Quantitative MRI Measurements Capture Pancreatic Cancer and Stroma Reactions to New KRAS Inhibitor

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Abstract

In pancreatic ductal adenocarcinoma (PDAC), KRAS mutations drive both cancer cell growth and formation of a dense stroma. Small molecule KRAS inhibitors (KRASi) represent a breakthrough for PDAC treatment hence clinical tools that can assess early response, detect resistance and/or predict prolonged survival are desirable for management of patients undergoing KRASi therapy. We hypothesized that diffusion-weighted MRI (DWI) can detect cell death while dynamic contrast enhanced MRI (DCE) and magnetization transfer ratio (MTR) imaging are sensitive to tumor microenvironment changes, and these metrics shed insights into tumor size (standard care assessment) change induced by KRASi treatment. We tested this hypothesis in multiple preclinical PDAC models receiving MRTX1133, an investigational new drug specific for $KRAS^{G12D}$ mutation. Quantitative imaging markers corroborated by immunohistochemistry (IHC) revealed significant and profound changes related to cell death accompanied by changes in tumor cellularity, capillary perfusion /permeability and stromal matrix as early as 48h and day-7 after initiation of KRASi treatment, and greatly prolonged median survival over controls in a genetic engineered mouse model of PDAC (KPC). The MRI markers also captured distinct responses to KRASi therapy from PDAC tumors carrying $KRAS^{G12C}$ *versus* $KRAS^{G12D}$ mutation. In tumors developed resistance to MRTX1133, the imaging markers exhibited a reversal from those of responding tumors. Our findings have established that multiparametric MRI provide biological insights including cell death, reduced cellularity and tumor microenvironment changes induced by KRASi treatment and set the stage for testing the utility of these clinically ready MRI methods in patients receiving KRASi therapy.

Translational relevance

Emerging small molecule KRAS inhibitors (KRASi) represent a new class of therapy for PDAC. Clinical tools that can provide biological insights beyond tumor size change are desirable for management of patients under KRASi therapy. DWI and DCE are frequently applied MRI methods for assessing cancer treatment responses in clinical trials. Using multiple PDAC models, we examined whether DWI, DCE and MTR can enhance the standard care assessment (tumor size) to MRTX1133, a KARSi with investigational new drug (IND) status. Our data demonstrate the abilities of DWI, DCE and MTR derived imaging markers to detect the early (48h) cell death, pronounced stromal changes and development of resistance to KRASi. This study has high translational relevance by testing clinically ready MRI methods, an IND and a genetic engineered mouse model that recapitulates saline features of human PDAC.

Introduction

The oncogene RAS is involved in 1/3 of human cancers, and among the 3 isoforms of RAS (KRAS, HRAS and NRAS), KRAS mutations account for a majority (85%) of RAS mutations and occur almost exclusively in pancreatic ductal adenocarcinoma (PDAC), where 98% patients carrying KRAS mutations at glycine 12 position ($KRAS^{G12X}$) (1). The mutant RAS protein exists predominantly in an active, GTP-bound state, leading to hyperactive signaling of cell proliferation and survival (2). KRAS mutation also drives the formation of a desmoplastic stroma, which restricts drug delivery and presents an immune suppressive tumor microenvironment (TME) (3-5). Recent breakthroughs in the development of small molecule RAS inhibitors (RASi) have led to FDA approval of two $KRAS^{G12C}$ inhibitors, Adagrasib and Sotorasib, for lung cancer treatment. Furthermore, RASi targeting G12D, G12V, G13X and Q61X mutations and wild type RAS are being evaluated in various phases of clinical trials (6-10). Together with other RAS inhibiting modalities (11-13), this new class of RAS inhibitory agents hold the potential to transform the treatment of RAS-driven cancers especially PDAC, which remains the third-leading cause of cancer-related deaths.

To assess responses of PDAC tumors to KRAS inhibitor (KRASi) therapy in the clinic, we expect RECIST-based tumor size (14) to provide an objective metric of tumor regression observed in earlier studies (9,15). However, insights into tumor size reduction are desirable. Specifically, cancer cell death can result from the blockade of ERK signaling upon engagement of KRASi to its target (16), meanwhile, a mechanism that KRAS inhibition induces T cells mediated cancer cell killing is plausible (17). Indeed, significant apoptosis of PDAC cells was detected in tumor specimens at early stage of KRASi treatment (15) hence clinical tools that can detect early cell death would be useful to confirm the drug-target engagement. Besides cell death, stromal changes induced by KRASi also contribute to tumor size regression and have a great impact on TME. Knowledge of microvascular perfusion and permeability is important since these properties influence lymphocytes attachment to capillary lumen and extravasation into tumor parenchyma (18-20).

Based on these considerations, we evaluated clinically ready MRI modalities including diffusion weighted MRI (DWI), dynamic contrast enhanced MRI (DCE) and magnetization transfer ratio (MTR) in addition to standard care tumor size measurement in the setting of KRASi therapy. While DWI markers associated with other diffusion regimens (21,22) have been applied in the clinic studies, apparent diffusion coefficient (ADC) derived from Gaussian diffusion model appears to be most robust, capable of early detection of tumor response and prediction of treatment outcomes in many clinical studies - reviews/ editorial (23-26). ADC quantifies the *hindered* diffusion of water molecules in *extracellular space* (ECS) of tumor tissues due to the presence of cell membrane and extracellular matrix components, making ADC most sensitive to *ECS volume fraction and geometry* (27). For example, significant cancer cell death induced by chemotherapy and radiotherapy respectively increased the tumor ADC compared to pretreatment values, while tumor ADC was shown to positively correlate with apoptosis and inversely correlate with tumor cellularity (28,29). We <u>hypothesized</u> that in tumors responding to KRASi, an increase of ADC early after KRASi treatment is indicative of cell death hence confirming drug-target engagement.

DCE offers a tool for evaluating microvascular function (perfusion and permeability) *in vivo*, and like ADC, the utility of DCE has been established in clinical studies of cancer therapies

specifically for assessing their anti-angiogenic and /or anti-vascular effects (30). K^{trans}, a DCE metric related to capillary perfusion and permeability, can detect early responses and predict complete pathological response to chemotherapy (31) and reveal vascular effect mediated by stroma directed drug against PDAC (32). We hypothesized that the DCE metrics K^{trans} and extracellular & extravascular volume fraction (V_e) can detect KRASi-induced changes in microvascular functional features.

MTR imaging is sensitive to the relative volume fractions of bound versus free water and the exchange rate between the two. Increased collagen deposition associated with pathological conditions such as fibrosis provides increased surface area for water molecules to bind, hence is associated with increased MTR (33,34). We therefore hypothesized that MTR is sensitive to changes in matrix collagen induced by KRASi treatment. Recently, however, changes in MTR were related to alterations in cellularity in a study of bone marrow malignancy (35).

Taken together, tumor size, DWI, DCE and MTR constitute a *multiparametric MRI* (mpMRI) tool (described in **SI Figure 1**) that can potentially provide insights into clinical biology of KRASi therapy. To assess this approach, we conducted a preclinical trial of an investigational new drug (IND), MRTX1133, a KRASi specific for $KRAS^{G12D}$ mutation in multiple PDAC models including 1) a genetically engineered mouse model of PDAC that features activating $KRAS^{G12D}$ mutation and recapitulates many key features of the human disease (36); subcutaneously (SubQ) implanted models from isogenic PDAC cells carrying 2) $KRAS^{G12C}$ and 3) $KRAS^{G12D}$ mutation, respectively; and 4) orthotopically implanted model of $KRAS^{G12D}$ PDAC cells. We assessed the imaging metrics for their ability to detect early responses at 48 hours (Day2) and stable responses on Day7 of treatment course. We further examined whether baseline mpMRI such as tumor size can predict median survival of MRTX1133 treated mice. Finally, we compared mpMRI and IHC signatures of tumors at resistant *versus* responding stages to gain insights of TME and cancer cell death and proliferation status which may facilitate the design of combinational therapy for overcoming the resistance.

Materials and Methods

All animal procedures were approved by the institutional animal care and use committee (IACUC) of the University of Pennsylvania.

Mouse models

A genetically engineered KrasLSL^{G12D}-Trp53LSL^{R172H}-Pdx1-Cre (KPC) mouse model of PDAC (36) was bred in the Mouse Hospital of Abramson Cancer Center, University of Pennsylvania. Additional PDAC models were generated from murine cell lines: 4662-G12D cells carrying KRAS^{G12D} mutation and its isogenic counterpart carrying KRAS^{G12C} mutation (15) were respectively inoculated in the flank of C57/B6 mice (Charles River) to grow subcutaneous (subQ) tumors. In separate mice, 4662-G12D cells were inoculated into the pancreas to grow orthotopic tumors as we described previously (32).

Study design

As outlined in **Figure 1**, four studies were conducted. Study in **A** assessed mpMRI in KPC mice after 2 days (Day2) and 7 days (Day7) of MRTX1133 treatment, respectively. Study in **B** assessed survival benefit of KARSi therapy and whether baseline mpMRI can predict the survival: KPC mice were enrolled in MRTX1133 (n=20, tumor volume = 227±74 mm^3) or CNTRL (n=20, tumor volume = 181±94 mm^3) after baseline mpMRI and their survival durations were recorded. In case a mouse needed be euthanized according to IACUC guidelines, the death was recorded for the next day. Study in **C** assessed whether mpMRI can detect the specificity of MRTX1133 to KRAS^{G12D} mutation using isogenic 4662-G12D and 4662-G12C model on Day2. Study in **D** assessed the development of resistance to MRTX1133 in KPC model and compared mpMRI in resistant versus responding stages: Tumor size was monitored by weekly T2W MRI. The treatment was paused if tumor size became radiographically undefined and resumed when the tumor was measurable again. Resistance is defined as tumor size increases from prior week while on treatment. The first time that a resistant tumor was detected was labeled as resistant stage-1 (R1) and the mouse was monitored for 2 additional weeks (R2 and R3) to confirm no regression as treatment continued. mpMRI data were collected at R1, R2 and R3 stages with the exception of DCE protocol, which was only applied at R1 due to relatively complex protocol.

In all studies, male and female mice were randomized and enrolled in MRTX1133 or control (CNTRL) group. MRTX1133 (Mirati Therapeutics) formulated in vehicle (15) was injected intraperitoneally (ip) at 30 mg/kg twice daily while 0.2 mL PBS was ip injected in CNTRL mice.

In vivo multiparameter MRI (mpMRI) studies

Animal preparation General anesthesia was induced during preparation and maintained during MRI studies via breathing of 1–3% isoflurane in air through a nose cone. A tail vein catheter was placed with an extension tubing preloaded with ProHance (Bracco Diagnostic, NJ, USA) diluted (50×) in PBS to 10 mM Gd to facilitate contrast agent injection during DCE acquisition. The animal was placed on a 3D printed bed, which was positioned in a 35 x 40 (ID x length) mm quadrature birdcage RF coil (M2M, Cleveland, OH, USA). During MRI, vital signs were

monitored via a rectal temperature probe and pneumatic respiration pillow (SAII, Stonybrook, NY, USA), and core body temperature was maintained at 37 ± 0.2°C by warm air (32,37-39).

T2W, DWI, DCE and MPR acquisitions: MRI studies were performed on a 9.4 T Avance III console (Bruker, Berillica, MA, USA), equipped with 12 cm ID, 40 G/cm gradients. Following calibrations of the scanner and generation of scout images, an axially oriented contiguous series of T2W images spanning the entire tumor was generated using a TurboRare protocol (effective TE = 30ms, TR = 1.8 s, echo train length = 8, matrix = 64 x 64, slices = 16, FOV = 32 x 32mm, thickness = 0.5 mm, averages = 4, total acquisition time ~2min). The image orientation and abdominal region coverage of the T2W scan were passed to DWI, DCE and MTR scans.

To mitigate respiratory motion-induced artifacts in DWI, a radial k-space sampling scheme (37,38) was employed with acquisition parameters of diffusion time (Δ) = 14 ms, diffusion gradient duration (δ) = 9 ms, b-value = 10, 535, 1070, 1479, and 2141 s/mm^2, TE/TR = 28.6/750 ms, matrix size = 64 × 403, averages = 1, bandwidth = 50 kHz with fat saturation and total acquisition time approx. 25 min. No respiration gating was employed while the mouse was breathing freely during acquisition.

To enable optimal special and temporal resolution of DCE, 3D stack-of-stars (SoS) sequence was applied to all acquisitions in the DCE protocol including B1 maps by actual flip angle imaging (AFI), T1 maps by variable flip angle (VFA) imaging and the DCE series by a golden-angle (111.25°) ordering scheme to obtain a uniform coverage of k-space we described previously (39). Two minutes after starting the DCE series, 0.2 mL of diluted Prohance (detailed in Animal Preparation) was injected over 10 s manually via the catheter. All components of the DCE protocol had matrix size = 64×201×16 and FOV = 32×32×8 mm^3.

For MTR, a magnetization prepared 3D GRE was acquired with FOV= 32x32x8 mm, matrix= 64x64x16, TR/TE /flip = 5.7 /2.8 ms /5°, averages = 4 with an 18 sec 2.5 µT saturation pulse applied at 4 kHz (MT_{on} image) and 250 kHz off-resonance (*Reference* image), respectively. Each saturation pulse was followed by acquisition of a full plane k-space data using centric phase encoding.

Data Analytics

The tumor volume was determined by manually tracing the tumor boundary on T2W images to generate tumor ROIs, summing the areas from all ROIs and multiplying the result by the slice thickness. DWI, DCE and MTR metrics were estimated over the same ROIs.

DW-MRI metrics: Radial k-space data were reconstructed to images using custom python codes (*https://github.com/PennPancreaticCancerImagingResource/DWIProcessing*). The reconstructed images were subject to pixel-wise least squares fit to Equation [1] using all five b-values as described previously (38), where S_0, *ADC*, and *KI* are the fitting parameters: S_0 is the signal intensity in the absence of diffusion weighting and *KI* (kurtosis index) is a constant that accounts for contributions from water molecules undergoing slow hence non-gaussian diffusion to the observed signal *S(b).*

$$S(b) = S_0 \exp\{-b \times ADC\} + KI \qquad [1]$$

DCE-MRI metrics: Radial k-space data were reconstructed using k-space weighted image contrast (KWIC) method to obtain optimal spatial and temporal resolution for DCE images as we

described previously (39). The shutter-speed kinetic model programmed in custom IDL codes (Harris Geospatial Solutions, Broomfield, CO, USA) was used for least-square fitting of the dynamic data to derive the DCE metrics: K^{trans} (rate constant of transferring unit volume of contrast agent from capillaries to interstitial space per minute), V_e (extracellular and extravascular volume fraction, %,) and τ_i (intracellular water life time in second) (40). Additional inputs to the fitting include T1 maps and a group arterial input function (AIF) derived from KPC mice (41).

MTR metrics: MTR value was calculated pixel-wise by equation [2] to generate MTR maps from tumor ROIs:

$$MTR = (Reference - MT_{on})/Reference \qquad [2],$$

Where the MT_{on} and *Reference* image were acquired with and without saturation of motion-restricted water, respectively.

The range of MTR value (0-1) was divided into 25 equal width bins and the number of pixels in each bin was normalized to total number of pixels in the tumor. Since tumor MTR values were primarily distributed between 0-0.56 (1st – 15th bins) with less than 10 pixels per tumor whose MTR were greater than 0.56 hence 16th - 20th bins were combined into the 15th bin. MTR histogram was generated from $MTR_{Bin[x]}$, where x is the bin number (1, 2, …, 15).

Immunohistochemistry, Immunofluorescence and Collagen Assay

Immunohistochemistry (IHC) for Sirius Red, H&E and CD31 of formalin fixed paraffin embedded (FFPE) tumor sections were conducted by the Pathology Core of Children's Hospital of Philadelphia (www.research.chop.edu/pathology/tools). Stained sections were scanned at ×40 magnification using Aperio ScanScope CS2 (Leica Biosystems Imaging, CA, USA) and uploaded to QuPath for analyses (42). For each section, tumor regions were defined, and hand drawn by a pathologist (EEF) of GI cancer. Sections stained with H&E, Sirius Red, and CD31 were used to determine viable cell density, % fibrosis, and microvascular density (MVD), respectively.

For immunofluorescence (IF) staining of pERK1/2, CK19, Ki-67, cleaved Caspase-3 (CC3), α-SMA, FFPE slides were deparaffinized and rehydrated through a series of xylene and ethanol washes. Antigen retrieval was followed by blocking with 5% donkey serum for 1 hour at room temperature. Based on dilution schemes in **SI Table-1**, primary antibodies were incubated with the slide and for 1 hour at 4°C followed by 2× wash with PBS and incubation with secondary antibodies for 1 hour at room temperature. Nuclei were counterstained with DAPI (1:1000). Slides were mounted with aqua-poly mount and cover slipped. Images were captured using an Olympus IX71 inverted microscope with 4× and 20× objectives and a DP71 camera, and 3-5 magnified views per sample were analyzed using FIJI software.

To estimate collagen content, tumor tissue was homogenized in DI water (500 µL per 50 mg of tissue) in a homogenizer (Bertin Technology, Rockville, MD). The homogenate was transferred to a screw-cap tube to which 100 µL of 10 N NaOH was added, and the mixture was heated at 120°C for 1 hour. Afterwards, the tube was cooled followed by addition of 100 µL of 10 N HCl and centrifugation at 10,000 x g for 5 minutes. The supernatant was collected for estimation of collagen concentration according to the manufacturer's instructions (ab222942, Abcam, Newark, DE).

Statistical Analysis

For every MRI metric (ADC, KI, MTR, K^{trans}, V_e), the median value is estimated from all pixels in the ROIs of each tumor. Mean +/- Stdev of each metric were compared between groups. Same analysis was applied to $MTR_{Bin[x]}$, where x is the bin number (1, 2, …, 15). Statistical analyses were conducted in GraphPad or by R software with α value set at 0.05. Shapiro-Wilk normality test was applied to all data. For data that passed the test, two-tailed t-test assuming unequal variance or paired-test were applied as appropriate (specified in figure captions); for a fraction of data sets that did not pass the normality test, nonparametric tests (Mann-Whitney or Sign Rank) were used instead and specified in captions.

Bootstrapping analysis was conducted to confirm the statistical significance of MTR_{Bin} values. MTR bins were categorized into 4 groups (i.e., 0-0.2, 0.2-0.4, 0.4-0.6, and 0.6-1), and the proportion of tumor pixels within each MTR range was calculated for baseline and Day2. Given the relatively small sample size (n=10), the upstrap method (43) was used to simulate a larger sample size and build the 95% CI for the mean difference in proportion between baseline and post-treatment.

To assess the ability of individual MRI metrics (tumor size, ADC, KI, MTR, K^{trans} and V_e) to predict survival and occurrence of resistance, Pearson correlation and regression analyses were performed.

Results

mpMRI captured the early (Day2) and stable (Day7) response to KRASi therapy

mpMRI study of therapeutic response on Day2 and Day7 enrolled separate KPC cohorts and tumor tissues were collected after imaging (**Figure 1A**). mpMRI and IHC results on Day2 are summarized in **Figure 2-3** and **SI Figure 2-3** while those on Dday7 in **Figure 4** and **SI Figure 4**.

At baseline, tumors were readily delineated on T2W images (yellow dotted line, **Figure 2A**) and appeared homogenous. Parametric maps of tumor ADC, KI, MTR, K^{trans} and V_e in pseudo color overlaid on the T2W images were more homogeneous at baseline vs. Day2 (**Figure 2A-F**). MRTX1133 group had a 36% reduction of tumor size (from 359±133 mm^3 to 231±99 mm^3, n=12, $P < 0.0001$) in contrast to a 32% increase in CNTRL (from 335±164 to 443±220, n=9, $P < 0.01$). Meanwhile, a 31% increase in tumor ADC (from 1.50±0.22 $x10^{-3}$ to 1.96±0.28 $x10^{-3}$ mm^2/s, n = 8, $P < 0.01$) in treated animals was highly significant as no change was observed in CNTRL (**Figure 2B**). To corroborate the mpMRI results, we evaluated cancer cell and stromal markers in tumor specimens collected after mpMRI (**Figure 3**): As a marker of KRAS/RAF/MEK pathway activity, a remarkable reduction in phospho-ERK (pErk1/2) level (15.2±2.3% vs. 3.0±1.0%/CNTRL, n=3 for both groups, $P < 0.01$, **Figure 3A**) confirmed the drug-target engagement. Consequently, significantly increased cancer cell death by CC3 staining (1.5±0.5% /Treated vs. 0.4±0.2%/CNTRL, $P < 0.001$, n = 5) and reduced cancer cell proliferation by Ki67 (2.5±0.7%/Treated vs. 5.2±0.1 /CNTRL, $P < 0.05$, n = 2-3) were observed and are consistent with an increased ADC since loss of membrane integrity and/or clearance of dead cells would increase diffusion path length and ADC.

On Day7, pErk1/2 remained significantly suppressed, indicating persistent $KRAS^{G12D}$ inhibition (**Figure 4G**), whereas increase in apoptosis (CC3) and reduction in proliferation (Ki-67) diminished compared to Day2, suggesting that extensive cell death occurred most intensively at early stage of KRASi therapy and waned overtime. However, the increase in ADC persisted to Day7 ($P < 0.05$, n = 7, **Figure 4B**), likely because clearance of dead cells sustained a low tumor cellularity. Combining Day2 and Day7 mpMRI and IHC data, a highly significant correlation between ADC and CC3 ($R = 0.70$, $P < 0.01$, **Figure 3C**) as well as an inverse correlation between ADC and cellularity ($P < 0.01$, $R = -0.68$, **Figure 3D**) were identified. These data provide a strong support that cell death and reduced cellularity underlie the increased ADC observed after KRASi therapy.

mpMRI also detected KRASi mediated changes in stroma and TME. First, a highly significant increase in DCE metric K^{trans} was observed on Day2 in treated animals (0.11±0.04 min^{-1} vs. baseline /0.07±0.04, n = 4, $P < 0.05$, **Figure 2E**), suggesting increased microvascular perfusion /permeability in response to KRASi therapy, whereas no changes were detected in CNTRL (**Figure 2E**). Increased K^{trans} persisted to Day7 ($P < 0.01$, n=5, **Figure 4E** upper). Paradoxically, MVD was significantly reduced on Day2 (1.2±0.0% /Treated vs. 3.3±1.2% /CNTRL, n = 3, $P < 0.01$, **Figure 3B**) with the same trend clearly shown on Day7 despite not reaching statistical significance (**Figure 4H**). Increased K^{trans} accompanied by reduced MVD on Day2 and Day7 led to a strong *inverse* correlation between K^{trans} *versus* MVD ($R = -0.72$, $P < 0.05$, **Figure 3E**).

Second, tumor collagen content was significantly increased on both Day2 and Day7 (**SI Figure 2**), consistent with significantly increased αSMA staining (**Figure 3B** and **Figure 4H**) and the trend of increased SR staining on Day7 (**Figure 4H**). However, *no increase* in the mean MTR or MTR_{bin} values were detected on either timepoint (**Figure 2D** and **Figure 4D**), suggesting MTR

parameters cannot mark the increased collagen content in KRASi therapy setting. Instead, *reductions* of MTR bin-12 and bin-13 (correspond to MTR ranging 0.4- 0.56) were detected on Day2 compared to baseline in treated tumors ($P < 0.05$, n = 10, **Figure 2D**). This result was confirmed by the bootstrap analysis of MTR_{bin} that 40% tumor voxels with MTR value of 0.4-0.6 at baseline was reduced to 23% on Day2 ($P < 0.05$, n=10 from both MTRX1133 and CNTRL group). Such reduction is consistent with cell death leading to reduced intracellular bound water pool.

The longer treatment period of 7 days led to more uniform treatment effects: the trend of reduction in KI detected on Day2 reached statistical significance on Day7 (12.14±2.77 vs. 15.37±2.15 / baseline, n = 7, $P < 0.01$, **Figure 4C** upper panel) so did DCE metric, V_e ($P < 0.05$, n = 5, **Figure 4F** upper) consistent with deeper tumor regression (Day7/ 97±87 mm^3 vs. Day2/ 231±99 mm^3, $P < 0.001$, n = 12, **Figure 4A**). On Day7, CNTRL group exhibited 14% reduction in ADC (n= 10, $P < 0.01$, **Figure 4B** bottom) and 28% reduction in K^{trans} (n= 6, $P < 0.05$, **Figure 4E** bottom) consistent with significant tumor progression (n= 10, $P < 0.001$, **Figure 4A** bottom).

Taken together, on Day2, pronounced increase of ADC and K^{trans} accompanying reduced tumor size revealed the pharmacodynamic effect on cancer cell and tumor microenvironment, providing biological insights at very early stage of KRASi therapy. Consistent behavior of these mpMRI metrics on Day7 suggest that they are robust that a responding tumor is likely to present with both elevated ADC and K^{trans} besides a reduced tumor size.

In the survival study (**Figure 1B)** where MRTX1133 treatment extended beyond Day7, a median survival of 57 days in treated (n=20) vs. 22 days in CNTRL (n=20, $P < 0.0001$, Mantel-Cox test, **SI Figure 6**) were detected. For treated mice, baseline tumor size (or other MRI metrics) did not appear to predict survival since neither Pearson correlation nor regression analyses reached statistical significance.

Responses of $KRAS^{G12D}$ *vs* $KRAS^{G12C}$ tumors to MRTX1133

Subcutaneous models from isogenic 4662 PDAC cells carrying $KRAS^{G12C}$ and $KRAS^{G12D}$ mutation, respectively were enrolled for mpMRI study of therapeutic response on Day2 and euthanized after imaging (**Figure 1C**). The results are summarized in **Figure 5** and **SI Figure 6**. Consistent with MRTX1133's specificity, G12D subQ tumors exhibited a significant regression (**Figure 5A**) and an increase of K^{trans} (**Figure 5D**) while the on-target effect was confirmed by reduced pERK1/2 (n = 3, $P < 0.05$) and proliferation (n = 3, $P < 0.001$) compared to treated G12C tumors (**Figure 5E**). In contrast to increased ADC observed in KPC mice (Figure 2B), a majority of subQ G12D tumors exhibited a *reduction* in ADC on Day2 vs. baseline (P = NS, n=5, **Fig. 5B**, stared panel). Given ADC's sensitivity to tumor cellularity, we suspect the unique feature of subQ G12D model might play a role: its fast growth was associated with the development of central necrosis in a fraction of tumors when tumor volume exceeded 50 mm^3 whereas G12C tumors grew much slower often in absence of gross necrosis. Although mice bearing visible necrotic tumors were not enrolled, the accumulation of inflammatory cells were observed in H&E sections of enrolled tumors (data not shown).

To test whether the unexpected ADC change is specific to subQ model, we inoculated 4662-$KRAS^{G12D}$ in the pancreas to produce orthotopic tumors and enrolled them when they grew to

approximately 200 mm^3. ADC increases were observed in all treated mice (from 1.81±0.22 $x10^{-3}$ mm^2/s to 2.21±0.16 $x10^{-3}$ mm^2/s, n = 3, $P < 0.05$, **Figure 5B, ortho G12D panel**).

Although the lack of difference in cancer cell markers between treated vs. CNTRL G12C tumors (**Figure 5E**) supports the specificity of MRTX1133 to G12D mutation, an unexpected finding in stromal markers was a highly significant decrease in SR staining in treated tumors (8.2±2.5 vs. 2.9±1.4 /CNTRL, n = 3-5, $P < 0.01$, **Figure 5F** stared panel). Interestingly, reduced SR was coincided with decreased tumor MTR values in G12C tumors after MRTX1133 treatment (n=4, $P = 0.0534$, **Figure 5C,** star-marked panel and **SI Figure 6C**), suggesting that MTR could mark reduced collagen in G12C tumors to which MRTX1133 did not have on-target effects hence not inducing significant changes in cellularity or cancer cell death.

In summary, results from 4662 isogenic models confirmed that the mpMRI can capture the drug's specificity to G12D mutation while revealing a potential stromal effect on G12C tumors.

mpMRI of tumors resistant to KRASi

Of the 27 KPC animals enrolled in the therapeutic resistance study (**Fig 1D**), resistance was confirmed in 17 mice while 10 died or were euthanized. Evolution of tumor size (**Figure 6A**) revealed that MRTX1133 treatment eradicated tumors in a subset of KPC mice temporarily, as their size fell beneath the radiographic threshold (dotted line) and became isointense with surrounding tissues on T2W MRI. However, tumor regrew shortly after treatment stoppage and eventually all surviving mice developed resistance defined as cancer outgrowth while under treatment (44). The first time that a resistant tumor was detected is labeled as Resistant stage-1 (R1) when tumor size increased from the prior week. The mouse was then monitored for 2 additional weeks (R2 and R3) to confirm no tumor regression. Tumor volume increased rapidly once resistance was established (R1/ 276±123 mm^3/ n=17, R2 / 502±258 mm^3/ n=14, R3 /688±481 mm^3 / n=9, **Fig 6B**). ADC and KI values at R1/2/3 stages were reversed (hence significantly different) from those on Day2 and Day7 ($P < 0.05$ and $P < 0.01$, **Fig 6C**) while trending toward the baseline values (**SI Fig 7B**). The reversal of mpMRI was corroborated by reversal of pERK1/2 (n=6, $P < 0.01$) and CC3 level in R3 tumors (n=6, $P < 0.0001$) compared to Day2 and/or Day7 (**Figure 6E**).

Assessing whether Day7 mpMRI can predict resistance development, we found that tumor size did not correlate with time to first resistance (R = 0.011, P =0.97, n=17). However, a trend of negative correlation was observed between ADC and time to R1 (R = -0.83, P = 0.08, n= 5). Despite relatively small sample size, the analysis of ADC's predictive power could help generate hypothesis for future studies.

In summary, upon development of resistance to KRASi, mpMRI metrics (ADC, KI and V_e) exhibited a reversal of values from responsive stages, revealing increased heterogeneity of diffusion (KI ++), reduced EES fraction (V_e --) consistent with increased cellularity (ADC --) and disease progression (tumor volume +++).

Discussion and Conclusion

In this study, we examined clinically ready quantitative MRI metrics including tumor volume, DWI (ADC, KI), DCE (K^{trans}, V_e), MTR to evaluate responses of PDAC tumors to KRASi (MRTX1133) treatment on Day2, Day7 and after prolonged treatment that leads to acquired resistance. While tumor size provides an objective measure of KRASi effect and a reference for the development of drug resistance, ADC and K^{trans} offer insights of cell death, reduced cellularity and significant stromal changes underlying tumor size reduction. On Day2 post treatment, significant increases in ADC are indicative of cell death that is confirmed by CC3 staining and pronounced reduction of pErk1/2 level in cancer cells, a marker of MRTX1133 engagement to its target. Maps of mpMRI metrics on Day2 revealed remarkable intratumor heterogeneity compared to baseline induced by KRASi treatment (**Figure 2**) corroborated by histopathology (**SI Figure 3**). On Day7, tumor ADC values remain elevated due to sustained suppression of pErk1/2. Additional markers include KI and V_e (EES) become significant on Day7 primarily due to deepened therapeutic effects. Our data demonstrate a strong positive correlation between ADC vs. CC3 and an inverse correlation between ADC vs. cellularity (**Figure 3C,D**), supporting the hypothesis that a sharp increase of ADC early after KRASi treatment marks cell death and/or reduced cellularity in responding autochthonous PDAC tumors. In contrast to KPC or orthotopic model, influx of inflammatory cells occurred in subQ G12D tumors masked the ADC increase induced by KRASi (**Figure 5B star panel**).

Besides the effects on cancer cells, KRASi induces rapid and pronounced changes in stroma markers. Significant and consistent increase of K^{trans} was detected on Day2 and Day7 and accompanied by reduction of MVD. A significant *inverse* correlation with MVD (**Figure 3E**) suggests that KRASi treatment may have vascular “pruning” effect that reduces angiogenesis, leading to vascular “normalization” and increased blood perfusion. Depletion of matrix hyaluronan (HA) by hyaluronidase (PEGPH20) also led to increased K^{trans} in KPC tumors without changes of MVD (32) via a different mechanism, where capillaries recovered from collapsed state and resumed perfusion when tumor interstitial fluid pressure (IFP) was reduced after PEGPH20 treatment (45). While K^{trans} metric obtained from current kinetic modeling is robust, perfusion and permeability contribution to the K^{trans} metric is inseparable by this analysis. We strive to resolve this issue either by additional experiment or by more sophisticated kinetic model (46) in future studies.

Our observation that MTR does not respond to increased collagen content in KPC or 4662-$KRAS^{G12D}$ tumors after MRTX1133 treatment suggest that the MTR value is determined by two opposite effects: an increase in bound water pool due to increased collagen deposition *versus* reduced bound water upon cell death, both mediated by KRASi. Hence, in treatments that induce substantial cell death, MTR would *not* be a suitable marker for collagen level. However, in 4662-$KRAS^{G12C}$ tumors where the treatment does not induce significant cell death or cellularity change, MTR indeed can mark the change of extracellular matrix collagen content.

Compared to MRTX1133, which binds to KRAS protein in GDP-bound (OFF) state, RASi specific to KRAS in GTP-bound (ON) state, to HRAS, NRAS or wild type RAS have been developed (7-10) as well as other modalities of direct RAS inhibition including binder protein, siRNA and CAR-T cells have been developed (11-13). Regardless of modalities that are used to inhibit RAS, the downstream effects of cancer cell death and stromal reprogramming upon RAS pathway blockade are likely to be similar therefore the mpMRI is expected to have general applicability for all forms of RAS inhibition.

Along with technical advancements in clinical MRI system that have greatly improved the DWI and DCE performance, international consensus is being developed for standardization of acquisition and analysis protocols for DWI and DCE across clinical MRI platforms (47-49). The coordinated efforts from academia, professional societies and industry aim to enhance robustness and repeatability of these MRI metrics in multi-center clinical studies, which are likely to be conducted in PDAC patients undergoing KRASi treatment.

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Figures captions:

Figure 1: **Experimental designs. (A)** For detection of early and stable treatment effects of KRASi (MRTX1133), respectively, a GEM model (KPC) was studied at baseline, on Day2 and Day7 after treatment initiation by mpMRI followed by euthanasia for IHC analyses. **(B)** Survival study in KPC model with KRASi monotherapy. **(C)** Isogenic 4662 PDAC models carrying $KRAS^{G12D}$ or $KRAS^{G12C}$ mutation, respectively were studied at baseline and Day2 after treatment initiation by mpMRI followed by euthanasia for IHC analyses. **(D)** Monitoring the development of resistance to KRASi monotherapy by weekly T2W MRI**.** Treatment was paused when the tumor was not measurable on MRI while weekly T2W MRI continued to capture tumor regrowth. Once the tumor size rose above radiographic threshold, treatment was resumed. This cycle was repeated until resistance was developed and captured by T2W MRI. Weekly mpMRI was performed on R1/2/3 stage. For all studies, KRASi or CNTRL treatment was initiated on Day0 after baseline MRI.

Figure 2: Day2 mpMRI of KRASi and CNTRL group (KPC mice). (**A**)Tumor volume, (**B**) ADC, (**C**) KI, (**D**) MTR bin histogram, (**E**) K^{trans}, and (**F**) V_e of the tumor from individual mice at baseline and Day2 (D2) are shown for treated and CNTRL mice. Autochthonous PDAC tumor was defined on T2W MRI (yellow dotted line in **A**) while parametric maps are overlaid on T2W images (**B-F**). Two-tail, paired t-test was conducted to compare Day2 vs. baseline. *P <0.05, ** P <0.01, *** P <0.001, **** P <0.0001.

Figure 3: **Day2 IHC markers of cancer and stroma and correlations with mpMRI markers.** (**A**) p-ERK1/2 & CK19 double staining marked KRAS inhibition in cancer cells while proliferation and death of cancer cells are assessed by double staining of Ki67 & CK19 and CC3 & CK19, respectively. (**B**) Stromal markers include αSMA, Sirius red (for collagen) and CD31 for tumor microvascular density (MVD). αSMA-positive but CK19 negative cells were estimated in the plot. CD31-positive cells stained in brown color while SR in red. (**C**) Correlation between ADC change vs. cancer cell death. (**D**) Inverse correlation between ADC change vs. cellularity estimated on the H&E-stained tumor sections. (**E**) Inverse correlation between K^{trans} vs. MVD. For C,D,E, mpMRI and IHC data from Day2 and Day7 are pooled. Two-tail, unpaired t-test was conducted to compare treated vs. CNTRL while Pearson correlation analysis was applied to C, D, E. *P <0.05, ** P <0.01, *** P <0.001.

Figure 4: **Day7 mpMRI and IHC of KRASi and CNTRL group (KPC mice)**. Tumor volume (**A**), ADC (**B**), KI (**C**), MTR (**D**), K^{trans} (**E**), and V_e (**F**) of the tumor from individual mice at baseline and Day7 (D7) are shown for treated and CNTRL mice. (**G**) KRAS inhibition in cancer cells is

marked by p-ERK1/2 & CK19 double staining, proliferation and death of cancer cells are assessed by double staining of Ki67 & CK19 and CC3 & CK19, respectively. (**H**) Stromal markers of αSMA, SR and CD31. αSMA-positive cells which are negative for CK19 were estimated in the plot. CD31-positive cells stained in brown color while SR in red. In (**A, B**), tumor volume and ADC of treated group didn't pass normality test and Mann-Whitney test was applied with $^{\#}P < 0.05$, $^{\#\#\#}P < 0.001$. For remaining data, two-tail, paired or unpaired t-test was applied when appropriate: *P <0.05, ** P <0.01, *** P <0.001.

Figure 5: **mpMRI and IHC of G12D vs. G12C mutated tumor responding to KRASi on Day2 (implant models).** At baseline and Day2 of MRTX1133 treatment, tumor size (**A**), ADC (**B**), K^{trans} (**C**) and MTR (**D**) of subQ 4662-PDAC tumors carrying G12C and G12D mutation, respectively. Tumor size and ADC were also measured from orthotopic G12D tumors (A-B). (**E**) Cancer cell markers including p-ERK1/2, proliferation and death are assessed by double staining of p-ERK1/2 & CK19, Ki67 & CK19 and CC3 & CK19, respectively, in treated G12D vs. treated G12C vs. CNTRL G12C tumors. (**F**) Stromal markers of αSMA, SR and CD31. αSMA-positive cells which are negative for CK19 were estimated in the plot. SR was stained in red and CD31-positive cells stained in brown color. Two-tail paired or unpaired t-test was applied when appropriate: *P <0.05, ** P <0.01, *** P <0.001. Starred panels represent unexpected results.

Figure 6: **mpMRI and IHC markers of resistant tumors (KPC mice)**. (**A**) Tumor volume evolution during the development of resistance. Each line represents a mouse (red portion corresponds to resistant stage). (**B**) Tumor volume, (**C**) DWI metrics and (**D**) DCE metrics at resistant stages (R1, R2, R3) vs. responsive stages (Day2 and Day7). (**E**) Cancer cell markers of p-ERK1/2, Ki67 and CC3 of resistant tumor at R3 stage compared with those on Day2 and Day7. IHC micrographs of Day2 and Day7 are replicated from Figure 3 and 4, respectively. In Mann-Whitney test was applied to (**B,C**) with $^{\#}P < 0.05$, $^{\#\#}P < 0.01$, $^{\#\#\#}P < 0.001$ while Two-tail unpaired t-test applied to the rest with *P <0.05, ** P <0.01, *** P <0.001, **** P <0.0001. Red * or # marks the mpMRI metrics at R1 stage whose values differed significantly from responding stages (Day2 or Day7).

SI Figure 1: **mpMRI metrics and maps of the tumor.** (**A**) Tumor size is obtained from T2-weighted (T2W) MR images. ROI defined for tumor, spinal muscle, phantom-1 (10% PVP) and 2 (40% PVP) are marked. The phantoms serve as references for ADC as their ADC values were quantified independently and bookend the ADC range of KPC tumors (38). (**B**) ADC and KI metric are calculated from diffusion weighted images of five b values (detailed in Methods). (**C**) DCE metrics (K^{trans}, V_e and τ_i) are derived from kinetic modeling of DCE series (40) along with T10 map and group arterial input function (AIF) with B1 correction as we described previously (39). (**D**) MTR metric is calculated from the reference image and MT_{on} image as detailed in Methods. MTR_{bin} histogram is also detailed in Methods.

SI Figure 2: Tumor collagen content from CNTRL and MRTX1133 treated KPC tumor
Tumors were collected from CNTRL (n=5) and treated mice on Day2 (n=8) and Day7 (n=4) after mpMRI. Tumor collagen content was estimated by biochemical assay (see Methods). Two-tail, unpaired t-test was used to compared treated vs. CNTRL. ** P <0.01, *** P <0.001

SI Figure 3: Day2 IHC revealed intratumor heterogeneities after KRASi treatment. H&E **(A)** and SR **(B)** micrographs of whole tumor section with selected regions labeled as box1-4. Both whole section and regional analysis of cellularity and collagen content was conducted by a GI pathologist (EEF) as detailed in Methods. Representative T2W images, ADC, KI and MTR maps of this tumor (from KPC mouse #30292) on Day2 and baseline are shown in **Figure 2A-D**.

SI Figure 4: Day7 mpMRI of treated vs. CNTRL mice. Three slices from the same tumor are shown for each metric acquired on Day7 and baseline. Tumor size and DW metrics (**A, B, C**) were from the same mouse whereas DCE metrics **(D** and **E)** from a different mouse in the treated group while all metrics were from the same mouse in CNTRL group.

SI Figure 5: Kaplan-Meier curve of treated and CNTRL KPC mice. Median survival is 57 days for MRTX1133 treated group (n=20) and 22 days for CNTRL group (n=20). ****$P < 0.0001$, Mantel-Cox nonparametric test.

SI Figure 6: Day2 mpMRI of 4662-KRAS^{G12D} and 4662-KRAS^{G12C} subQ tumors and 4662-KRAS^{G12D} orthotopic tumors. Tumor ROIs are marked on T2W images with dotted lines (**A**), maps of ADC (**B**), MTR (**C**) and K^{trans} (**D**) at baseline and on Day2 are overlaid on T2W MRI. Four image slices are shown for the same tumor at each time point.

SI Figure 7: mpMRI markers at resistant stages vs. baseline. Tumor size (**A**), DWI metrics (**B**), MTR_{bins} (**C**) at R1, R2, R3 stage respectively are compared with baseline while DCE Metrics (**D**) was only obtained at R1. Two-tail unpaired t-test was conducted. *P <0.05, ** P <0.01. Red star (*) marks the mpMRI metric whose values differed significantly at early resistant stage (R1) vs. baseline.

SI Table -1: Catalog numbers for monoclonal antibodies and dilution schemes used in immunofluorescence.

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Figure 1

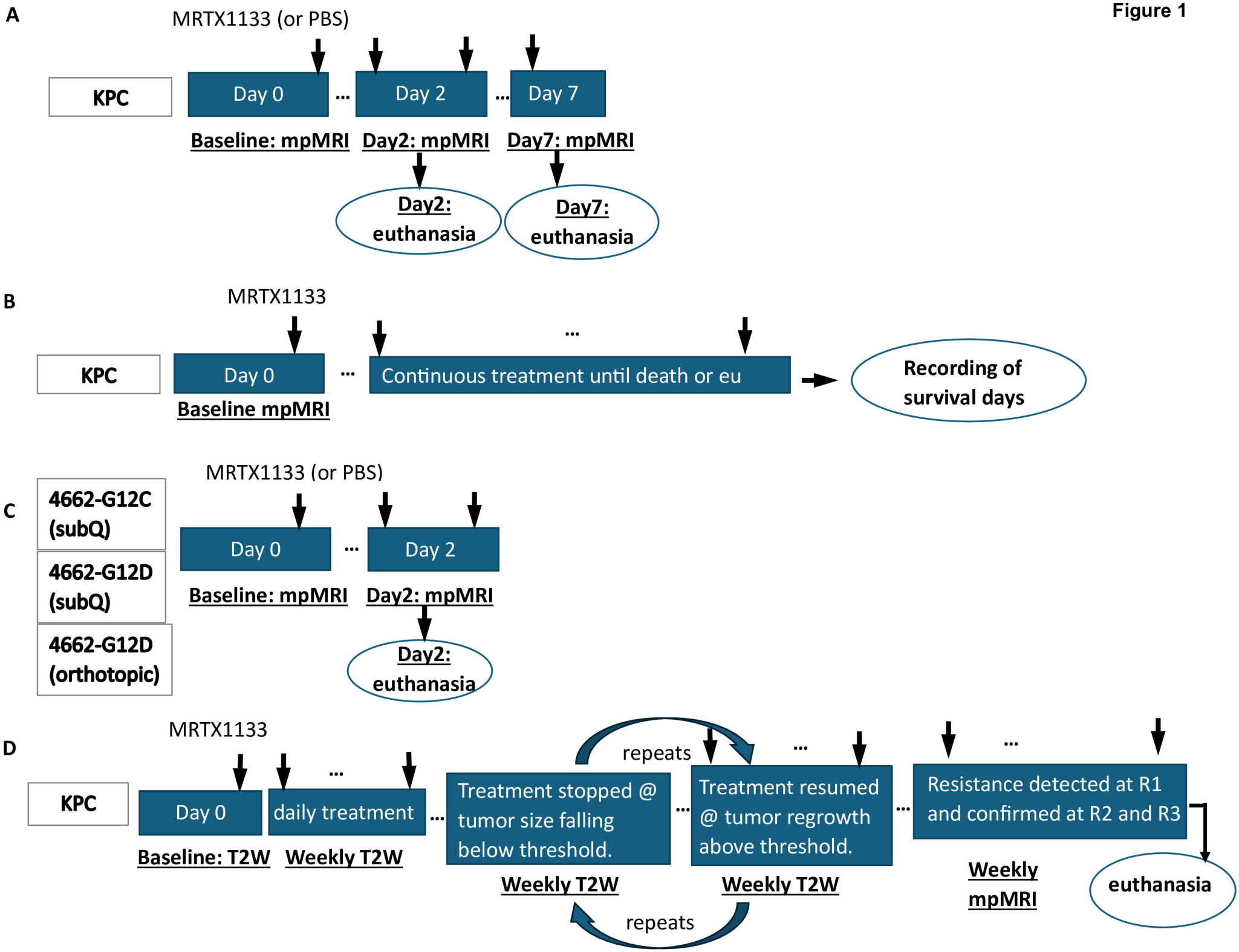

A
MRTX1133 (or PBS)
KPC
Day 0
Day 2
Day 7
Baseline: mpMRI
Day2: mpMRI
Day7: mpMRI
Day2: euthanasia
Day7: euthanasia
B
MRTX1133
KPC
Day 0
Continuous treatment until death or eu
Baseline mpMRI
Recording of survival days
C
MRTX1133 (or PBS)
4662-G12C (subQ)
4662-G12D (subQ)
4662-G12D (orthotopic)
Day 0
Day 2
Baseline: mpMRI
Day2: mpMRI
Day2: euthanasia
D
MRTX1133
KPC
Day 0
daily treatment
Baseline: T2W
Weekly T2W
Treatment stopped @ tumor size falling below threshold.
Weekly T2W
repeats
Treatment resumed @ tumor regrowth above threshold.
Weekly T2W
repeats
Resistance detected at R1 and confirmed at R2 and R3
Weekly mpMRI
euthanasia

Figure 2

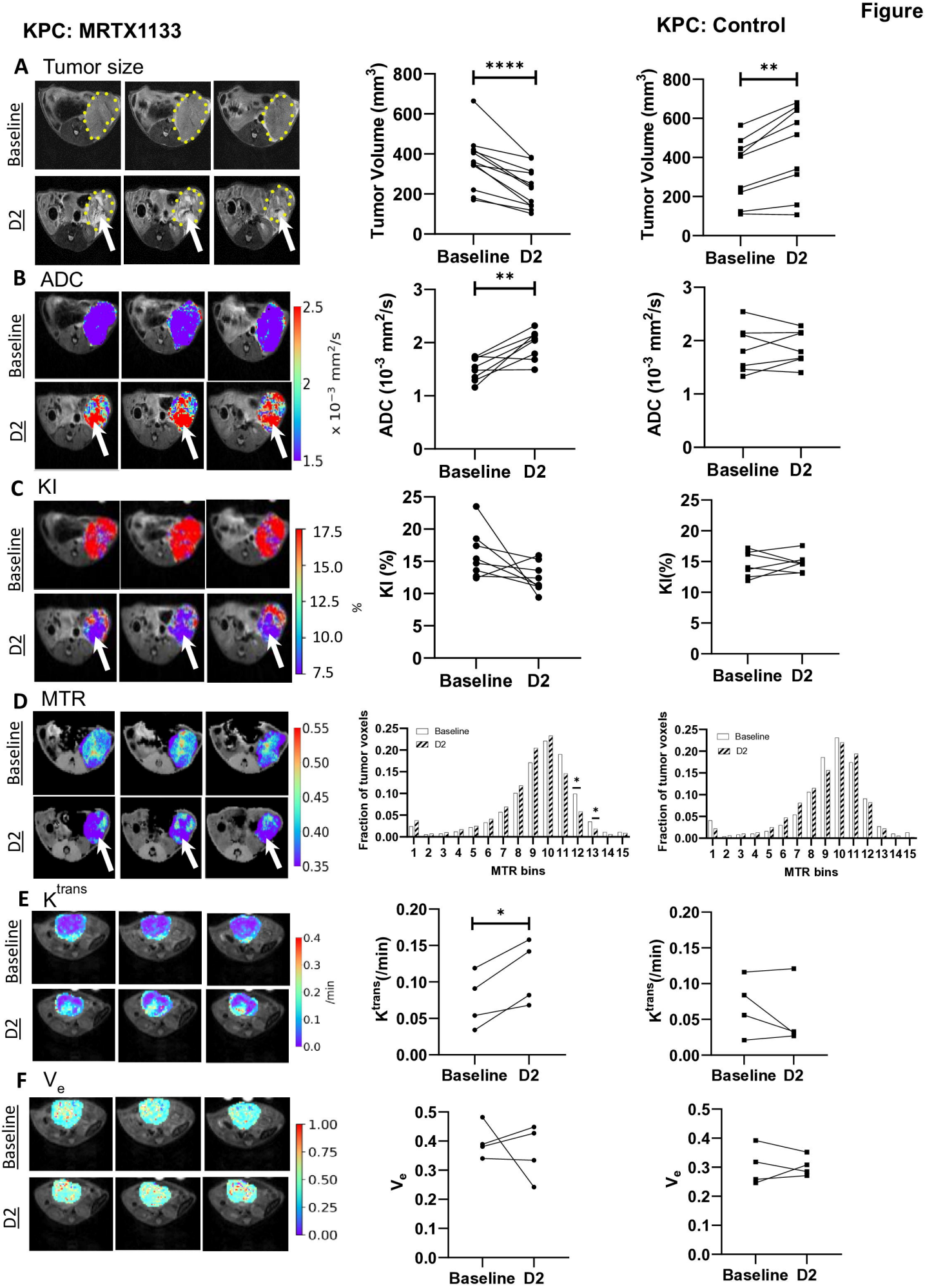

KPC: MRTX1133
KPC: Control
A Tumor size
Baseline
D2
Tumor Volume (mm3)
****
**
Baseline D2
B ADC
x 10−3 mm2/s
ADC (10-3 mm2/s)
C KI
%
KI (%)
D MTR
Fraction of tumor voxels
MTR bins
E Ktrans
/min
Ktrans(/min)
F Ve

Figure 3

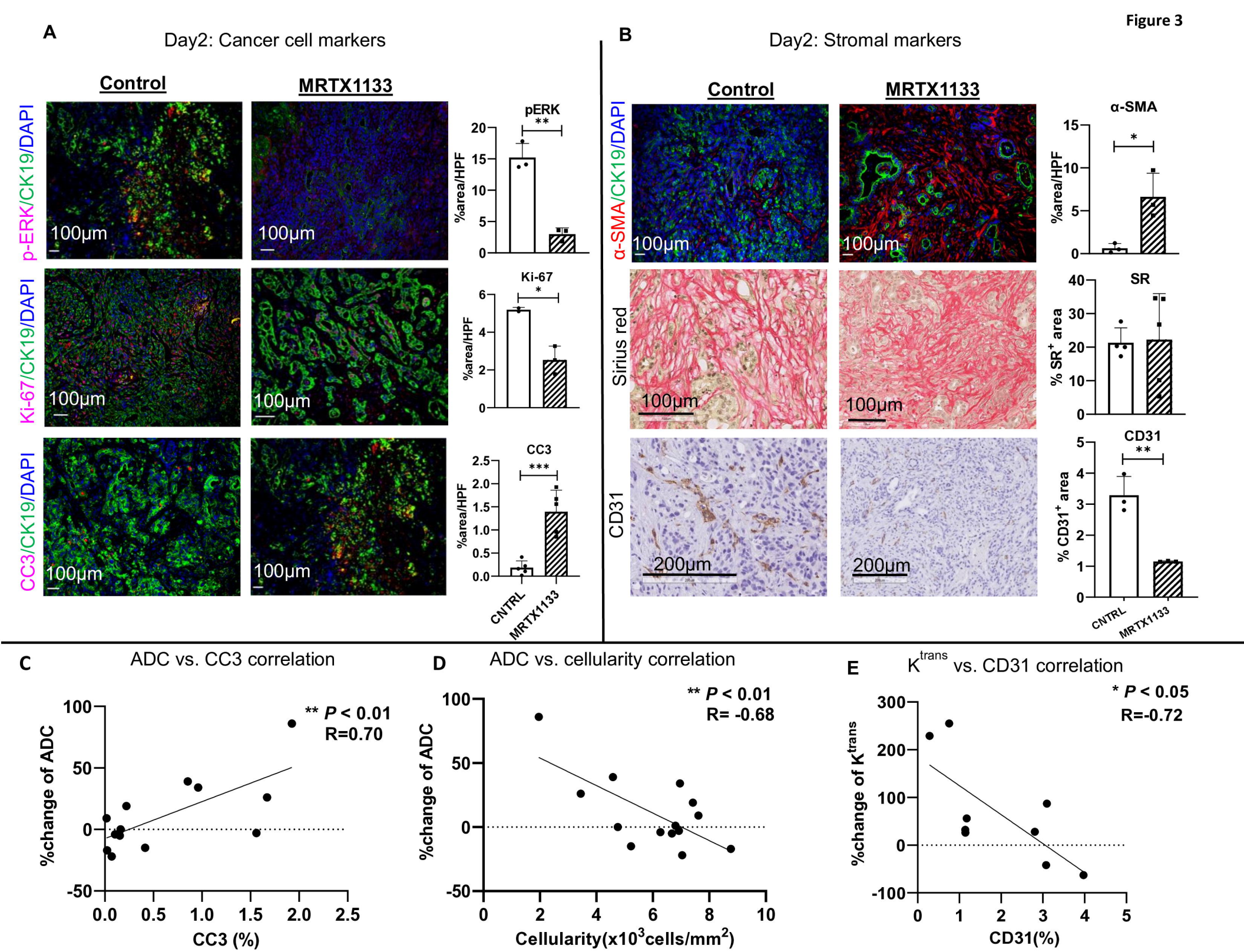
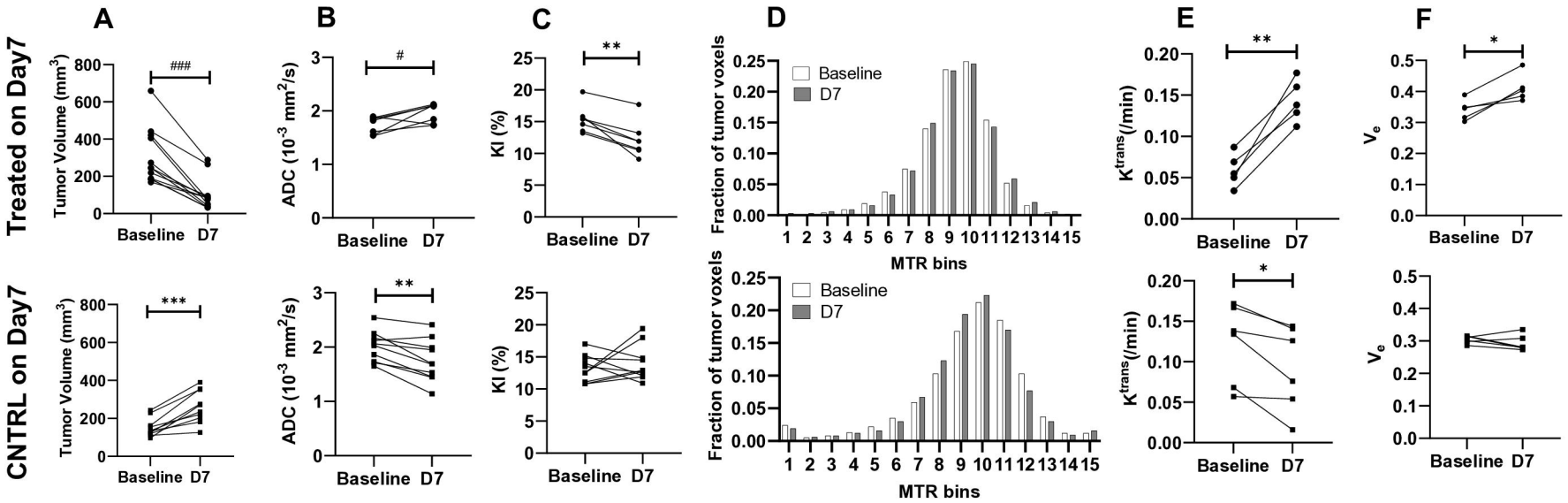
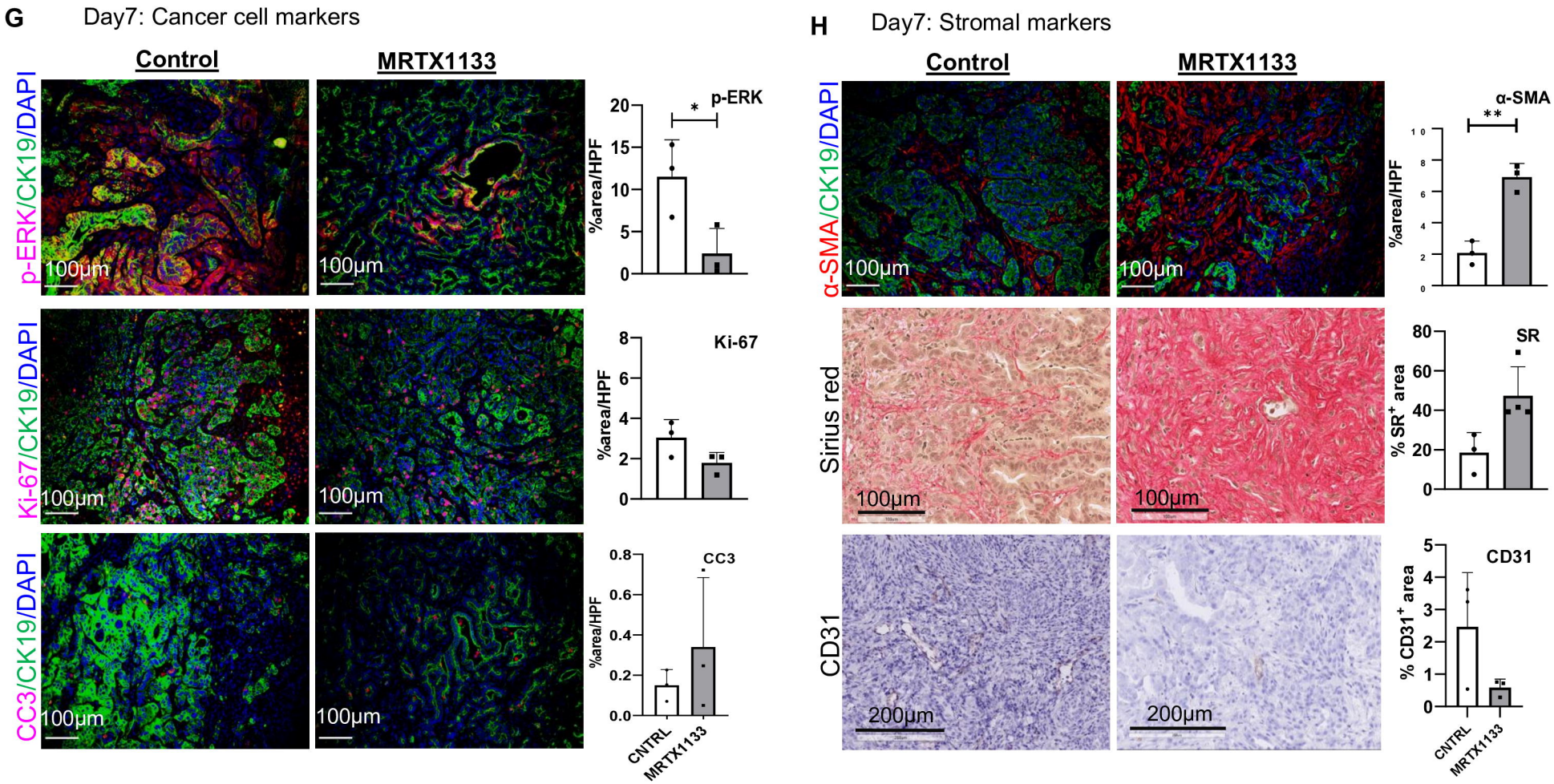

A
Day2: Cancer cell markers
Control
MRTX1133
p-ERK/CK19/DAPI
Ki-67/CK19/DAPI
CC3/CK19/DAPI
100µm
pERK
Ki-67
CC3
%area/HPF
CNTRL
MRTX1133
B
Day2: Stromal markers
α-SMA/CK19/DAPI
Sirius red
CD31
200µm
α-SMA
SR
% SR+ area
CD31
% CD31+ area
C
ADC vs. CC3 correlation
** P < 0.01
R=0.70
%change of ADC
CC3 (%)
D
ADC vs. cellularity correlation
** P < 0.01
R= -0.68
Cellularity(x10³cells/mm²)
E
Ktrans vs. CD31 correlation
* P < 0.05
R=-0.72
%change of Ktrans
CD31(%)

Figure 4


A
B
C
D
E
F
Treated on Day7
CNTRL on Day7
Tumor Volume (mm3)
ADC (10-3 mm2/s)
KI (%)
Fraction of tumor voxels
MTR bins
Baseline
D7
Ktrans(/min)
Ve
Baseline D7
###
#
**
***
*


G
Day7: Cancer cell markers
Control
MRTX1133
p-ERK/CK19/DAPI
Ki-67/CK19/DAPI
CC3/CK19/DAPI
100μm
p-ERK
Ki-67
CC3
%area/HPF
CNTRL
MRTX1133
H
Day7: Stromal markers
α-SMA/CK19/DAPI
Sirius red
CD31
200μm
α-SMA
SR
% SR+ area
CD31
% CD31+ area

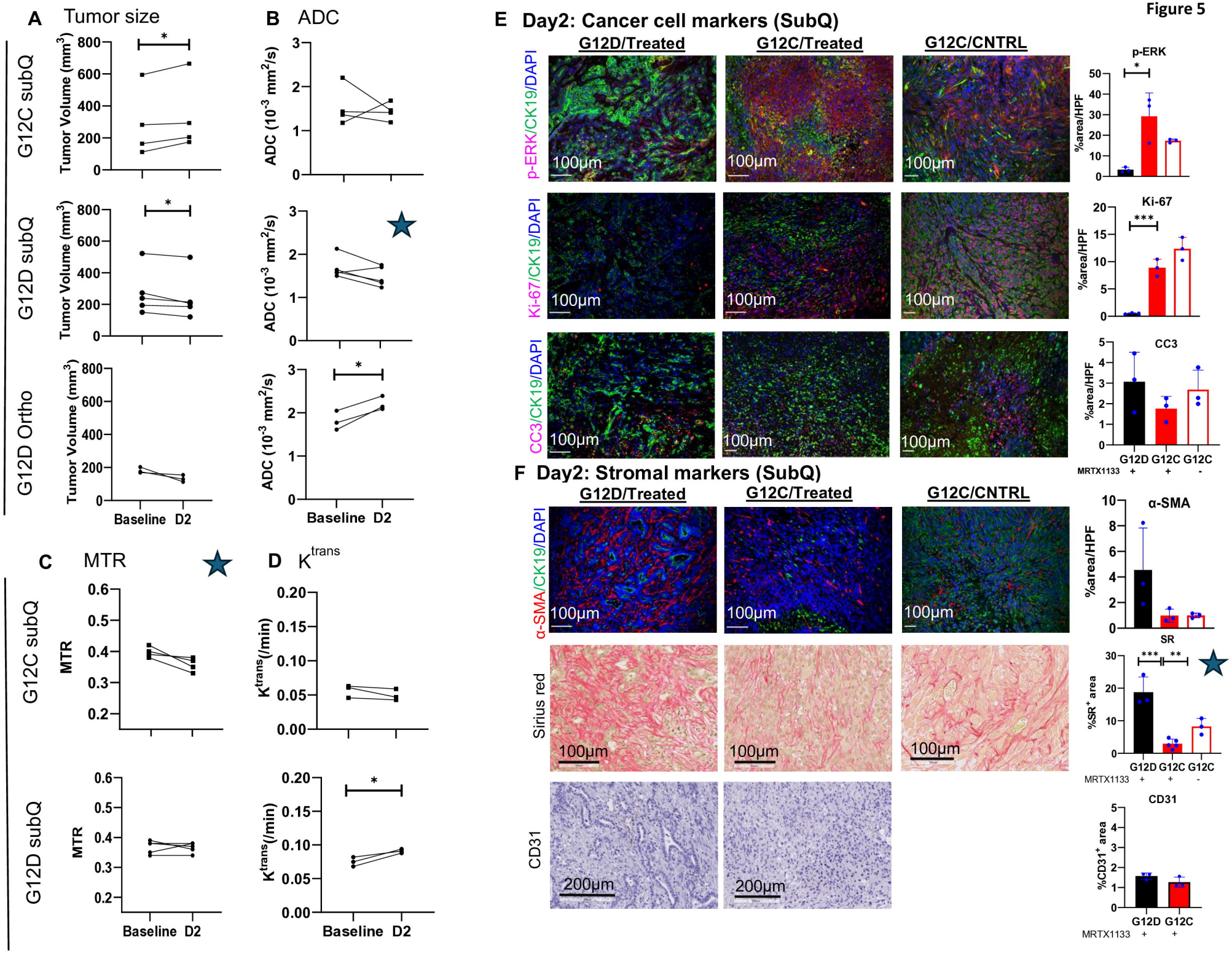
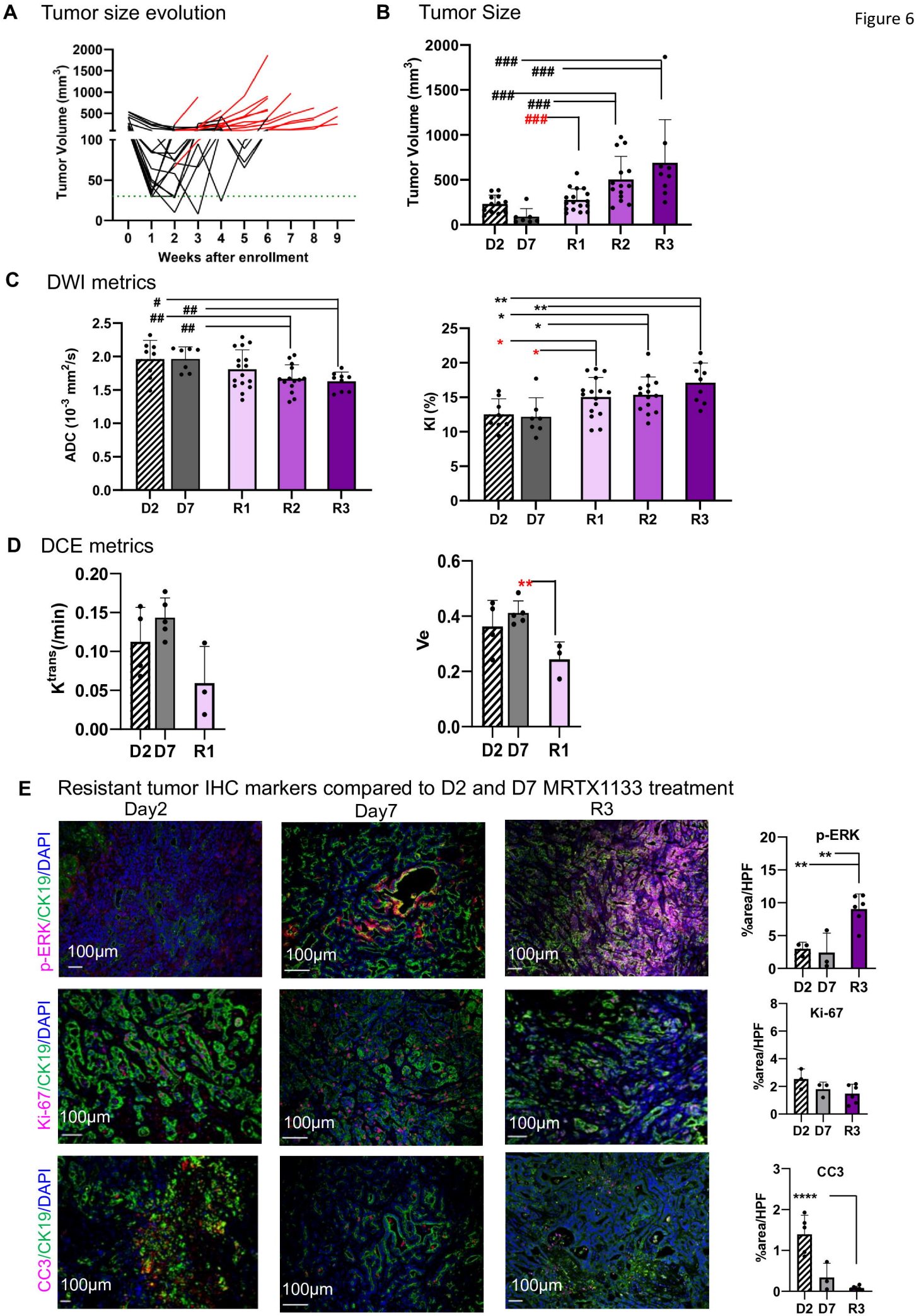


Figure 5
A Tumor size
B ADC
C MTR
D K^trans
G12C subQ
G12D subQ
G12D Ortho
Tumor Volume (mm³)
ADC (10⁻³ mm²/s)
MTR
K^trans(/min)
Baseline D2
E Day2: Cancer cell markers (SubQ)
G12D/Treated
G12C/Treated
G12C/CNTRL
p-ERK/CK19/DAPI
Ki-67/CK19/DAPI
CC3/CK19/DAPI
100μm
p-ERK
Ki-67
CC3
%area/HPF
G12D G12C G12C
MRTX1133 + + -
F Day2: Stromal markers (SubQ)
α-SMA/CK19/DAPI
Sirius red
CD31
200μm
α-SMA
SR
%SR⁺ area
CD31
%CD31⁺ area
G12D G12C
MRTX1133 + +

Figure 6


A Tumor size evolution
Tumor Volume (mm3)
Weeks after enrollment
B Tumor Size
Tumor Volume (mm3)
D2 D7 R1 R2 R3
C DWI metrics
ADC (10-3 mm2/s)
KI (%)
D DCE metrics
Ktrans(/min)
Ve
E Resistant tumor IHC markers compared to D2 and D7 MRTX1133 treatment
Day2
Day7
R3
p-ERK/CK19/DAPI
Ki-67/CK19/DAPI
CC3/CK19/DAPI
100μm
p-ERK
Ki-67
CC3
%area/HPF