression in A498, KIJ265T, and Caki2 NT versus sh1676 GluR4 knockdown cell populations. E, 7-day proliferation assay of A498, KIJ265T, and Caki2 NT versus sh1676 clones. F, cell death of A498, KIJ265T, and Caki2 NT versus GluR4 knockdown cells analyzed via flow cytometry. G, Western blot analysis for total and cleaved PARP in A498, KIJ265T, and Caki2 NT versus GluR4 knockdown cells. Cells collected for cell death analysis (F and G) correspond to day 7 of proliferation assay (E). *, P < 0.05.
with a promigratory phenotype, and additionally promotes 
c RCC cell invasion in an in vitro setting (Fig. 2).

We further identify GluR4 as a receptor for NPTX2 (Fig. 3, 4) 
in ccRCC. In a normal physiologic context, GluR4 expression 
seems to be predominantly localized to specific neuronal and 
glial cells in the central nervous system (CNS), where it 
mediates fast synaptic neurotransmission (17, 59, 60). Current 
investigations in the role of AMPA receptors have additionally 
defined this group of receptors as fundamental for neuronal 
cell migration in the developing CNS (61, 62). ccRCC is thought 
to arise from the epithelial cells of the proximal renal tubule 
(63), for which there currently is no defined role for AMPA 
receptors in a normal context of this cell type. Therefore, the 
AMPA receptor expression profile in ccRCC is unique, and our 
findings show that GluR4 is important for ccRCC viability and 
invansion. Recently, AMPA receptor activity has been linked to 
nervonal cancer cell migration (64–66). Furthermore, glutamate, 
the excitatory neurotransmitter for 2 major receptor 
families: the metabotropic-glutamate (mGluR) and iGluR 
receptors, is linked to cell proliferation and metastasis in a 
number of cancers (62, 67–69). Taken together, our data lend 
support to an important prosurvival role of AMPA receptors in 
ccRCC. The regulation of this receptor complex warrants 
further exploration to define its role in the development and/or 
progression of ccRCC.

NPTX2 induces intracellular calcium influx in ccRCC cells in 
a GluR4-dependent manner, which can be suppressed via treat-
ment with CFM-2, an allosteric AMPA receptor antagonist.
Furthermore, CFM-2 treatment reduces invasion in ccRCC cells with high endogenous NPTX2 expression (Fig. 5). These results suggest a role for NPTX2 in promoting ccRCC tumor cell migration, in part facilitated downstream through its interaction with GluR4. Recent literature establishes that intracellular calcium dynamics contribute to cell mobilization. Localized Ca$^{2+}$ gradients, or calcium flickers, can be found at the leading edges of migrating fibroblasts, where they are thought to regulate calcium-dependent actin cytoskeletal reorganization (70, 71). We propose that NPTX2-mediated influx of Ca$^{2+}$ via GluR4 expressing AMPAR complexes results in reorganization of the actin cytoskeleton, and promotes cell migration. In addition to reduced tumor cell migration, decreased NPTX2 expression leads to attenuated tumor cell proliferation and induction of cell death of ccRCC cells. Similar results are observed with decreased GluR4 in ccRCC cells. Although our results demonstrate a role for NPTX2 in ccRCC tumor cell viability and migration, further characterization of its interaction with AMPAR as well as delineation of immediate downstream signaling needs to be investigated.

Collectively, our results demonstrate that NPTX2 is a novel tumor-specific factor that demonstrates a consistent pattern of overexpression in the clear cell subtype of RCC, whose activity mediates tumor cell survival and invasion. We propose NPTX2 as a strong candidate for targeted therapy, whose inhibition may demonstrate a clinical benefit in patients suffering from metastatic ccRCC. In addition, NPTX2 may serve as a predictive biomarker in patients presenting with localized disease at risk of developing metastatic disease, and subsequently should also be investigated as a preventative therapeutic target. As NPTX2 is a secreted protein, development of neutralizing antibodies may provide a feasible therapeutic option. Furthermore, we identify GluR4 as a downstream mediator of NPTX2 activity whose expression also seems to be vital for ccRCC viability, and additionally should be investigated as a therapeutic target.

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Neuronal Pentraxin 2 Supports Clear Cell Renal Cell Carcinoma by Activating the AMPA-Selective Glutamate Receptor-4

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