Title: Mapping Immune Landscape in Clear Cell Renal Carcinoma by Single-Cell Genomics

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**Abstract**:

Human clear cell renal cell carcinoma (ccRCC) is one of the most immunologically distinct tumor types due to high levels of tumor-infiltrating immune cells including T cells, yet not every patient responds to immunotherapy. Interestingly, in contrast to other cancers, infiltration with cytotoxic CD8+ T cells is associated with poorer overall survival in ccRCC, suggesting that sub-populations of CD8+ and other immune cells may underlie this observation. To characterize the tumor immune microenvironment of ccRCC, we applied single-cell-RNA sequencing (SCRS) along with T-cell-receptor (TCR) sequencing to map the transcriptomic heterogeneity of 25,688 individual CD45+ lymphoid and myeloid cells in matched tumor and blood from patients with ccRCC. Will need to update based on new findings. This report represents the first such characterization of the ccRCC immune landscape using scRNA-seq. With further characterization and functional validation, these findings may identify novel sub-populations of immune cells amenable to therapeutic intervention.

**Introduction**

Clear cell renal cell carcinoma (ccRCC) is the most common type of renal cell carcinoma arising from epithelial cells of the proximal tubule of the kidney, comprising more than 70% of all renal cancers (1). ccRCC represents an immune sensitive tumor type well known for early advances in systemic immunotherapy using T cell proliferation cytokine IL-2 and interferon (IFN) -ɑ2b therapy (2). Recent novel immunotherapies targeting T cell checkpoints as standard of care has transformed the treatment paradigm of ccRCC (3,4). However, a substantial subset of renal cancer patients still do not respond to these therapies and patients who initially do can eventually progress (5,6). Cytotoxic tumor-infiltrating lymphocytes (TILs), in particular CD8+ T cells are key effectors of the adaptive anti-tumor immune response (7) and abundance of CD8+ T cells in solid cancers is generally associated with better survival in cancer patients (8–10). However, in RCC, immune cell abundance is inversely correlated with survival, specifically TILs (11–13). Biomarker analysis results from recent clinical trials comparing PD-1 blockade versus anti-angiogenic inhibitors and combination therapies in treatment-naïve ccRCC patients also supported the negative prognostic significance of T cell infiltrate in the absence of immunotherapy (14,15). Other abundant immune players in the ccRCC tumor microenvironment include monocytes, dendritic cells and tumor-associated macrophages (TAMs) (16) which are now being harnessed for discovery of novel gene programs but remain far less studied than T cells.

Quantifying and inferring immune cell abundance from transcriptional analysis of primary or metastasized bulk tumor samples is inadequate to provide a clear picture of the immune cell types (17,18). While these studies are suggestive, they lack single cell resolution for characterizing heterogeneous cell subpopulations that ultimately shape anti-tumor response, as has been demonstrated in breast cancer and melanoma (19,20). Single-cell methodologies including flow cytometry, immunohistochemistry, and mass cytometry (13,16,21) have revealed immune cell states in ccRCC but only as discrete phenotypes when in vivo they typically display diverse spectrum of differentiation or activation states. Also, these methods require use of antibody panels targeting known immune cell components, and by design are not capable of identifying novel sub-populations of cells. SCRS has enabled comprehensive characterization of heterogeneous lymphoid and myeloid immune cells in several cancers (22–25), providing an unbiased approach to profiling cells and enabling molecular classification of different subpopulations and identification of novel gene programs. Transcriptome mapping of T lymphocytes coupled with TCR sequencing allows additional measurement of clonal T cell response to cancer at an unprecedented depth (26,27).

Here, we report the single cell RNA profiling of the immune landscape in ccRCC mapping a total 25,688 of immune single cells (5’ gene expression and recombined V(D)J region of the T cell receptor) in matched samples of tumor and peripheral blood isolated from three treatment-naïve ccRCC patients. Will need to update with results. Analysis of myeloid cells revealed a complex mixture of pro- and anti-inflammatory polarized phenotypes across patients. This represents the first such report of the immune landscape of ccRCC using SCRS for gene expression.

**Results**

*Single-cell expression profiling of immune cells in ccRCC.*

In order to define the immune microenvironment of human ccRCC, we obtained tumor and peripheral blood specimen of three treatment-naïve ccRCC patients and subject flow-sorted lymphoid and myeloid cells to SCRS. The general workflow for isolation and sequencing is available in Supplemental Figure 1. To these samples, we added immune cells from peripheral blood and normal renal parenchyma (20) to obtain an integrated UMAP projection of 22 clusters across 37,055 primary immune cells (Figure 1A). Across the three tissues, peripheral blood (n=21,160), tumor (n=12,239) and normal kidney (n=3,556), we a number of clusters with similar gene expression notably in Clusters 0, 1, 3 and 7 (Figure 1B). Despite the integration of sequencing runs to reduce tissue-type divergence, each tissue type had enrichment for clusters: peripheral blood formed the majority of Cluster 2, tumor tissues were enriched for Clusters 14, 17, 18, and 19, and normal kidney was enriched for Cluster 11. Using gene expression, we assigned cell lineages to each cluster using a three method approach: 1) examining expressions of canonical markers for T cells (*CD3E*, *CD8A*, *CD4*, and *IL7R* or CD127), B cells (*CD19* and *MS4A1*), myeloid cells (*CD14* and *FCGR3A* or CD16) and natural killer (NK) cells (*KLRD1* and *NKG7*) (Figure 1C), 2) correlations with pure-cell gene signatures derived from ENCODE (28) (Figure 1D), and 3) assigning clonotypes based on the TCR sequencing (Supplemental Figure 2). Based on these approaches we annotated clusters as monocytes (Clusters 0, 5, 11, 12, and 16), CD4+ T Cells (Clusters 4, 6, 10, 13, 15, and 20), CD8+ T cells (Clusters 1, 8, 9 and 17), NK cells (Clusters 3 and 7), B cells (Cluster 2), macrophages (Mφ, Cluster 14) and dendritic cells (DC, Clusters 18 and 19) (Figure 1E). Based on these annotations, we also examined the relative proportion of cell types comprising the sequencing runs by tissue type (Figure 3E). We observed a decrease in CD4+ T cells and B cells comparing peripheral blood to normal kidney tissue or tumor (Figure 1E). Conversely and as expected, we also found an increase in CD8+ T cells and Mφ in ccRCC versus peripheral blood (Figure 1E).

*CD8+ T cells in ccRCC tumors exhibit a transcriptional continuum with distinct populations*

The presence of CD8+ T cells in the tumor microenvironment is recognized as key effectors in the anti-tumor immune response (29) and have been associated in with response to immunotherapy (30). Sub-clustering of CD8+ T cells revealed 8 distinct clusters (Figure 2A) with relative tissue-specific distribution (Figure 2B). To understand the distribution of these new CD8+ clusters along the UMAP, we first examined the relative percent of single-cells represented in each cluster by tissue type. Tissue-infiltrating CD8+ T cells (both tumor and normal kidney) comprised the majority of CD8\_0, CD8\_1, CD8\_3, CD8\_5, CD8\_6 and CD8\_7. Only Clusters CD8\_2 and CD8\_4 had increased relative levels of peripheral blood cells (Figure 2B). Going from right to left across the x-axis of the UMAP there is a change in tissue-specific contribution starting from peripheral blood (right) to kidney (middle) to increasing levels of ccRCC tumor CD8+ T cells (left) and may represent the process of tissue infiltration itself. Within SCRS literature, these is a concern for variations in cell cycle leading to increased heterogeneity or obscure subpopulations (31), however proliferation of CD8+ T cells is an important surrogate markers of anti-tumor immune response (cite). We next examined the variation in proliferative gene signatures, finding a similar distribution to the tissue-type with increasing cells in S or G2M phases from right to left, peaking with Cluster CD8\_6 (Figure 3C).

In order to better characterize the CD8+ clusters, we next used canonical and differential T cells markers to examine gene expression differences along the UMAP (Figure 2D) with several patterns. The first pattern was the discovery of a naïve *CCR7*+ *SELL*+ *TCF7*+ being seen in CD8\_4 (Figure 2D). Looking for effector CD8+ T cells, we next observed two populations of *IFNG*+ *PRF1*+ T cells, principally in CD8\_1 and CD8\_0 (Figure 2D). The latter also expressed negative immune checkpoint, such as *CTLA4*, *HAVCR2*, *PDCD1*, and *TIGIT* (Figure 2D). These negative immune checkpoints were expressed at more moderate levels in both CD8\_5 and CD8\_6, however, CD8\_6 exclusively expressed a number of proliferation markers, such as *CDK1*, *MKI67*, *STMN1*, and *TOP2A* (Figure 2D). In order to examine gene expression patterns above single or selected genes, we used slingshot (32) to building minimum spanning trees between clusters, generating curves based on the most varied genes (Figure 2E). We identified 5 distinct curves (labeled B1 to B5) with the origin in the *CCR7*+ *SELL*+ *TCF7*+ CD8\_4. With the exception of B1 extending into CD8\_2, the remining curves graphed along a similar trajectory with a common node of CD8\_1 and branching at distinct clusters with increased levels of tumor-infiltrating CD8+ T cells (Figure 2E). Although based on gene expression, these curves also varied by CD8+ clonotypes based on TCR sequencing, with the root having no clonal expansion and the B3, B4 and B5 curves terminating into regions with higher levels of clonal expansion compared to B1 or B3 (Figure 2E). In order to assess possible functional differences based on these branching, we performed gene set enrichment analysis (Figure 2F). As expected based on the immune checkpoint inhibitors expression, Clusters CD8\_0 and CD8\_5 showed increased terminal differentiation and exhaustion (Figure 2F). Cytolytic gene enrichment was seen in CD8\_1, the PRF1+ IFNG+ population lacking immune checkpoints (Figure 2F). The highly proliferative CD8\_6 population was enriched for metabolic activity, such as the tricarboxylic acid cycle and glycolysis, and DNA repair (Figure 2F). The B2 curve termination cluster, CD8\_2, has preferential enrichment of cytokine signaling, such as IL-2/STAT5, TGFβ, and type 1 interferons (Figure 2G). With immune checkpoint inhibitor responsiveness associated with distinct CD8+ T cell populations (20), we next examined enrichment of signatures associated with response or nonresponse to anti-PD-1 therapies (Figure 2G). Using the ordinal construction of the trajectories, we created a pseudotime variable for cells, allowing us to see the difference in the enrichment along the curves. This approach allowed us to see an overall enrichment in responsiveness to anti-PD-1 at the terminal points of B2 and midpoints of B3, B4 and B5, corresponding to cells in CD8\_1 (Figure 2F, blue lines). Likewise, we observed an overall increase in gene expression associated with no response or progression was observed at the terminal points of B3, B4, and B5 (Figure 2F, red lines).

*Single-cell CD4+ T cell characterization in ccRCC finds disparate intratumoral with common endpoints.*

CD4+ T cells can target the tumor cells in various ways, either directly through cytolytic mechanisms or indirectly by modulating the tumor immune microenvironment. While CD4+ helper T cells promote T cell priming and both the effector and memory functions of CD8+ T cells, regulatory CD4+ T cells play key role for dampening responses from immune system against cancer. Subclustering of CD4+ T cells revealed 9 distinct clusters (Figure 3B), with a similar pattern to tissue distribution of predominantly peripheral blood CD4+ T cells on the right leading to tissue-infiltrating CD4+ T cells on the left (Figure 3B). The CD4\_8 was comprised solely of peripheral blood cells from the heathy donor and was eliminated from the remaining analysis. Like the CD8+ T cells, we next examined the canonical and differential T cells markers differences along the UMAP (Figure 3C). The first pattern that emerged was a naïve *CCR7*+ *SELL*+ *TCF7*+ being seen in CD4\_1 and CD4\_3 (Figure 3C). Within the tumor-infiltrating CD4\_4 cluster, we observed increased expression of the Th1 driver *TBX21* (T-bet), activation marker *LAG3* and *NR4A2* and cytokine expression (Figure 3C). Both CD4\_5 and CD4\_7 had expression of regulatory T (Tregs) cell markers (Figure 3C), with higher levels of *FOXP3*, *IL2RA* (CD25), *CTLA4* and *TNFRSF18* (GITR) in the tumor-predominant CD4\_5 (Figure 3C).

The pro- and anti-tumor role of CD4 T cell landscape within ccRCC remains relatively unexplored. Constructing the cell trajectory curves based on the CD4+ subclustering, we observed two origin points of the *CCR7*+ *SELL*+ *TCF7*+ Clusters CD4\_1 and CD4\_3 leading to a common CD4\_4 termination (Figure 3D). Unlike the other CD4+ T cells, the curve generated for Tregs was divergent, starting at CD4\_5 through CD4\_7 and into CD4\_4 (Figure 3D). This likely represents a distinct expression pattern for Tregs (shared by CD4\_5 and CD4\_7) compared to other tumor-infiltrating CD4+ T cells. In addition, compared to the CD8+ subclustering, modest clonal expansion was seen in CD4\_4 and CD4\_5 and was not a clear pattern for cell trajectory. With the common termination point for the curves at Cluster CD4\_4, we next wanted to examine if there were common markers for CD4+ T cell infiltration in ccRCC by comparing tumor-infiltering to peripheral-blood CD4+ T cells (Figure 3E). Within tumor-infiltrating CD4+ T cell, 203 genes adjusted p-value < 0.05, log-fold change ≥ 0.5 and ∆ cell percent > 10% (Supplemental Table 4). Upregulated within the tumor-infiltrating CD4+ T cells were heat shock proteins (*HSPA1A* and *HSPA1B*), Jun and FOS constituents (*FOS*, *JUN*, *JUNB*), MHC-II molecules (HLA-DRB), and secreting molecules (*CCL5*, *GZMA*, *GZMK*) (Figure 3E). Several of the upregulated genes are shared across all the tumor-predominant CD4 Clusters (Figure 3E), however each cluster also had unique expression markers. For example, Cluster CD4\_4 had cytotoxic component and there was expression of *CD8A*, which likely represents modest contamination of CD8+ T cells (Figure 3E). These cells also had increased enrichment for cytolytic and type 1 interferons (Figure 3F). The CD4\_5 and CD4\_7 Treg cluster had preferential enrichment for metabolic pathways, with high levels of terminal differentiation in tumor-infiltrated CD4\_5 (Figure 3F).

**Methods**

*Subject Details and Tissue Collection*

Fresh blood and primary clear cell renal cell carcinoma (ccRCC) samples were obtained from the University of Iowa Tissue Procurement Core and GUMER repository through the Holden Comprehensive Cancer Center from subjects providing written consent approved by the University of Iowa ethics board committee. The patients were males with an age range of 67 to 74 years old. Tumor grades were histologically determined by a pathologist. Primary tumor stage for Patient 1 and Patient 2 were reported as pT1b without extension, while Patient 3 was reported as pT3a with vascular invasion into renal vein. Three ccRCC tumor specimens paired with individual blood samples were used in the study. Will need IRB FOR publication

*Tumor Dissociation and Isolation of Mononuclear Cells*

Renal tumor samples were dissociated into single cells by a semi-automated combined mechanical/enzymatic process. The tumor tissue was cut into pieces of (2-3mm) in size and transferred to C Tubes (Miltenyi Biotech, Bergisch Gladbach, Germany) containing a mix of Enzymes H, R and A (Tumor Dissociation Kit, human; Miltenyi Biotech). Mechanical dissociation was accomplished by performing three consecutive automated steps on the gentleMACS Dissociator (h\_tumor\_01, h\_tumor\_02 and h\_tumor\_03). To allow for enzymatic digestion, the C tube was rotated continuously for 30 min at 37°C, after the first and second mechanical dissociation step (33). Cells from fresh tumor specimens were incubated with FcR blocking reagent (StemCell Technologies, Vancouver, Canada) for 10 min at 40C and labelled with 1ug/ml of the FITC anti-human CD45 antibody (BioLegend, San Diego, CA) per 107 cells for 20 min at 40C. CD45+ cells were isolated using the EasySepTM FITC Positive Selection Kit (StemCell Technologies). Alternatively, mononuclear cells (MNCs) from whole peripheral blood of paired subjects were isolated using SepMate Tubes (StemCell Technologies) by density gradient centrifugation. Cells were then viably frozen in 5% DMSO in RPMI complemented with 95% FBS. Cryopreserved cells were resuscitated for flow cytometry analyses by rapid thawing and slow dilution.

*Cell Sorting for Single-Cell RNA sequencing*

Viable immune (CD45+ Hoechst-) single cell suspensions generated from three ccRCC tumor samples and blood were FACS sorted on a FACS ARIA sorter (BD Biosciences) for lymphoid and myeloid cells (Ratio 3:1). The cells were sorted into ice cold Dulbecco’s PBS + 0.04% non-acetylated BSA (New England BioLabs, Ipswitch, MA). Sorted cells were then counted and assessed viability MoxiGoII counter (Orflo Technologies, Ketchum, ID) ensuring that cells were re-suspended at 1000 cells/ul with a viability >90%.

Library Preparation, Single-Cell 5’ and TCR Sequencing

Single-cell library preparation was carried out as per the 10X Genomics Chromium Single Cell 5' Library and Gel Bead Kit v2 #1000014 (10x Genomics, Pleasanton, CA). Cell suspensions were loaded onto a Chromium Single-Cell Chip along with the reverse transcription (RT) master mix and single cell 5′ gel beads, aiming for 7,500 cells per channel. Following generation of single-cell gel bead-in-emulsions (GEMs), reverse transcription was performed using a C1000 Touch Thermal Cycler (Bio-Rad Laboratories, Hercules, CA); 13 cycles were used for cDNA amplification. Amplified cDNA was purified using SPRIselect beads (Beckman Coulter, Lane Cove, NSW, Australia) as per the manufacturer’s recommended parameters. Post-cDNA amplification reaction QC and quantification was performed on the Agilent 2100 Bioanalyzer using the DNA High Sensitivity chip. For input into the gene expression library construction, 50ng cDNA and 14 cycles was used. To obtain TCR repertoire profile, VDJ enrichment was carried out as per the Chromium Single Cell V(D)J Enrichment Kit, Human T Cell #1000005 (10x Genomics) using the same input sample. Sequencing libraries were generated with unique sample indices (SI) for each sample and quantified. Libraries were sequenced on an Illumina HiSeq 4000 using a 150-pair-end sequencing kit. Gene expression FASTQ files were aligned to the human genome (GRCh38) using the CellRanger v2.2 pipeline, while clonotype sequencing was aligned to the vdj\_GRCh38\_alts\_ensembl genome build provided by the manufacturer.

*Incorporation of other SCRS data sets*

SCRS and TCR sequencing data processed using Cell Ranger v2.2 for healthy donor peripheral blood immune cells were acquired from the 10x Genomics website on 6/20/2020. Filtered gene matrix and contig annotations were used in the incorporation of the uniform manifold approximation and project (UMAP). Total number of cells from healthy peripheral blood control were 7,726. SCRS of normal immune populations in the kidney were derived previously published data (34). Gene expression matrices were downloaded from the EGAS00001002325 and filtered for normal renal parenchyma cells using the provided cell manifest for the samples RCC1, RCC2, and RCC3. These processed using the procedure as described above to form a UMAP. Immune cells were identified using canonical markers for lineage and were then isolated. Isolated immune cells for normal renal parenchyma were: RCC1 (n=1,011), RCC2 (n=888), and RCC3 (n=1,757).

*SCRS Integration*

Initial processing of cells isolated from ccRCC patients; Patient 1 (n=10,694), Patient 2 (n=5,174) and Patient 3 (n=9,805) were processed and integrated with the above samples using the Seurat R package (v3.0.2) (35,36). Samples were normalized using the *SCTtransform* approach (37) with default settings. Preparation for integration used 3,000 anchor features and *PrepSCTIntegration*. The integration of sequencing runs occurred with the SCT-transformed data. The dimensional reduction to form the UMAP utilized the top 30 calculated dimensions and a resolution of 0.7. Data characteristics by sequencing run can be found in Supplemental Table 1. Cell type subclustering used the SCTtransform approach as described above, but integrating the data across samples instead of individual sequencing runs. The adjusted dimensional inputs for the subclustering analysis can be found in Supplemental Table 2.

*SCRS Data Analysis and Visualizations*

The schex R package (v1.1.5) was used to visualize mRNA expression of lineage-specific or highly differential markers by converting the UMAP manifold into hexbin quantifications of the proportion of single-cells with the indicated gene expressed. Default bins across all cells was 80 and 40 for subcluster analyses, unless otherwise indicated in the figure legend. Differential gene expression utilized the Wilcoxon rank sum test on count-level mRNA data. For differential gene expression across clusters or subclusters, *FindAllMarkers* function in the Seurat package using the log-fold change threshold > 0.25, minimum group percentage = 10%, and the pseudocount = 0.1. Differential comparisons between condition utilized the *FindMarkers* function in Seurat, without filtering and a pseudocount = 0.1. Multiple hypothesis correction was reported using the Bonferroni method. Cell cycle regression was performed in Seurat using the *CellCycleScoring* function and genes derived from Nestorowa et alia (38). Genes were isolated by calling *cc.genes.updated.2019* in R.

Cell type identification utilized the SingleR (v1.0.1) R package (39) with correlations of the single-cell expression values with transcriptional profiles from pure cell populations in the ENCODE (28). In addition to correlations, canonical markers for cell lineages (Supplemental Table 3) and corresponding TCR sequences were used. Gene set enrichment analysis was performed using the escape R package (v0.99.0). Gene sets were derived from the Hallmark library of the Molecular Signature Database and from previous publications (20,23). Enrichment for anti-PD-1 therapy response was derived from Sade-Feldmen et alia to develop gene signatures for the CD8\_B (nonresponsive) and CD8\_G (responsive) single-cell populations(20). Differential enrichment analysis was performed using the *getSignificance* function in escape that is based on the limma R package linear fit model. TCR analysis utilized our previously described scRepertoire R package (v0.99.3) (40) with clonotype being defined as the combination of the gene components of the VDJ and the nucleotide sequence for both chains and assigned on the integrated Seurat object. Cell trajectory analysis used the slingshot (v1.6.0) R package (32) with default settings for the *slingshot* function and using the embedding from the subclustering for each cell type. Inferred start and end clusters were applied in the CD8+ T cell trajectory based on gene expression markers. Ranked importance of genes were calculated using the top 300 variable genes and rsample (v0.0.9) and tidymodels (v0.1.0) R packages were used to generate random forest model based on a training data set of 75% of the cells. The *rand\_forest* function in the parsnip (v0.1.1) R package was used, with mtry set to 200, trees to 1400, and minimum number of data points in a node equal to 15 across all cell types. The code for all analysis is available at <https://github.com/ncborcherding/ccRCC>.

*Statistical Analysis*

Statistical Analyses were performed in R (v4.0.1). Two-sample significance testing utilized Welch’s T test, with significance testing for more than three samples utilizing one-way analysis of variance (ANOVA) with Tukey honest significance determination for correcting multiple comparisons. Two-proportion Z-tests was performed using the total number of cells in each condition as the number of trials and without a prior for proportion.

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**Author contributions**

**Conception and design:** AV, YZ, WZ

**Development of methodology:** AV NB WZ

**Acquisition of data:** KN, YZ, AV

**Analysis and interpretation of data:** NB AV AS RWJ WZ YZ

**Writing, review, and/or revision of the manuscript:** AV NB AS RWJ WZ YZ

Supervision: YZ, WZ, RWJ

**Declaration of interests**

Dr. Russell W. Jenkins has a financial interest in XSphera Biosciences Inc., a company focused on using ex vivo profiling technology to deliver functional, precision immune-oncology solutions for patients, providers, and drug development companies. Dr. Jenkins’ interests were reviewed and are managed by Massachusetts General Hospital and Partners HealthCare in accordance with their conflict of interest policies.

**Data and materials availability:**

Quantified gene expression counts and V(D)J T cell receptor sequences for single-cell RNA sequencing are available at the Gene Expression Omnibus (GEO) at [GSE121638](https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE121638). Code for the analysis and visualizations are available at <https://github.com/ncborcherding/ccRCC>

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**Figures**

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**Figure 1: Single-cell sequencing results for immune cells in ccRCC.** A. UMAP of 37,055 primary immune cells of peripheral blood, normal renal parenchyma and tumor-infiltrating ccRCC patients. **B**. Distribution of cells by tissue type, peripheral blood (blue), tumor (red), and kidney (light blue). Arrows indicated potential enriched or unique immune cells populations for tissue type. **C**. Percent of cells expressing canonical immune cell markers across the UMAP. **D**. Normalized correlation values for predicted immune cell phenotypes based on the SingleR R package for each cluster. **E**. UMAP demonstrating inferred immune cell types in ccRCC, clusters are colored by cell type and proportion of single-cell per sequencing run by tissue type. P values based on one-way ANOVA; lack of p-values equates to value > 0.05.

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**Figure 2: CD8+ T cells in ccRCC tumors exhibit a transcriptional continuum with distinct populations. A.** UMAP subclustering of CD8+ T cells (original clusters 1, 8, 9, and 17). **B**. UMAP distribution of single cells by tissue type with relative percent of cells by tissue in each cluster. **C**. Cell cycle regression assignments for CD8+ T cells by cluster assignment. **D**. Percent of cells expressing selected markers for T cell biology. **E**. CD8+ UMAP of clusters (upper panel) and clonotype frequency (lower panel) overlaid with slingshot-based (32) cell trajectory starting at CD8\_4 and proceeding into 5 distinct curves: branch 1 (B1), B2, B3, B4, and B5. **F**. Z-transformed normalized enrichment scores from ssGSEA for selected gene sets by subcluster. **G**. Normalized enrichment scores for therapeutic response or lack of response to anti-PD-1 therapy across the CD8+ T cells (upper panel) and by pseudotime of each branch (lower panel).

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**Figure 3: Single-cell CD4+ T cell characterization in ccRCC finds disparate intratumoral with common endpoints.** **A**. UMAP subclustering of CD4+ T cells (original clusters 4, 6, 10, 13, 15, and 20). **B**. UMAP distribution of single cells by tissue type with relative percent of cells by tissue in each cluster. **C**. Percent of cells expressing selected markers for T cell biology. **D**. CD4+ UMAP of subclusters (upper panel) and clonotype frequency (lower panel) overlaid with slingshot-based (32) cell trajectory starting from CD4\_1 (root 1) and CD4\_1 (root 2) with relative pseudotime for all curves calculated using slingshot. **E**. Percentage difference (∆ percent of cells) and log-fold change based on the Wilcoxon rank sum test results for differential gene expression comparing TI to PB CD4+ T cells in ccRCC patients (left panel), colored points indicate adjusted p-values < 0.05. Right panel includes top 10 markers for TI-predominant CD4+ subclusters. Size of points are relative percent of cells in cluster expressing the indicated mRNA species. **F**. Z-transformed normalized enrichment scores from ssGSEA for selected gene sets by subcluster.