Development of siRNA Payloads to Target KRAS-Mutant Cancer

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ABSTRACT

RNAi is a powerful tool for target identification and can lead to novel therapies for pharmacologically intractable targets such as KRAS. RNAi therapy must combine potent siRNA payloads with reliable in vivo delivery for efficient target inhibition. We used a functional “Sensor” assay to establish a library of potent siRNAs against RAS pathway genes and to show that they efficiently suppress their targets at low dose. This reduces off-target effects and enables combination gene knockdown. We administered Sensor siRNAs in vitro and in vivo and validated the delivery of KRAS siRNA alone and siRNA targeting the complete RAF effector node (A/B/CRAF) as promising strategies to treat KRAS-mutant colorectal cancer. We further demonstrate that improved therapeutic efficacy is achieved by formulating siRNA payloads that combine both single-gene siRNA and node-targeted siRNAs (KRAS + PIK3CA/B). The customizable nature of Sensor siRNA payloads offers a universal platform for the combination target identification and development of RNAi therapeutics.

SIGNIFICANCE: To advance RNAi therapy for KRAS-mutant cancer, we developed a validated siRNA library against RAS pathway genes that enables combination gene silencing. Using an in vivo model for real-time siRNA delivery tracking, we show that siRNA-mediated inhibition of KRAS as well as RAF or PI3K combinations can impair KRAS-mutant colorectal cancer in xenograft models. Cancer Discov; 4(10); 1182–97. © 2014 AACR.

INTRODUCTION

Mutations in the RAS family of small GTPases, particularly KRAS, occur in 30% of all human cancers and are often associated with resistance to chemotherapy and targeted therapy. Somatic mutations lock RAS in the GTP-bound state, leading to constitutive activation of its downstream effector pathways. Despite intense efforts, pharmacologic inhibition of KRAS itself (1) and inhibition of individual effector kinases downstream of KRAS such as RAF (2, 3) and MEK (4–6) have so far been unsuccessful in treating KRAS-mutant tumors. Combinations of MEK and PI3K inhibitors are currently being evaluated in clinical trials, although toxicity in normal tissue could limit their therapeutic window (7). Thus, effective and targeted treatment against KRAS-driven cancer is an urgent and unmet clinical need.

RNAi provides an alternative therapeutic approach to small-molecule and antibody-based therapeutics for inhibiting gene function. RNAi can, in principle, be applied to reversibly silence any target gene (reviewed in refs. 8 and 9), thereby increasing the druggable landscape from 10% to virtually 100% of the genome (10, 11). Because all siRNAs bear structural similarity and are likely to have comparable pharmacokinetic profiles, their use as therapeutics would facilitate drug formulation, preclinical testing, and development of combination therapies. Although delivery is still a major challenge, more reliable lipid and polymeric nanoparticles are in development to deliver siRNA payloads to target tissues (reviewed in ref. 12). Regardless, treatment efficacy would benefit from the development of optimized siRNA payloads that potently and specifically silence well-validated target genes at low dose.

Beyond its potential as a therapeutic modality, RNAi is a useful tool for identifying and validating new drug targets. This has proved particularly powerful in cancer research, where shRNA or siRNA screens have been used to identify genes that are selectively required for the proliferation and survival of cancer cells. However, the identification and current in silico prediction of effective shRNAs and siRNAs remains imprecise, resulting in low success rates. Consequently, screening high-order shRNA/siRNA combinations is not possible without first establishing a collection of functionally validated RNAi triggers. In addition, off-target effects, which can be due to sequence-dependent and sequence-independent gene deregulation (reviewed in ref. 13), must be minimized for meaningful interpretation of phenotypic outcomes.

To overcome these limitations, we used a previously described “Sensor” assay (14) to generate a functionally validated library of RNAi sequences against RAS pathway genes. We show that Sensor siRNAs efficiently ablate their gene targets at low nanomolar concentrations in vitro, which decreased off-target effects and enabled the use of
high-order siRNA combinations to codeplete multiple genes. By applying Sensor siRNAs in vitro and in vivo, we identified single-gene and combination-gene payloads that inhibit the growth of KRAS-mutant colorectal cancer. Thus, the use of Sensor siRNAs for target discovery and development of customized siRNA payloads can lead to nanoparticle-based treatments for KRAS-mutant cancer and provide a blueprint for similar strategies to target other key nodes in cancer maintenance.

RESULTS
A Functionally Validated RNAi Library Targeting KRAS Pathway Genes

To identify potent shRNAs targeting the RAS network, we applied the Sensor assay to evaluate candidate shRNA sequences targeting 75 human genes and their mouse orthologs (Fig. 1A). These genes encode many classes of proteins, including kinases, GTPases, and transcription factors. The Sensor assay interrogates large numbers of shRNAs under conditions of single genomic integration (“single-copy”) for their ability to repress a cognate target sequence (Fig. 1B). Although we have previously established this assay and shown its potential to identify very potent shRNA sequences through full gene tiling, here we applied it to evaluate the efficiency of preselected candidate sequences targeting a much larger set of genes to establish a functionally validated RNAi library. To assemble the initial candidates, 65 shRNAs per gene were selected using a combination of bioinformatics predictions (15) and “Sensor rules” requiring shRNA-specific features (14). This resulted in a total of approximately 10,000 shRNAs (split into sets targeting mouse and human genes), including 17 control shRNAs added at 1-fold representation to monitor the functional behavior and stoichiometric fluctuations of the assay. Deep sequencing after two-step cloning of the shRNA-Sensor libraries (14) revealed that >99.8% of all designed human (4,958 of 4,967) and mouse (4,828 of 4,837) shRNA set vectors were successfully constructed.

To evaluate shRNA efficiency through the enrichment of potent shRNAs and depletion of nonfunctional constructs, five iterative rounds of FACs were run (Sort 1–5), with gates set to progressively select for only the most potent, functional shRNAs (14). Compared with our previous libraries generated by complete tiling of transcripts, the preselected RAS pathway libraries showed a less drastic reduction in shRNA complexity during early selection cycles (Supplementary Fig. S1A and S1B), indicating that the bioinformatics shRNA preselection process enriched the pools for potent shRNAs. Importantly, shRNA representation in independent biologic replicates correlated throughout the sorting procedure (Fig. 1B and Supplementary Table S1), whereas the correlation to the initial population was progressively lost, showing that the assay can reproducibly identify potent shRNAs regardless of their initial representation in the library (Fig. 1C and Supplementary Table S1).

The recovery of all positive control shRNAs indicates that the assay robustly enriched for potent single-copy shRNAs, while depleting weak and intermediate ones (Fig. 1D and Supplementary Table S1). Strikingly, there was nearly no correlation between the initial algorithmic rank and the rank obtained through the biologic Sensor assay (Fig. 1E), showing that prediction tools alone are still insufficient to select the most potent shRNAs (see also Supplementary Fig. S1C and S1D). Conversely, the Sensor assay identified potent shRNAs for nearly every gene, with top-ranked shRNAs showing similar scores across all genes (Fig. 1F and Supplementary Table S2). More than 91% of the top five human (344 of 375) and >88% of the top five mouse (333 of 375) shRNAs scored >3 (Supplementary Fig. S1C and S1D), a threshold score defined by positive-control shRNAs. This indicates that the preselection process of 65 shRNAs per gene provided sufficient coverage to identify several very potent shRNAs per gene.

Sensor siRNAs Are Potent and On-Target

Synthetic shRNAs and siRNAs enter the endogenous microRNA pathway at different stages, but ultimately use the same conserved machinery to downregulate their target genes. We thus hypothesized that potent shRNA sequences could be directly converted into potent siRNA triggers. On the basis of top-scoring Sensor shRNA sequences, we generated corresponding 22mer Sensor siRNAs targeting human KRAS, KSR1, ARAF, BRAF, RAF1/CRAF, MAP2K1, MAP2K2, MAPK1, MAPK3, PI3KCA, PI3KCB, PI3KCD, AKTI, AKT2, and AKT3. We then measured the knockdown efficiency of three top Sensor shRNAs and two corresponding siRNAs targeting endogenous KRAS, and found that Sensor siRNAs retain >80% mRNA knockdown when transfected at concentrations as low as 0.5 nmol/L (Fig. 2A and 2B and Supplementary Fig. S2A). We extended this validation to ARAF, BRAF, and RAF1 siRNAs in a human osteosarcoma cell line, U2OS, which does not have mutations in the RAS–MAPK pathway and is not sensitive to knockdown of these genes. Transfection of four of six of these Sensor siRNAs resulted in >70% mRNA knockdown and >80% protein knockdown at 0.1 nmol/L, and all six siRNAs conferred >80% protein knockdown at 0.5 and 2 nmol/L (Fig. 2C and Supplementary Fig. S2A). Finally, we tested at least two of the top-scoring siRNAs for select genes in U2OS cells. Among 46 Sensor siRNAs tested, approximately 90% (41) knocked down their target mRNA at >70% when transfected at 2 nmol/L (Fig. 2D). The Sensor assay thus serves as a powerful and reliable strategy to identify potent siRNA sequences to generate functionally validated shRNA/siRNA libraries.

To biologically validate KRAS Sensor siRNAs for specificity, we transfected two siRNAs, siKRAS_234 and siKRAS_355, into a panel of nine human colorectal cancer cell lines with or without mutant KRAS alleles. We observed a strong correlation between siKRAS-induced cell death and KRAS mutational status and a strong correlation between the behaviors of the two siRNAs (Fig. 2E). The antiproliferative effect of the siRNAs in KRAS-mutant cells was attributable to apoptosis (Supplementary Fig. S2B), although, as previously reported, heterogeneity among cell lines was observed (16). To verify that the cell death observed in KRAS-mutant cells was an on-target effect, we generated SW1116 cells (KRAS-mutant and KRAS-dependent) stably expressing an siRNA-resistant, tetracycline-inducible KRASG12V cDNA (Supplementary Table S2). As expected, both KRAS siRNAs effectively knocked
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Figure 1. Functionally validated RAS pathway RNAi libraries for potent and specific gene silencing. A, the Sensor assay enables the generation of functionally validated shRNA libraries. The potency of candidate shRNAs was biologically probed in a pooled assay by quantifying knockdown of a Venus reporter cDNA fused to the cognate target site of shRNA. B–F, human RAS set (hRAS) Sensor assay results. Comparable results were obtained for the mouse RAS set (mRas, Supplementary Table S1 and S2). B, correlations in read numbers of technical vector pool replicates (V1 and V2), and biologic duplicates (R1 and R2) at different selection stages of the Sensor assay (S3, Sort 3; S5, Sort 5; r, Pearson correlation coefficient). C, correlations in read numbers between the initial vector library (mean of technical duplicates) and the endpoint populations after the indicated sorts (geometric mean of biologic replicates), and the final Sensor scores. D, Sensor scores of control shRNAs of strong (orange), intermediate (blue), or weak (yellow) potency. E, rank correlation between input (Algorithm rank) and output library (Sensor rank), showing that the Sensor rank is not predicted by the informatics tool (a Spearman rank correlation coefficient). F, Sensor shRNA scores for a selection of direct “RAS effector” genes (for a full list, see Supplementary Table S2). The dotted line indicates a threshold for potent shRNAs, based on known controls. 65 shRNAs/gene; controls are represented multiple times for better visibility.
resistant viability (Fig. 2G). Doxycycline-induced expression of siRNA-MEK and phospho-ERK (pERK; Fig. 2F) and decreased cell down endogenous KRAS, which led to a decrease in phospho-MEK and phospho-ERK (pERK; Fig. 2F) and decreased cell viability (Fig. 2G). Together, these results indicate that siKRAS_234 and siKRAS_355 are potent at low dose, and their cytotoxic effect on KRAS-mutant cells is due to KRAS depletion.

Low-Dose shRNA and siRNA Minimize Off-Target Effects

Off-target effects remain a major concern with RNAi experiments and can occur through several mechanisms, including
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(i) sequence-dependent cross-hybridization to unintended mRNA targets (17, 18); (ii) sequence-independent saturation of the RNAi machinery (19); and (iii) other as-yet-undefined mechanisms. As competition of RNAi triggers for incorporation and retention in the RNA-induced silencing complex (RISC) is concentration dependent (20) and as bulk transfected siRNAs can outcompete endogenous miRNAs for RISC loading (19), we set out to specifically investigate dose-dependent RNAi off-target effects by testing shRNAs and siRNAs in cells in which their cognate target genes are absent. In such a system, any changes in gene or miRNA expression should result from off-target effects.

We analyzed shRNA-based off-target effects by transducing Tryp53−/− mouse embryonic fibroblasts (MEF; ref. 21) at single copy and high copy with six well-characterized potent or weak Tryp53 shRNAs (14). Small RNA sequencing showed that high-copy shRNA transduction resulted on average in 20- to 70-fold more shRNA-derived mature small RNAs than single-copy transduction (Fig. 3A), suggesting that each high-copy transfected cell contained at least 20 to 70 viral integrations. Interestingly, endogenous microRNA levels were unchanged at both conditions (Supplementary Fig. S3A and S3B), raising the possibility that common gene perturbations might be due to unintended competing endogenous RNA (ceRNA)-like effects of vector-based mRNA transcripts (22) or increased engagement of the transcription and translation machinery. Gene-expression analysis revealed several hundred sequence-based off-target effects at high-copy conditions (550 up and 301 down, P < 0.05), whereas only seven altered genes were found under single-copy conditions (Supplementary Fig. S3C). Gene perturbations commonly found across all six shRNAs numbered in the thousands at high-copy transduction (1,821 up and 2,910 down, P < 0.05), but again were absent at single-copy (Fig. 3B and Supplementary Fig. S3D). Interestingly, potent and weak shRNAs perturbed gene expression to a similar degree. We also observed that potent Sensor shRNAs lead to preferential retention of the designed guide strands (Supplementary Fig. S3E; ref. 14), which might reduce passenger strand–mediated off-target effects, and thus designed all Sensor siRNAs as 22mers—rather than conventional 21mers—to guard the same sequence properties for both strands.

To test dose-dependent off-target effects of such Sensor-derived siRNAs, we transfected siKRAS_234 and siKRAS_355, which target both human and mouse KRAS, into KRAS−/− MEFs (23) at 0.2, 2, 20, and 50 nmol/L and measured global gene-expression changes. Higher concentrations (20 and 50 nmol/L) of siRNAs caused significant gene-expression changes (>2-fold downregulated genes, 12–16 for siKRAS_234 and 63–93 for siKRAS_355), whereas lower concentrations (0.2 and 2 nmol/L) perturbed only a limited number of genes (>2-fold downregulated genes, 0–1 for siKRAS_234 and 3–6 for siKRAS_355; Fig. 3C and Supplementary Fig. S3F–S3G). In addition, we found that at 20 and 50 nmol/L, siKRAS_355 downregulated more genes than siKRAS_234 and that the differentially downregulated genes were largely nonoverlapping (Supplementary Fig. S3H), indicating that these effects are sequence dependent. Together, our data show that although both shRNAs and siRNAs can induce aberrant gene perturbations at high concentrations, lowering their dosage does not eliminate but critically reduces both sequence-specific and general off-target effects.

Sensor siRNAs Can Be Used in High-Order Combinations to Identify Therapeutic siRNA Cocktails

We next tested whether the high potency of Sensor siRNAs allows for low-dose transfection of multiple siRNA species without affecting the efficiency of individual siRNAs. We performed high-order combination siRNA delivery into U2OS cells, such that individual siRNAs were transfected at 2 nmol/L each in a pool of four different siRNAs. The majority of Sensor siRNAs exhibited no decrease in potency when transfected in combination compared with when transfected alone (Supplementary Fig. S4A). At the protein level, transfection of a complex pool of seven potent Sensor siRNAs at 2 nmol/L each—targeting ARAF, BRAF, RAF1/CRAF, MEK1, MEK2, ERK1, and ERK2—resulted in strikingly efficient depletion of all seven proteins simultaneously (Fig. 4A). Notably, the potency of each siRNA was not compromised as siRNA complexity increased. In contrast, for siRNAs that are less potent, their knockdown efficiency was preserved only when pooled with equally weak siRNAs, but further declined when pooled with potent siRNAs (Supplementary Fig. S4B). Apparently, only siRNAs of equally high potency can be used in high-order combinations to consistently achieve robust multigene knockdown, further emphasizing the value of the Sensor assay in identifying such equally potent sequences across various genes.

Next, we set out to use Sensor siRNAs to identify siRNA combinations that could selectively inhibit the proliferation of KRAS-mutant cell lines. As shown above (Fig. 2E), siRNAs targeting KRAS itself are one viable option. To identify alternative targets, we assessed the functional dependency of different RAF and PI3K isoforms in colorectal cancer cells by depleting single and multiple isoforms in cell lines carrying wild-type KRAS and BRAF alleles (Caco-2 and SW48), mutant KRAS alleles (SW1116 and SW620), and mutant BRAF alleles (RKO and LS411N). Cell viability was measured to identify lethal siRNA combinations, and downstream signaling was monitored to validate on-target knockdown.

We first investigated how KRAS mutational status affects sensitivity to knockdown of various RAF isoforms. Caco-2 and SW48 cells, two KRAS wild-type cell lines, were relatively resistant to individual and combinations of RAF isoform knockdown, as measured by cell viability. As expected, the two BRAF-mutant cell lines, RKO and LS411N, were uniquely sensitive to BRAF depletion (Fig. 4B), indicative of their addiction to the BRAF oncopgene. The KRAS-mutant cell lines, SW1116 and SW620, showed partial sensitivity to the depletion of either BRAF or CRAF (Fig. 4B). This finding is consistent with recent reports that CRAF plays a critical role in RAS-driven lung carcinoma and melanoma (24–26). Combined depletion of BRAF and CRAF in these cells resulted in additive toxicity, although depletion of all three RAF isoforms led to the strongest reduction in cell viability that was comparable to that of KRAS depletion.

To investigate the mechanism by which codepletion of multiple RAF isoforms in KRAS-mutant cells photocopies KRAS knockdown, we analyzed apoptosis, ERK phosphorylation, and the accumulation of the proapoptotic protein BIM in these cells. Progressive depletion of RAF isoforms...
Figure 3. Low-dose shRNA and siRNA minimizes off-target effects. A, Trp53−/− MEFs were infected at single or high copy with one of six Trp53 shRNAs. RNA deep sequencing showed that high-copy shRNA transduction resulted in increased levels of mature Trp53 shRNAs in all cases. Endogenous microRNA expression was unperturbed (see also Supplementary Fig. S3A, S3B, and S3E and Supplementary Table S3 for details; r, Pearson correlation coefficient). B, microarray analysis was performed on Trp53−/− MEFs not expressing any shRNA (WT and empty vector) or transduced at single or high copy with one of 6 Trp53 shRNAs. Shown are the top 1,500 genes that are sequence-independently upregulated and downregulated across all six shRNAs. Significant perturbations were observed only at high-copy transduction (P < 0.05). For more details, see Supplementary Fig. S3C and S3D. C, gene-expression changes were analyzed in Kras−/− MEFs transfected with Sensor siKRAS_234 or siKRAS_355 at various concentrations after 72 hours. Unsupervised clustering of significantly downregulated genes (>2-fold) showed a similar gene-expression pattern between control cells and cells transfected with low concentrations (0.2 and 2 nmol/L) of siRNAs. More profound gene perturbation occurred in cells transfected with high concentrations (20 and 50 nmol/L) of siRNAs (see also Supplementary Fig. S3F–S3H).

in the Kras-mutant SW620 cells led to progressive reduction in pERK levels, such that BRAF/CRAF and ARAF/BRAF/CRAF codepletion reduced pERK to levels comparable with those seen upon Kras knockdown (Supplementary Fig. S4C). This correlated with higher accumulation of BIM protein (Supplementary Fig. S4C). Furthermore, codepletion of multiple RAFs led to a stronger apoptotic response in the Kras-mutant cells (Fig. 4C), indicating that depletion of multiple RAF isoforms is necessary to effectively inhibit ERK activation and induce apoptosis in the Kras-mutant context. In the Kras wild-type Caco-2 cells, individual and combined RAF depletion also downregulated pERK, but this did not
Figure 4. Sensor siRNAs can be used in high-order combinations. A, U2OS cells were transfected with Sensor siRNAs targeting MAPK pathway genes. Each siRNA was transfected at 2 nmol/L ± a nontargeting siNEG for a total of 14 nmol/L siRNA. Target protein knockdown was assessed by Western blot 72 hours after transfection. B, viability of colorectal cancer cells was measured 5 days after siRNA transfection or treatment with PLX4032 (1 μmol/L). C, apoptosis of colorectal cancer cells was assessed by measuring caspase-3/7 activity 72 hours after siRNA transfection. Apoptosis was adjusted by viability and normalized to a siNEG-transfected control. D, colorectal cancer cells were treated for 72 hours with 5 nmol/L of the indicated siRNA(s) ± siNEG for a total of 30 nmol/L siRNA. Where indicated, cells were treated with AZD6244 (1 μmol/L), BEZ235 (1 μmol/L), or PLX4032 (10 μmol/L for SW48, Caco2, SW620, and SW1116; 1 μmol/L for RKO and LS411N) for 24 hours. Lysates were analyzed for pMEK, pERK, pAKT, and pS6 levels with the ViBE bioanalyzer. ND, not determined.
strongly induce BIM (Supplementary Fig. S4C) or lead to a significant apoptotic response (Fig. 4C). Finally, in the BRAF-mutant LS411N cells, pERK was primarily sensitive to BRAF depletion (Supplementary Fig. S4C and Fig. 4C). These results emphasize the importance of inhibiting complete effector nodes, including the RAF and PI3K isoforms, presumably due to functional redundancy that can lead to compensation or feedback reactivation of the pathway. In comparison, the small-molecule BRAF inhibitor PLX4720 did not inhibit the proliferation of KRAS-mutant cells (Fig. 4B), as previously reported (2, 3, 26). Thus, RAF inhibition by siRNA and small molecules may exert distinct biologic effects, probably owing to the unique mechanism of RAF activation (27, 28).

We next investigated how depletion of various PI3K isoforms in combination with RAF depletion would modulate cell viability. Although the KRAS wild-type Caco-2 and SW48 cells were resistant to individual and combinations of RAF isoform knockdown (Fig. 4B), the PI3K node, on the other hand, in particular the PIK3CA gene, is critical for their viability (Fig. 4D). Across all cell lines tested, ablation of all three PI3K isoforms decreased cell viability to some extent, and the combined knockdown of all RAF and PI3K isoforms most severely decreased viability (Fig. 4D). However, the fact that this siRNA cocktail impaired viability in all cell lines tested indicates a lack of selectivity for KRAS-mutant cells. Hence, our experiments support the notion that targeting complete effector nodes, particularly the RAF kinases, can inhibit proliferation in KRAS-mutant colorectal cancer cells and confer a selective therapeutic benefit in KRAS-mutant colorectal cancer.

Sensor siRNAs Can Be Effectively Delivered In Vivo

To test the therapeutic efficacy of Sensor siRNAs in vivo, we used previously characterized cyclodextrin-polymer nanoparticles (29, 30) to deliver Sensor siRNAs to tumors in mice. These particles are transferrin-tagged for endocytic uptake in tumor cells and size-selected to extravasate from leaky tumor vessels. Preclinical studies indicate that they are safe in animals (31, 32) and, indeed, these particles have been used in human clinical trials for the treatment of solid tumors (30). To carefully monitor nanoparticle-payload delivery, we developed a fluorescent reporter system to noninvasively and longitudinally monitor nanoparticle transduction using stable expression of DsRed and enhanced GFP (EGFP) in tumors. Successful transduction of cells with nanoparticles carrying siDsRed resulted in loss of DsRed expression as monitored in real time (Supplementary Fig. S5A). This system thus reports on the terminal step of nanoparticle transduction, which is target knockdown within tumor cells. EGFP fluorescence can be concomitantly tracked to monitor tumor size and treatment efficacy.

These cyclodextrin nanoparticles assemble at a fixed polymer-to-payload ratio of 3:1. Given that high-dose RNAi leads to significant changes in gene expression (Fig. 3 and Supplementary Fig. S3), we designed a nontargeting, non-RISC binding “filler” siRNA, siANC_22 (Supplementary Fig. S5B), that facilitates particle assembly through charge neutralization, but does not compete with processing of Sensor siRNAs when transfected at up to 40-fold higher concentrations (Supplementary Fig. S5C). To monitor nanoparticle delivery, nanoparticles containing siANC_22 and siDsRed, hereafter denoted NP(ANC_22+DsRed), were intravenously administered to mice bearing DsRed;EGFP-positive subcutaneous xenografts at varying frequencies. Untreated mice displayed minor fluctuations in DsRed fluorescence, whereas mice treated two or three times a week displayed two or three distinct reductions in DsRed fluorescence per week, respectively (Supplementary Fig. S5D). Moreover, untreated tumor sections displayed homogeneous DsRed and EGFP staining, whereas treated tumors displayed heterogeneous DsRed staining, with particularly low DsRed levels proximal to blood vessels (Supplementary Fig. S5E). Together, these results indicate that the nanoparticles were capable of successfully delivering an siRNA payload.

To test the processing efficiency of a combination siRNA payload targeting two genes, we treated mice with nanoparticles packaging siKRAS and siDsRed, NP(KRAS+DsRed), and harvested the tumors 2 days later. Tumors were enzymatically digested into single-cell suspensions and FACS sorted for transduced (EGFP<sup>hi</sup>;DsRed<sup>hi</sup>) and untransduced (EGFP<sup>lo</sup>;DsRed<sup>lo</sup>) populations (Supplementary Fig. S5F). Western blot analysis showed that both KRAS and DsRed were suppressed in transduced cells compared with untransduced cells, confirming successful combination siRNA payload delivery.

**Nanoparticle-Mediated Delivery of siKRAS to KRAS-Mutant Tumors Impairs Tumor Growth**

To test the therapeutic efficacy of siKRAS<sub>234</sub> delivery to tumors, we treated mice bearing DsRed;EGFP-positive SW620 xenografts (KRAS<sup>32,34</sup>) with nanoparticles packaging differing doses of siKRAS<sub>234</sub> (Fig. 5A). Mice were treated twice a week beginning when tumors reached 100 mm<sup>3</sup>, and tumor growth and nanoparticle uptake were monitored daily. Over 3 weeks, siKRAS 4 mg/kg treatment significantly slowed tumor growth compared with control siKRAS<sub>22</sub> treatment (Fig. 5B). Lower doses of 2 mg/kg and 1 mg/kg siKRAS also elicited antitumor effects, although with greater variability (Supplementary Fig. S5G). We suspect that the amount of siRNA released into each cell is limiting, which emphasizes the importance of using very potent siRNAs that achieve target knockdown at low concentration.

In most siKRAS-treated tumors, resected tumor tissue (Fig. 5C) and FACS-isolated transduced tumor cells (Supplementary Fig. S5H) showed decreased levels of KRAS protein. Accordingly, concomitant decreases in pERK and pCRAF and increased levels of p21 were observed (Fig. 5D). To monitor the effects of KRAS knockdown during tumorigenesis, EGFP fluorescence was measured daily to track tumor cell viability. siKRAS-treated tumors displayed a dose-dependent decrease in EGFP signal during the first week of treatment, indicating tumor regression (Fig. 5D, left). Synchronous dips in DsRed and EGFP fluorescence further indicated that siRNA delivery and cell death occur concordantly, thus validating our real-time reporter approach (Fig. 5D, right).

Tumor regression was not maintained after the first week of treatment. However, the growth-suppressive effects of siKRAS treatment persisted throughout the treatment course. Immunohistochemistry on tumor sections harvested...
Figure 5. SW620 xenografts treated with varying doses of siKRAS. A, three doses of NP(siKRAS+siDsRed) were prepared by varying the ratios of siKRAS_234 and siANC_22. Nanoparticles were administered via tail-vein injection on days 1, 3, 8, 10, and 15, beginning when tumors reached 100 mm^3. B, NP treatment of siKRAS at 4 mg/kg was able to significantly slow tumor growth compared with control siANC_22-treated tumors. C, at day 19, whole-tumor lysate was analyzed by Western blot for KRAS expression and markers of MAPK signaling and cell-cycle progression. D, tumor volume and relative tumor viability were measured daily with optical imaging of EGFP fluorescence. Left, raw EGFP images of two representative tumors from each treatment group are shown, where NP siRNAs were injected on days 1 and 3. Right, viability of transduced cells was monitored by concomitant tracking of DsRed and EGFP. Concurrent drops in DsRed and EGFP signals (synchronous arrowheads) illustrate siRNA-induced lethality, whereas DsRed drops that do not induce EGFP drops (opposing arrowheads) indicate no siRNA effect on viability. E, tumors were analyzed by immunohistochemistry for pERK and pS6 levels. F, immunohistochemistry staining and quantification of Ki67- and CC3-positive cells in tumors (***, P < 0.001; ****, P < 0.0001).
at the terminal time point revealed decreased pERK staining in 4 mg/kg siKRAS-treated tumors, particularly in regions proximal to blood vessels (Fig. 5E). Ki67 positivity was also significantly decreased in 4 mg/kg and 2 mg/kg siKRAS-treated tumors, and cleaved caspase-3 (CC3) positivity was increased in 4 mg/kg siKRAS-treated tumors compared with siANC-treated tumors (Fig. 5F). These data collectively indicate that loss of KRAS protein via siKRAS_234 delivery attenuates, but does not ablate, SW620 tumor growth through inhibition of the MAPK pathway, decreased proliferation, and increased apoptosis.

**Nanoparticle-Mediated Delivery of Combination Payloads Allows for Multigene Knockdown In Vivo**

As we were able to concomitantly knock down up to seven genes in vitro using high-order combinations of Sensor siRNAs, we evaluated the possibility of using Sensor siRNAs to concurrently knock down multiple genes in vivo. Our in vitro data indicated that combined knockdown of the RAF effector node (A/B/C RAF) mimics KRAS knockdown in SW1116 and SW620 colorectal cancer cell lines (Fig. 4B). We thus packaged 2 mg/kg of each individual siRNA in various combinations into nanoparticles and administered these formulations 3 times a week to animals carrying SW1116 (KRAS112D) xenografts (Fig. 6A).

Over the 2.5-week treatment course, siKRAS and siA/B/CRAF treatment equally inhibited tumor growth (Fig. 6B), whereas siB/CRAF treatment had no therapeutic efficacy, as predicted by in vitro experiments (Fig. 4B). Resected tumor tissue (Fig. 6C) and FACS-sorted, transduced tumor cells (Supplementary Fig. S5I) showed decreased levels of all intended target genes, albeit with some variability at this low dose. It is possible that the low vascularity of this xenograft model prevented penetration of the nanoparticles to the entire tumor. Accordingly, siKRAS and siA/B/CRAF treatment equally inhibited tumor growth in this xenograft model and did not induce regression, as indicated by relatively stable levels of EGFP in tumor tissue (Fig. 6D). Nevertheless, a significant decrease in Ki67 positivity and corresponding increase in CC3 positivity was observed in siKRAS- and siA/B/CRAF–treated tumors compared with siANC- or siB/CRAF–treated tumors (Fig. 6E). These data demonstrate that four genes can be concurrently knocked down in tumor tissue, allowing for inhibition of complete effector nodes and the potential to rationally design complex combination therapies.

**Concomitant Knockdown of KRAS and PI3K Improves KRAS-Mutant Tumor Growth Inhibition**

To improve the therapeutic efficacy of single-agent siKRAS treatment in SW620 tumors (Fig. 5), we formulated a combination payload targeting both KRAS and the PI3K node. In the mouse lung, PI3K activation is dependent on oncogenic KRAS and is required for tumor maintenance (33, 34). However, in other tissues, PI3K can be activated through RAS-independent mechanisms, such as direct binding to receptor tyrosine kinases. To more thoroughly eliminate PI3K activity, we sought to target the PI3K node directly in combination with KRAS. We administered nanoparticles targeting KRAS alone, PIK3C-A/B, KRAS+PIK3C-A/B, or ANC_22 three times a week for 2 weeks at 2 mg/kg per individual siRNA (Fig. 7A). As observed previously (Fig. 5B and D), siKRAS alone induced an initial tumor regression that was not sustained over time (Fig. 7B). Cotargeting of PIK3C-A/B together with KRAS induced a similar level of tumor inhibition during the early stages of treatment but, importantly, provided significantly better inhibition of tumor growth during later stages of treatment, even surpassing the efficacy of the high-dose (4 mg/kg) siKRAS treatment (Fig. 5B).

Resected tumor tissue showed at least partial knockdown of all intended target genes (Fig. 7C), and for all experimental treatment arms, concomitant dips in both the red and green channels indicate loss of cell viability concurrent with target knockdown (Fig. 7D). As shown previously, the loss of cell viability in siKRAS-treated tumors resulted from decreased proliferation and increased apoptosis (Fig. 7E), whereas siPIK3CA/B–treated tumors primarily underwent increased apoptosis. Accordingly, the combination therapy only slightly further decreased proliferation and increased apoptosis but not in an additive manner. This indicates that the sustained growth inhibition was likely a consequence of perturbing other KRAS- and PI3K-regulated cellular functions. Taken together, these data demonstrate that the therapeutic efficacy of anti-KRAS RNAi therapies can be increased through the delivery of combination payloads. In the absence of small molecules against most putative cancer targets, the ability to validate such combination targets in vivo with siRNA also has the potential to accelerate both RNAi therapy and small-molecule development.

**DISCUSSION**

In this study, we used the Sensor assay (14) to build two focused, functionally validated RNAi libraries targeting 75 human RAS pathway genes and their mouse orthologs (Supplementary Table S2). Inhibiting the RAS signaling pathway has been a challenging but important area in translational research. Our library of KRAS pathway genes was curated to contain both direct KRAS effectors (RAF, PI3K, and RAL) and indirect and noncanonical effectors (apoptosis, metabolism, and stress pathway genes), and we believe that this library will be a useful tool for the broader research community. Sensor siRNAs against RAS pathway genes efficiently depleted their targets at nanomolar concentrations in vitro (Figs. 2 and 3) and accordingly reduced both sequence-dependent and sequence-independent off-target effects. Furthermore, low-dose activity facilitates higher-order combinatorial gene knockdown by eliminating interference between siRNA species.

Using Sensor siRNAs targeting KRAS, we demonstrate KRAS addiction in a panel of KRAS-mutant colorectal cancer cell lines and provide in vivo proof-of-principle evidence that direct targeting of KRAS by RNAi is a viable strategy to inhibit KRAS-mutant cancer (Figs. 2 and 5). These results are corroborated by a parallel study from Xue and colleagues (35), in which nanoparticle-mediated delivery of KRAS siRNA and other small RNAs was shown to inhibit the growth of KRAS-mutant lung cancers. We further show that targeting the complete RAF effector node by codepleting all three RAF kinases, but not any single RAF kinase or...
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Figure 6. SW1116 xenografts treated with siKRAS or combination siA/B/CRAF. A, four NP treatments delivering 2 mg/kg of each siRNA species were prepared as depicted. Nanoparticles were administered via tail-vein injection on days 1, 3, 5, 8, 10, 12, and 15, beginning when tumors reached 100 mm³. B, siKRAS and siA/B/CRAF treatment slowed tumor growth to a similar extent, compared with siANC_22 and siB/CRAF–treated tumors. The inset (bottom) shows growth of all individual tumors analyzed. C, at day 17, whole-tumor lysate was analyzed by Western blot for KRAS and RAF isoform expression. D, tumor volume and relative viability were measured daily with optical imaging in the EGFP channel, and DsRed fluorescence tracked nanoparticle delivery, as described in Fig. 5C. NP siRNAs were injected on days 8, 10, and 12. E, tumors were analyzed by immunohistochemistry for Ki67- and CC3-positive cells (**, P < 0.01; ***, P < 0.001; ****, P < 0.0001).

Dual combination, can phenocopy the therapeutic efficacy of siKRAS in KRAS-mutant colorectal cancer cells in vitro and in vivo (Figs. 4 and 6). Functional redundancy between RAF isoforms probably allows for compensatory kinase activity when fewer than all three genes are targeted, thereby incompletely shutting off RAF signaling. As most major RAS effectors are indeed composed of multi-isoform families (MEK1/2, ERK1/2, PIK3CA/B/D, RALA/B, etc.), it may be important to consider entire effector nodes as targets for drug development. Although such combination targeting can most easily be achieved using RNAs, pan-specific small molecules may achieve similar ends.

The ability to multiplex Sensor siRNAs for combination target knockdown is particularly useful in the context of KRAS-driven cancers, where numerous effector pathways are activated. We show that KRAS knockdown alone...
conferred considerable growth inhibition in vivo. However, we further show that targeting KRAS in combination with the PI3K effector node potentiated this effect (Fig. 7). Thus, the delivery of a combination payload targeting both the driver oncogene and an effector node offers the potential to more thoroughly disable mitogenic and survival signaling pathways. Many KRAS effectors, including RAF, PI3K, RAL, and RAC, have RAS-independent means of activation (36), which can be circumvented through direct targeting of effector nodes in addition to KRAS. Furthermore, concurrent targeting of effector nodes may also be effective in disabling feedback-mediated pathway reactivation or in delaying acquired resistance. Our system provides a robust and rapid means for exploration of such combinatorial space, allowing for the rational discovery and validation of optimal target combinations for RAS-driven cancers.

Figure 7. SW620 xenografts treated with combination siKRAS+siPIK3CA/B. A, four NP treatments delivering 2 mg/kg of each siRNA species were prepared as depicted. Nanoparticles were administered via tail-vein injection on days 1, 3, 5, 8, 10, and 12, beginning when tumors reached 70 to 100 mm³. B, siKRAS and siPIK3CA/B treatment induced mild tumor regression and slowed the rate of tumor growth during the first week of treatment compared with siANC_22-treated tumors. siKRAS+PIK3CA/B treatment potentiated the growth inhibition throughout the course of treatment. The inset (bottom) shows growth of all individual tumors analyzed. C, whole-tumor lysate was collected on day 15 and analyzed by Western blot for KRAS, p110α, and p110β expression. D, tumor volume and relative viability were measured daily with optical imaging in the DsRed channel, and EGFP fluorescence tracked nanoparticle delivery, as described in Fig. 5C. NP siRNAs were injected on days 1, 3, and 5. E, tumors were analyzed by immunohistochemistry for Ki67- and CC3-positive cells (*, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001).
METHODS

Sensor Library Design and Construction

The shRNA-Sensor libraries were constructed as previously described (14), with a few improvements to enhance pooled cloning performance. A recipient vector for the first pooled cloning step, pTNL (TREⅣⅣⅣ-NeoⅣ-5′-miR30-BamHI-MfeI-EcoRI), was cloned by replacing the XbaI/ClaI fragment in pSSENSOR, with a linker containing a BamHI-MfeI-EcoRI multiple cloning site (CTCGAG GGATCCATGGAATTCGATGAGAT). To generate the RAS pathway shRNA-Sensor libraries, we designed approximately 5,000 185mer oligonucleotides per library, each containing a 101mer miR30-shRNA fragment, an EcoRI/BamHI/MluI cloning site, the cognate 50 nt Sensor cassette, and an 18 nt primer-binding site (CTTAG GATCGACGCGGAC). For the 75 human RAS pathway genes and their 75 mouse orthologs (Supplementary Table S2), we generated 65 candidate shRNAs each by taking the common transcript of all gene variants and designing the Top300 DSIR predictions (15). We then further selected and ranked these shRNAs using Sensor rules (14) that demand features recurrently found in potent shRNAs and excluded sequences containing restriction sites or endonucleases used for cloning. The 65 top-ranked candidates for each gene (Supplementary Table S2) were synthesized on custom 27k oligonucleotide arrays (Agilent Technologies) that also contained 17 control shRNAs-Sensor oligonucleotides included at 1-fold representation. The final libraries were constructed according to the previously described two-step cloning procedure, with an additional MfeI digestion of the ligation product from cloning step 1 and BamHI digestion of the ligation product from cloning step 2. Briefly, in step 1, oligonucleotides were amplified via PCR with the Sens5′Xho (TACAATCTCGAGAAGGTATATTGCTGTTGACAGTGAGCG) and Sens3′Mfe (ATTCTACACAAAGGCGGTCGATGAGCG) primers, XhoI/MfeI digested, and ligated into XhoI/EcoRI cut pTNL backbone vector. The ligation product was then digested with MfeI to reduce background noise from concatamers. In step 2, the missing 5′miR30-PGK-Venus fragment was cloned into the EcoRI/MluI site, separating each shRNA and its cognate target Sensor, followed by BamHI digestion of the ligation product to further reduce background noise. During each cloning step, a representation of at least 1,000-fold the complexity of the library was maintained.

Cell Lines and Reagents

The human osteosarcoma cell line U2OS and human colorectal cancer cell lines SW620, SW403, SW1116, LoVo, LS123, Caco-2, SW48, RKO, and LS411N were obtained from Dr. Thomas Reid (NCI, Bethesda, MD) and grown in McCoy’s 5A media (Lonza) supplemented with 10% FBS. SW620 and SW1116 cells stably expressing DsRed and EGFP were made by lentiviral infection. Cells were FACS sorted for double-positive cells and pooled populations were propagated for engraftment. All mouse experiments were done in compliance with UCSF and Institutional Animal Care and Use Committee (IACUC) policies. Two to 3 × 10⁶ cells in PBS/Matrigel (1:1) were subcutaneously injected in the right flank of 5- to 8-week-old female C57BL/6 mice. In addition, tumors were optically imaged for DsRed and EGFP fluorescence daily using a G1 Xenogen IVIS 100 System. Total RNA samples extracted from cells transfected with lipid only were used as a gene-expression baseline control. Gene-expression analysis was performed using Partek Genomics Suite 6.0. The data discussed in this publication have been deposited in the NCBI’s Gene Expression Omnibus and are accessible through GEO Series accession numbers GSE59592 and GSE59823.

Sensor siRNA Transfection and Validation

Cells were transfected with Sensor siRNAs at the indicated concentrations by using Lipofectamine RNAiMAX (Invitrogen) following the manufacturer’s instructions. AllStars Negative Control siRNA and AllStars Human Cell Death Control siRNA (Qiagen) were transfected as controls. To validate the Sensor siRNAs and to test knockdown efficiency, U2OS cells were transfected with Sensor siRNAs at the indicated concentrations. Cells were collected 72 hours post-transfection for total cell lysate preparation or total RNA isolation using the RNeasy Mini Kit (Qiagen) followed by cDNA conversion using the High Capacity cDNA Reverse Transcription Kit (Applied Biosystems). To measure the mRNA level, quantitative real-time PCR was performed using the SYBR Green method on a 7900HT Fast Real-Time PCR System platform (Applied Biosystems). GAPDH mRNA was measured as an endogenous control. Each quantitative RT-PCR assay was performed in triplicate. To measure the protein level, total cell lysates were subjected to immunoblotting as previously described (37).

Cell Viability and Apoptosis Assay

Cell viability was measured 5 days after transfection by performing the CellTiter-Glo Luminescent Cell Viability Assay (Promega), whereas apoptosis was measured 3 days posttransfection by performing the Caspase-Glo 3/7 Assay (Promega) following the manufacturer’s instructions. Cell viability and apoptosis rate were normalized against AllStars Negative Control siRNA-transfected cells.

Off-Target Effects and Gene-Expression Analysis

Trp53⁻/⁻ MEFs were transduced with retroviral LMP vectors (38) expressing Trp53 shRNAs at single copy (11%–21% infection efficiency) and high copy (>98% infection efficiency), selected on puromycin, and grown in the absence of the selection agent before harvest. Uninfected Trp53⁻/⁻ MEFs and Trp53⁻/⁻ MEFs infected with an empty vector control served as “no shRNA” reference. Total RNA was extracted from at least 5 × 10⁶ cells per sample using TRIzol (Invitrogen), followed by acidic phenol-chloroform/IAA (125:24:1, pH 4.5; Ambion) purification and isopropanol precipitation. All samples were DNase I (Roche) treated and again purified by acid phenol-chloroform/IAA extraction and isopropanol precipitation. Gene-expression analysis was performed on MoGene-1.0-st-v1 microarrays (Affymetrix). To test siRNA off-target effect, RAS-less MEFs stably expressing exogenous NRAs were transfected with siRNA Kras_234 and Kras_355 at 0.2, 2, 20, and 50 nmol/L in triplicate for 72 hours. Total RNA was extracted and subjected to microarray hybridization on Mouse Gene ST 2.0 microarrays (Affymetrix). Total RNA samples extracted from cells transfected with lipid only were used as a gene-expression baseline control. Gene-expression analysis was performed using Partek Genomics Suite 6.0. The data discussed in this publication have been deposited in the NCBI’s Gene Expression Omnibus and are accessible through GEO Series accession numbers GSE59592 and GSE59823.

Disclosure of Potential Conflicts of Interest

C. Fellmann is the CSO of Mirimus, Inc. J. Zuber is a consultant/advisory board member for Mirimus, Inc. No potential conflicts of interest were disclosed by the other authors.

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