RNA-seq Reveals Aurora Kinase Driven-mTOR Pathway Activation in Patients with Sarcomatoid Metastatic Renal Cell Carcinoma

Sumanta K. Pal,1 Miaoling He2, Tommy Tong,3 Huiqing Wu,3 Xueli Liu,4 Clayton Lau,5 Jin-Hui Wang,6 Charles Warden,3 Xiwei Wu,6 Sabina Signoretti,7 Toni K. Choueiri,8 Jose A. Karam,9 Jeremy O. Jones2

1Department of Medical Oncology & Experimental Therapeutics, City of Hope Comprehensive Cancer Center, Duarte, CA
2Department of Molecular Pharmacology, City of Hope Comprehensive Cancer Center, Duarte, CA
3Department of Pathology, City of Hope Comprehensive Cancer Center, Duarte, CA
4Department of Biostatistics, City of Hope Comprehensive Cancer Center, Duarte, CA
5Department of Surgery, City of Hope Comprehensive Cancer Center, Duarte, CA
6Functional Genomics, City of Hope Comprehensive Cancer Center, Duarte, CA
7Department of Pathology, Dana Farber Cancer Center, Boston, MA
8Department of Medical Oncology, Dana Farber Cancer Center, Boston, MA
9Department of Urology, The University of Texas MD Anderson Cancer Center, Houston, TX

*Corresponding Author:
Jeremy O. Jones, PhD
Beckman Research Institute
City of Hope Comprehensive Cancer Center
1500 East Duarte Road
Duarte, CA 91010
Office: (626) 256-4673
Fax: (626) 301-8233
E-mail: jjones@coh.org

Running Head: Aurora kinase - mTOR signaling in sarcomatoid mRCC

Keywords: sarcomatoid, metastatic renal cell carcinoma, mTOR, aurora kinase, RNA-seq, VEGF signaling

Conflict of Interest: The authors have no conflicts to disclose

Total Words (Abstract Words): 4071 (177)
Figures: 5
Tables: 3
ABSTRACT

Sarcomatoid metastatic renal cell carcinoma (mRCC) is associated with a poor prognosis and the biology of the disease has been inadequately characterized. RNA sequencing (RNA-seq) was performed on adjacent benign, clear cell, and sarcomatoid components from clinical specimens with sarcomatoid mRCC. M phase and cell cycle pathways were enriched in sarcomatoid versus adjacent clear cell components, suggesting greater cell proliferation. The expression of aurora kinase A (AURKA) was increased as part of these pathways, and its increased expression was validated by quantitative PCR (qPCR). Immunohistochemical (IHC) analysis revealed that AURKA levels were increased in sarcomatoid tissue compared to their benign or clear cell parts. The increase in AURKA correlated with increased mTOR pathway activity, as evidenced by increased expression of phosphorylated mTOR (S2448) and ribosomal protein S6K (T389). When AURKA was stably expressed in a RCC cell line (Renca), it resulted in increased expression and activity of mTOR, suggesting that over-expression of AURKA can activate the mTOR pathway. These results warrant the analysis of a larger clinical cohort and suggest that targeting AURKA and/or mTOR in patients with sarcomatoid mRCC should be explored.

Implications: Comparative RNA-seq of adjacent sarcomatoid and clear cell histology renal cell carcinoma indicates a proliferative phenotype and increased AURKA-dependent activation of mTOR signaling in sarcomatoid RCC, which could be targeted by available agents.

Abbreviations: metastatic renal cell carcinoma (mRCC), formalin-fixed, paraffin-embedded (FFPE), mammalian target of rapamycin (mTOR), vascular endothelial growth factor receptor (pVEGFR2), ribosomal S6 kinase (S6K), aurora kinase a (AURKA), Phosphatase and tensin homolog (PTEN).
INTRODUCTION

The landscape of therapy for metastatic renal cell carcinoma (mRCC) has evolved markedly in recent years. Acknowledging that clear cell mRCC (representing 80-85% of cases) is driven by aberrations in the \textit{VHL} gene and resultant increases in vascular endothelial growth factor (VEGF), agents have evolved to inhibit VEGF-mediating signaling.(1) These agents include VEGF-tyrosine kinase inhibitors, VEGF-directed monoclonal antibodies, and mammalian target of rapamycin (mTOR) inhibitors.(2) Though the introduction of these agents appears to have improved overall outcomes for patients with mRCC, there are still subsets of patients that warrant further study, including those patients with mRCC and a sarcomatoid component. Sarcomatoid elements may co-exist with any other RCC histology and are found in only a small percentage of patients, but they generally portend a poor prognosis.(3, 4) Prospective studies have examined combinations of cytotoxic therapy, yielding modest results at best. For instance, in Eastern Cooperative Oncology Group (ECOG) trial 8802, examining adriamycin and gemcitabine chemotherapy in a series of 39 patients, a median overall survival (OS) of 8.8 months was observed. Retrospective efforts have identified similarly modest benefit with VEGF-directed therapies – in our own institutional series, no difference in survival was noted amongst patients treated with chemotherapy or targeted agents (5, 6). In a recent retrospective analysis of RCC patients treated with mTOR inhibitors (temsirolimus or everolimus), which included 23 patients with clear cell RCC with sarcomatoid features, Voss and colleagues found that 13% of patients had partial response as their best response, 30% had stable disease, and 57% had progressive disease, suggesting a modest benefit in a subset of these patients (7). With the lack of prospective studies, there is no consensus as to the systemic management of “sarcomatoid” mRCC.

Sarcomatoid mRCC is characterized histologically by the appearance of spindle-shaped mesenchymal cells (4). The observation that the greater percentage of sarcomatoid involvement is associated with a worse outcome and apparent rapid progression of disease suggests
Aurora kinase - mTOR signaling in sarcomatoid mRCC

increased proliferative capacity (8). Interestingly, sarcomatoid components are typically interspersed throughout RCC tumors, leading to complex histological assessment. This tumor heterogeneity may contribute to the poor response of patients with sarcomatoid RCC to targeted therapies. Despite the high lethality of sarcomatoid RCC, little is known concerning the biology of this disease. In this study, we sought to gain a better understanding of sarcomatoid RCC using an RNA-sequencing approach to provide a direct comparison to adjacent clear cell carcinoma and histologically benign-appearing tissues.

MATERIALS AND METHODS

Patient Identification and Ethics Statement

Through a City of Hope Comprehensive Cancer Center Institutional Review Board (IRB) approved protocol (COH 12109), we identified patients with sarcomatoid mRCC using an IRB-approved institutional database (COH 11079). The database contains clinicopathologic information, treatment-related data, and information pertaining to clinical outcome from patients who had provided written consent for information and tissues to be used for research purposes. Given the retrospective nature of the current study and the preservation of anonymity of study results as specified by protocol 12109, a waiver of consent has been granted for the current study by the City of Hope Comprehensive Cancer Center IRB. Clinicopathologic characteristics noted in the database include a Memorial Sloan-Kettering Cancer Center (MSKCC) risk score (either good, intermediate or poor). (9) Patients included in the analysis had to have paraffin-embedded tissue derived from nephrectomy. Five patients were selected for RNA-seq analysis, and an additional three patients for subsequent assays.

RNA-sequencing

Tissue punches were procured by one of the study pathologists (HW) and contained nearly 100% pure benign, clear cell, or sarcomatoid component. RNA was recovered using the FFPE-RNA kit (Qiagen). RNA sequencing was performed by the City of Hope Functional
Aurora kinase - mTOR signaling in sarcomatoid mRCC

Genomics Core facility. RNA sequencing sample quality results are shown in Supplementary Table 1. Transcriptome libraries were constructed using Ribo-Zero™ rRNA Removal Kits (Illumina Epicenture, Madison, Wisconsin) and TruSeq RNA Sample Preparation Kit V2 (Illumia, San Diego, USA) with minor modifications. In brief, 1µg of total RNA from each FFPE sample was treated with 8 µl of rRNA Removal Solution (Ribo-Zero™ rRNA Removal Kits). The rRNA depleted RNA was ethanol precipitated. The pallet was washed with 70% of cold ethanol and resuspended in 17 µl of Elute/Prime/Fragment Mix (Illumina). First strand cDNA was synthesized using random oligonucleotides and SuperScript II. Second strand cDNA synthesis was subsequently performed using DNA Polymerase I and RNase H. Double stranded cDNA was further subjected to end repair, A-tailing, and adapter ligation in accordance with the manufacturer supplied protocols. Purified double strand cDNA templates with ligated adaptor molecules on both ends were selectively enriched by 10 cycles of PCR for 10 s at 98°C, 30 s at 60°C, and 30 s at 72°C using Illumina PCR Primer Cocktail and Phusion DNA polymerase (Illumina). Products were cleaned using 1.0 x AmpureXP beads (Beckman Coulter, Beverly, USA). Purified libraries were validated using Bioanalyzer 2100 system with DNA High Sensitivity Chip (Agilent) and quantified with Qubit (Life Technologies, Grand Island, NY). All libraries were sequenced on the Illumina Hiseq 2500 with single read 40 bp reads following the manufacturer's recommendations. The 40-bp long single-ended sequence reads were mapped to human genome (hg19) using TopHat and the frequency of Refseq genes was counted with customized R scripts. The raw counts were then normalized using trimmed mean of M values (TMM) method and compared using Bioconductor package “edgeR” (10). The average coverage for each gene was calculated using the normalized read counts from “edgeR”. Differentially expressed genes were identified if the average coverage >= 1 in at least one sample, fold change >= 2, and P value <= 0.05. Gene enrichments were analyzed using DAVID (Database for Annotation, Visualization, and Integrated Discovery), which is a bioinformatic resource available online at http://david.abcc.ncifcrf.gov for functional interpretation of large lists of genes.
RT-qPCR

RNA was recovered using the FFPE-RNA kit (Qiagen) from scrapings from slides that had been marked for pure clear cell and pure sarcomatoid components by a study pathologist (TT). RNA was reverse-transcribed and qPCR was performed using a StepOne real time PCR machine (Life Technologies) using SYBR green (Invitrogen) as the detecting dye and Rox (Invitrogen) as the reference dye. Samples were tested in technical triplicate. Differences between experimental (x) and control (y) samples were normalized to RPL19 transcript levels and determined with the following calculation: \((2^{[C_{tx gene1}/C_{ty gene1}]})/(2^{[C_{tx RPL19}/C_{ty RPL19}]}))\). To test for differences in means, ANOVA methods were used for planned comparisons between treatment groups that were defined by linear contrast statements. For qPCR assessment of Renca cell line RNAs, samples were tested in biological duplicates and technical triplicates. Primer sequences are shown in Supplementary Table 2.

Immunohistochemistry

The following biomarkers of interest were examined via immunohistochemical (IHC) staining: phospho-Ser2448 mTOR (pmTOR), total mTOR, phospho-Thr389 p70 S6 Kinase Beta (pS6K), total S6K, PTEN, AURKA, N-Cadherin, and phospho-Tyr1175 VEGF receptor 2 (pVEGFR2). Tissue sections were deparaffinized, the endogenous peroxides were quenched with 3% hydrogen peroxide, and sections were treated for antigen retrieval by boiling in a pressure cooker in antigen unmasking solution (Vector Laboratories). Sections were blocked with 10% normal goat serum in TBS–0.1% Tween-20 and probed with primary antibodies: rabbit anti-PTEN (Genetex) 1:150, rabbit anti-AURKA (Biorbyt) 1:100, rabbit anti-pmTOR (Genetex) 1:150, rabbit anti-mTOR (Genetex) 1:250, rabbit anti-phospho-Tyr1175 VEGF receptor 2 (Biorbyt) 1:200, rabbit anti-phospho-Thr389 p70 S6 Kinase Beta (Biorbyt) 1:250, rabbit anti-S6K (Genetex) 1:250, mouse anti-N-Cadherin (DAKO) 1:50. Biotinylated goat secondary antibodies and streptavidin-peroxidase label (LabVision) were added, and DAB substrate kits were used for peroxidase detection (Vector Laboratories).
Pathologic Analysis and Scoring

IHC staining was performed by two laboratory-based investigators (J.J. and M.H.), and stained slides were reviewed independently by the study pathologists. An estimate of the average percentage of positively staining cells (0-100%) and their staining intensity (0-3) in the sarcomatoid and clear cell sections of each slide was recorded for each biomarker; the extent and intensity values were multiplied for a final staining score. A Student’s t test was used to compare the staining for each biomarker between sarcomatoid- and clear cell components.

Cell Culture and Western blotting

Renca cells were cultured in RPMI with 10% FBS and antibiotics. Cells were transfected with an AURKA expression vector (AddGene plasmid 8510) (11) using lipofectamine transfection reagents (Life Technologies) and two independent clones were selected using puromycin. Cells were lysed in TBS with 0.1% Tween with protease inhibitors. Lysates were resolved by SDS-PAGE and transferred to membranes for blotting with the antibodies described above, or actin (Santa Cruz, sc-1616) as a loading control.

RESULTS

Patient Characteristics

Clinicopathologic and treatment-related characteristics of the cohorts are noted in Table 1. Mean age of the patients was 60 years old, and patients were mainly male. Treatment patterns were heterogeneous amongst the two groups. Few patients received third-line therapy.

RNA-seq

RNA recovered from tissue punches from adjacent clear cell and sarcomatoid components was of high enough yield to prepare libraries and perform 40bp reads on all samples. Exon coverage ranged from 4-24%, with an average coverage of 13.2% (Supplementary table 1). Interestingly, the samples clustered by patient, not collectively by histologic subtype (benign, clear cell or sarcomatoid), suggesting an evolution of disease from
benign to clear cell to sarcomatoid that is unique to each patient (Figure 1a). Focusing specifically on mRNAs, we found a number of differentially expressed genes (Figure 1b, Supplementary Table 4) among groups, including many differences between sarcomatoid and surrounding clear cell disease sections. Gene ontology analysis revealed significant differences between sarcomatoid and adjacent clear cell cancers (Tables 2 and 3). The most striking differences appear to involve increased proliferation in sarcomatoid tissue, including M phase and cell cycle pathways. To validate the RNA-seq findings, we extracted RNA from corresponding tissue samples and performed RT-qPCR for several genes found to be significantly regulated by RNA-seq. We were able to extract RNA from four of the five patient samples from the RNA-seq analysis, plus an additional three patients that had archived tissue containing adjacent sarcomatoid and clear cell RCC. We chose to examine the expression of several of the most highly altered genes, as determined by RNA-seq, as well as the expression of Aurora kinases A and B, as they are known to be involved in increased mitosis and cell cycle progression (12, 13). Although the magnitude of change as determined by qPCR wasn't identical to that detected by RNA-seq, all of the genes we examined were altered in the same direction (Figure 2).

**Aurora kinase and mTOR pathway activation in sarcomatoid RCC**

We next used IHC to determine if AURKA was increased at the protein level as well as at the transcript level. In six of the seven patient samples, AURKA expression was elevated in sarcomatoid areas compared to clear cell areas, although all clear cell tissue had some staining (Figure 3). Aurora kinases have been shown to interact with mTOR to regulate cell cycle progression and even the transformation of cells (14, 15). As mTOR signaling has shown to be a valid target in clear cell RCC (16), and is more significantly altered in high-grade tumors and tumors with poor prognostic features (17), we examined the correlation between AURKA over-expression and mTOR pathway activation. Expression of phosphorylated (active) mTOR and S6K were used to assess the status of the mTOR signaling pathway. Auto-phosphorylation of
mTOR at serine 2448 is thought to indicate an active complex (18), and phosphorylation of S6K at Thr389 is a widely accepted marker of mTOR pathway activation and most closely correlates with p70 kinase activity in vivo (19). We observed a greater extent and intensity of pmTOR and pS6K expression in sarcomatoid vs. clear cell components of tumor samples, although both were expressed to some extent in all clear cell areas (Figure 3). In the seven samples that included both sarcomatoid and clear cell carcinoma components on the same slide, pmTOR (p=0.006), pS6K (p=0.001), and AURKA (p=0.05) staining were significantly elevated in sarcomatoid areas compared to clear cell areas (Figure 3).

To explore the dependence of mTOR activation on AURKA over-expression, we also examined the expression of PTEN, which when lost, is known to activate mTOR signaling (20), and of phosphorylated VEGFR2, as a marker of the VEGF signaling (21), which has also been shown to activate mTOR signaling (22). We found no difference in PTEN expression between sarcomatoid and clear cell components (p=0.18) and no obvious overlap with pmTOR or pS6K staining (Figure 3). Likewise, there was no difference in pVEGFR2 staining between sarcomatoid and clear cell components (p=0.25). This suggests that activation of mTOR signaling in our samples was not likely dependent on VEGFR2 signaling or PTEN loss, especially in sarcomatoid mRCC.

**AURKA over-expression drives mTOR activation in clear cell RCC cells**

As the correlation between AURKA over-expression and mTOR pathway activation was strong, we wanted to determine if AURKA over-expression could cause mTOR pathway activation. We chose to use the Renca cell line as a model as it has a low level of AURKA and mTOR expression and recapitulates several features of sarcomatoid RCC in mice (e.g. distant metastases including liver). Two independent clones were selected with a varying degree of AURKA expression (Figure 4). Over-expression of AURKA caused an increase in total and phosphorylated mTOR, as well as total and phosphorylated S6K, demonstrating that AURKA over-expression can drive mTOR expression and signaling in RCC cells. The increase in mTOR

Aurora kinase - mTOR signaling in sarcomatoid mRCC

protein levels does not appear to be caused by increased transcription, as RT-qPCR demonstrates a lack of increased mTOR transcript (Figure 4). Likewise, the increased expression of AURKA has no effect on the transcription of aurora kinase B. However, a known AURKA target, ccnb1 (23), was found to be increased by RT-qPCR and in the RNA-seq comparison of sarcomatoid to clear cell tissue (Figure 4, Supplementary Table 3).

Sarcomatoid RCC has been proposed as an example of epithelial-to-mesenchymal (EMT), as evidenced by increased expression of N-Cadherin and Snail among other markers (24-26). We were able to show in our samples that the expression of N-cadherin was higher in sarcomatoid tissue compared to surrounding clear cell tissue (P=0.05, Figure 5). We also observed increased N-Cadherin transcript levels in one of the two AURKA-over expressing Renca cell lines by RT-qPCR (Figure 5). No changes in the expression of several other EMT markers in cells over-expressing AURKA (Figure 5) were seen, nor did we observe any morphological changes that might be indicative of EMT (data not shown). Thus, our results do not rule out EMT in the evolution of sarcomatoid disease but do suggest that over-expression of AURKA does not contribute to the EMT process, only to the activation of mTOR signaling.

DISCUSSION

The molecular characterization of sarcomatoid RCC has been limited, but several groups have shown that sarcomatoid disease may be an example of epithelial-to-mesenchymal (EMT), as evidenced by increased expression of N-Cadherin and Snail among other markers (24-26). We also observed increased expression of N-cadherin in sarcomatoid sections, but interestingly, EMT pathways were not identified in the gene ontology analysis of the RNA-seq data. Other groups have shown that sarcomatoid RCC from tumors with clear cell pathology maintained the high expression of HIF pathway proteins found in the surrounding clear cell tissue (27). Other small studies have suggested greater expression of FAS ligand (28) or c-KIT (29), although the c-KIT finding has been refuted (30). Our unbiased RNA-seq exploration of
Aurora kinase - mTOR signaling in sarcomatoid mRCC

sarcomatoid tissue from clear cell RCC suggested an increased expression of AURKA, which was confirmed at the transcript and protein level. AURKA is known to be involved in increased mitosis and cell cycle progression (12, 13), and is often over-expressed in cancer, thus several agents inhibiting AURKA activity are in clinical trials (31). Two studies have shown that AURKA expression is increased in clear cell RCC compared to normal kidney tissue, and that higher expression levels correlate with advanced tumor stage and poor patient survival (23, 32). We, too, saw higher AURKA transcript levels in clear cell components compared to benign kidney tissue in the RNA-seq data, but the sarcomatoid tissue had even greater expression than the clear cell tissue. Neither previous study indicated whether patients from whom samples were taken had sarcomatoid involvement, but greater sarcomatoid involvement is also known to correlate with advanced disease and poorer outcome (8), so the fact that AURKA levels correlated with more advanced disease and poorer patient survival might suggest that AURKA levels also correlated with sarcomatoid involvement.

Our observations also suggest an increase in the activity of the mTOR signaling pathway, as measured by phosphorylation of mTOR and S6K, in patients with sarcomatoid mRCC. mTOR is a serine/threonine protein kinase that regulates cell growth, cell proliferation, cell motility, cell survival, protein synthesis, and transcription (18). mTOR forms two distinct complexes, mTORC1 and mTORC2. mTORC1 controls protein synthesis in part by regulating the phosphorylation status of p70 s6 kinase 1 (S6K), and the phosphorylation of S6K is often used to assess the activity of mTOR (33). Our results clearly demonstrate that mTOR signaling is active in the clear cell component of the RCC but is further elevated in the sarcomatoid tissue. In support of our findings, one other study also identified increased pS6K expression in patients with sarcomatoid RCC (34). The mTOR pathway has been examined in clear cell RCC to a greater extent, with different studies suggesting activation of mTOR in 60%-85% of clear cell RCC (17, 35). Interestingly, rare mutations have been observed in the mTOR pathway in clear cell RCC, including mutations in the mTOR gene itself (36, 37). In a cohort of 77 fresh frozen
clear cell samples and matched benign tissue, Kucejova and colleagues identified additional mutations in the mTOR pathway, including three mutations in TSC1, one in PTEN, and one in REDD1, which is a negative regulator of mTOR (38). REDD1 is a HIF1 target gene, and its expression increases upon loss of VHL and concomitant HIF1 activation, which occurs in approximately 90% of sporadic tumors (39, 40). REDD1 expression should inhibit mTOR signaling, yet mTOR signaling appears to be active in the majority of clear cell RCC. It appears that somatic mutations in the mTOR pathway can overcome VHL/HIF1/REDD1-mediated mTOR suppression in rare cases, but other mechanisms must exist to account for the majority of mTOR activation in clear cell RCC. We were unable to sequence genes in the mTOR pathway due to the fragmented nature of the DNA in the FFPE samples, but our data would suggest that pathogenic over-expression of AURKA can activate mTOR signaling, thus overcoming REDD1-mediated suppression. In fact, it has been shown that AURKA is a transcriptional target of HIF1α, and that AURKA expression increases with loss of VHL, which helps to explain the elevated levels of AURKA observed in clear cell RCC (41-43). Our results suggest a model where loss of VHL causes increased HIF1α expression, which in turn causes increased AURKA expression, which activates mTOR signaling. This is likely a general model for clear cell RCC which may be exacerbated in sarcomatoid tissue. Further studies will be needed to confirm the activity status of the mTOR pathway in ccRCC and more importantly, if such markers correlate with response to mTOR-targeted therapies, but our studies suggest that mTOR pathway activation is highly relevant in patients with sarcomatoid RCC. Although two FDA approved mTOR inhibitors are in clinical use for mRCC, the activity of these compounds in sarcomatoid mRCC is limited to one retrospective study in 23 patients (7) and two other case reports (44, 45). To our knowledge, there are no current trials investigating aurora kinase inhibitors in renal cell carcinoma, but perhaps dual targeting of mTOR and aurora kinases in patients with sarcomatoid RCC would be an effective strategy. Our findings in cultured RCC cells that over-expression of AURKA can drive mTOR pathway signaling support this hypothesis. Developing a
Aurora kinase - mTOR signaling in sarcomatoid mRCC

We did not observe a significant difference in expression of pVEGFR2 or PTEN when comparing tissues with adjacent sarcomatoid and clear cell components, suggesting that neither PTEN loss nor VEGF signaling was responsible for mTOR activation. VEGF signaling is sensitive to numerous targeted agents which are thought to act primarily through VEGFR2. The lack of significant differences in pVEGFR2 staining between sarcomatoid and clear cell components does not completely rule out differences in VEGF-VEGFR signaling in these patients that could be targeted by current therapies. It is possible that VEGFR2, though thought to be the primary mediator of VEGF signaling, is not the most important receptor for VEGF in sarcomatoid tissue. It would be beneficial to examine the expression of other VEGFRs and whether they are active (phosphorylated) or not. It would also be beneficial to examine downstream markers of VEGF-VEGFR signaling to determine if this pathway is active in sarcomatoid and non-sarcomatoid mRCC. The lack of overlap between VEGF and mTOR signaling in sarcomatoid and clear cell components in patients harboring both cancers suggests that there may be rationale to treat these patients with the combination of VEGF- and mTOR-directed approaches. Although recent randomized phase II and III studies exploring these combinations have shown little improvement in efficacy and increased toxicity as compared to existing single agent regimens, these studies explored a generalized population of patients with mRCC and did not particularly include an analysis of patients with sarcomatoid component (46-49). A more specific evaluation of these combinations in a subgroup of patients with sarcomatoid mRCC may be warranted.

There are several limitations to our study, primarily the small sample size and the use of FFPE tissue for deep sequencing approaches. Patient samples with clearly documented sarcomatoid components are rare, and often overlooked, but this RNA-seq assessment of five patients provides important insights into the biology of sarcomatoid disease that can now be
Aurora kinase - mTOR signaling in sarcomatoid mRCC

explored in larger cohorts. Our RNA-seq methodology produced only an average of 13.2% exon coverage, which is on par with other studies that have used FFPE tissue for RNA-seq; however, the RNA quality and exon coverage would likely be improved using frozen samples instead. Furthermore, because of nucleic acid fragmentation, we were unable to perform reliable exome sequencing on most of the samples, even following several methods of library preparation. Such data would be useful to identify chromosomal gains and losses as well as the accumulation of somatic mutations as clear cell carcinoma evolves into sarcomatoid disease. Fragmented nucleic acid also limited the confidence in findings from 100bp paired end RNA-seq reads. We identified two fusion transcripts from this approach, but could not independently confirm either (Supplementary Table 3). Despite our admittedly small sample size, our study provides important biological insights and the data presented herein should be used to inform larger translational studies investigating sarcomatoid mRCC. These findings could also suggest previously untested therapeutic avenues for the disease, such as combinations of aurora kinase and mTOR inhibitors. Until such efforts are undertaken, the prognosis of sarcomatoid mRCC will likely remain dismal.

ACKNOWLEDGEMENTS: This work was supported by NIH K12 2K12CA001727-16A1 (S.K.P.). The authors would like to thank Sofia Loera and the Pathology core facility for assistance with slide preparation. Tissue samples were provided by the City of Hope Biospecimen Repository which is funded in part by the National Cancer Institute. Other investigators may have received specimens from the same patients. We would also like to acknowledge the generous contributions of Frank Di Bella and Paul Musco.
REFERENCES

Aurora kinase - mTOR signaling in sarcomatoid mRCC


Aurora kinase - mTOR signaling in sarcomatoid mRCC

**Table 1.** Clinicopathologic and treatment-related characteristics of patients with sarcomatoid mRCC.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>(n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age – yr</strong></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>60.0</td>
</tr>
<tr>
<td>Range</td>
<td>(42.7-78.2)</td>
</tr>
<tr>
<td><strong>Gender – no.</strong></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
</tr>
<tr>
<td>Female</td>
<td>2</td>
</tr>
<tr>
<td><strong>Sites of metastasis – no.</strong></td>
<td></td>
</tr>
<tr>
<td>Bone</td>
<td>4</td>
</tr>
<tr>
<td>Lung</td>
<td>4</td>
</tr>
<tr>
<td>Brain</td>
<td>3</td>
</tr>
<tr>
<td>Liver</td>
<td>4</td>
</tr>
<tr>
<td><strong>Risk group – no.</strong></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>1</td>
</tr>
<tr>
<td>Intermediate</td>
<td>7</td>
</tr>
<tr>
<td>Poor</td>
<td>0</td>
</tr>
<tr>
<td><strong>Treatment – no.</strong></td>
<td></td>
</tr>
<tr>
<td>First-line</td>
<td></td>
</tr>
<tr>
<td>VEGF-TKI</td>
<td>4</td>
</tr>
<tr>
<td>mTOR</td>
<td>0</td>
</tr>
<tr>
<td>Immunotherapy</td>
<td>0</td>
</tr>
<tr>
<td>Chemotherapy</td>
<td>1</td>
</tr>
<tr>
<td>None</td>
<td>3</td>
</tr>
<tr>
<td>Second-line</td>
<td></td>
</tr>
<tr>
<td>VEGF-TKI</td>
<td>1</td>
</tr>
<tr>
<td>mTOR</td>
<td>1</td>
</tr>
<tr>
<td>Immunotherapy</td>
<td>0</td>
</tr>
<tr>
<td>Chemotherapy</td>
<td>1</td>
</tr>
<tr>
<td>None</td>
<td>5</td>
</tr>
<tr>
<td>Third-line</td>
<td></td>
</tr>
<tr>
<td>VEGF-TKI</td>
<td>1</td>
</tr>
<tr>
<td>mTOR</td>
<td>0</td>
</tr>
<tr>
<td>Immunotherapy</td>
<td>0</td>
</tr>
<tr>
<td>Chemotherapy</td>
<td>0</td>
</tr>
<tr>
<td>None</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 2: GO pathways increased in sarcomatoid vs. clear cell

<table>
<thead>
<tr>
<th>Term</th>
<th>Count</th>
<th>Fold Enrichment</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M phase</td>
<td>53</td>
<td>8.55</td>
<td>1.36E-33</td>
</tr>
<tr>
<td>Cell cycle phase</td>
<td>57</td>
<td>7.30</td>
<td>1.57E-32</td>
</tr>
<tr>
<td>Mitosis</td>
<td>42</td>
<td>10.13</td>
<td>2.00E-29</td>
</tr>
<tr>
<td>Nuclear division</td>
<td>42</td>
<td>10.13</td>
<td>2.00E-29</td>
</tr>
<tr>
<td>M phase of mitotic cell cycle</td>
<td>42</td>
<td>9.95</td>
<td>4.24E-29</td>
</tr>
<tr>
<td>Organelle fission</td>
<td>42</td>
<td>9.73</td>
<td>1.06E-28</td>
</tr>
<tr>
<td>Mitotic cell cycle</td>
<td>50</td>
<td>7.17</td>
<td>5.52E-28</td>
</tr>
<tr>
<td>Cell cycle process</td>
<td>59</td>
<td>5.54</td>
<td>3.13E-27</td>
</tr>
<tr>
<td>Cell cycle</td>
<td>66</td>
<td>4.51</td>
<td>1.55E-25</td>
</tr>
<tr>
<td>Cell division</td>
<td>39</td>
<td>7.01</td>
<td>2.44E-21</td>
</tr>
</tbody>
</table>
Table 3: GO pathways decreased in sarcomatoid vs. clear cell

<table>
<thead>
<tr>
<th>Term</th>
<th>Count</th>
<th>Fold Enrichment</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coenzyme metabolic process</td>
<td>17</td>
<td>5.06</td>
<td>2.38E-07</td>
</tr>
<tr>
<td>Oxidation reduction</td>
<td>36</td>
<td>2.57</td>
<td>5.19E-07</td>
</tr>
<tr>
<td>Response to drug</td>
<td>19</td>
<td>4.01</td>
<td>1.26E-06</td>
</tr>
<tr>
<td>Cofactor metabolic process</td>
<td>18</td>
<td>4.20</td>
<td>1.34E-06</td>
</tr>
<tr>
<td>Fatty acid metabolic process</td>
<td>17</td>
<td>3.91</td>
<td>7.34E-06</td>
</tr>
<tr>
<td>Amine biosynthetic process</td>
<td>11</td>
<td>6.19</td>
<td>1.03E-05</td>
</tr>
</tbody>
</table>
Aurora kinase - mTOR signaling in sarcomatoid mRCC

FIGURE LEGENDS

Figure 1: RNA-seq results. RNA-seq was performed on benign, clear cell, and sarcomatoid tissue punches from five patient samples. (A) Hierarchical clustering demonstrates a strong dependence on the patient from which the sample was obtained, not on histological disease designation. (B) A Venn diagram of significant differentially regulated genes among sarcomatoid (S), clear cell (C), and benign (B) tissue sections.

Figure 2: RT-qPCR confirmation of RNA-seq findings. RNA was extracted from four of the five patient samples from the RNA-seq analysis, plus an additional three patient samples with adjacent sarcomatoid and clear cell RCC. qPCR demonstrates a pattern of expression similar to that observed in the RNA-seq analysis (inset) for all genes examined.

Figure 3: Expression of AURKA and mTOR pathway proteins in sarcomatoid RCC. IHC was performed for the indicated proteins on samples from seven patients which had both sarcomatoid and clear cell components on the same slide. (Top) Representative whole slide imaging for one patient sample is shown. (Bottom) Extent x intensity scoring was averaged from seven samples that had both sarcomatoid and clear cell carcinoma components. AURKA, pmTOR and pS6K, but not pVEGFR2 or PTEN expression was significantly different between cancer components. Bars represent standard error. A Student’s T-test was used to determine significance (* p< 0.05).

Figure 4: AURKA over-expression drives mTOR activation in Renca cells. Renca cell lines were transfected with an AURKA expression vector and two independent cell lines were selected. After several weeks of selection, lysates were harvested from both AURKA cell lines, as well as parental Renca cells, separated by SDS-PAGE, and immunoblotting was performed.
Aurora kinase - mTOR signaling in sarcomatoid mRCC

For the indicated proteins (A), or RNA was harvested for RT-qPCR (B). Over-expression of AURKA caused increased expression of mTOR and S6K, as well as phosphorylation of both proteins. The increased expression of mTOR was not reflected at the transcript level, although the AURKA target ccnb1 was increased. Bars represent standard error. ANOVA methods were used to derive p values (* p<0.05).

Figure 5: AURKA over-expression does not cause EMT in Renca cells. (A) Extent x intensity scoring was averaged from seven samples that had both sarcomatoid and clear cell carcinoma components. N-Cadherin expression was significantly different between cancer components. Bars represent standard error. A Student’s T-test was used to determine significance (* p<0.05). (B) RT-qPCR wase performed on parental and AURKA-overexpressing Renca cells as in Figure 4. Bars represent standard error. ANOVA methods were used to derive p values (* p<0.05).
Figure 1

A) Heatmap showing expression levels of genes across different samples.

B) Table showing the number of upregulated and downregulated genes for different comparisons:

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>E vs B</td>
<td>184</td>
<td>191</td>
</tr>
<tr>
<td>S vs B</td>
<td>247</td>
<td>401</td>
</tr>
<tr>
<td>S vs E</td>
<td>381</td>
<td>455</td>
</tr>
</tbody>
</table>

C) Venn diagram illustrating the overlap of genes across different comparisons:

- C vs B: 133 genes
- S vs B: 340 genes
- C vs S: 170 genes
- S vs C: 562 genes
- S12 B: 138 genes
- S12 E: 5 genes
- S12 S: 99 genes

Downloaded from mcr.aacrjournals.org on June 14, 2017. © 2014 American Association for Cancer Research.
<table>
<thead>
<tr>
<th>Gene</th>
<th>logFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AURKA</td>
<td>1.27</td>
</tr>
<tr>
<td>AURKB</td>
<td>1.38</td>
</tr>
<tr>
<td>WISP2</td>
<td>2.49</td>
</tr>
<tr>
<td>NKX6-3</td>
<td>4.54</td>
</tr>
<tr>
<td>C4B</td>
<td>-3.74</td>
</tr>
</tbody>
</table>

Figure 2
Figure 3
Figure 4
RNA-seq Reveals Aurora Kinase Driven-mTOR Pathway Activation in Patients with Sarcomatoid Metastatic Renal Cell Carcinoma

Sumanta K. Pal, Miaoling He, Tommy Tong, et al.

Mol Cancer Res  Published OnlineFirst September 2, 2014.

Updated version
Access the most recent version of this article at:
doi:10.1158/1541-7786.MCR-14-0352

Supplementary Material
Access the most recent supplemental material at:
http://mcr.aacrjournals.org/content/suppl/2014/09/04/1541-7786.MCR-14-0352.DC1

Author Manuscript
Author manuscripts have been peer reviewed and accepted for publication but have not yet been edited.

E-mail alerts
Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions
To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions
To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.