Mutated *KRAS* Results in Overexpression of *DUSP4*, a MAP-Kinase Phosphatase, and *SMYD3*, a Histone Methyltransferase, in Rectal Carcinomas

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Abstract

Mutations of the *KRAS* oncogene are predictive for resistance to treatment with antibodies against the epithelial growth factor receptor in patients with colorectal cancer. Overcoming this therapeutic dilemma could potentially be achieved by the introduction of drugs that inhibit signaling pathways that are activated by *KRAS* mutations. To identify comprehensively such signaling pathways we profiled pretreatment biopsies and normal mucosa from 65 patients with locally advanced rectal cancer - 30 of which carried mutated *KRAS* - using global gene expression microarrays. By comparing all tumor tissues exclusively to matched normal mucosa, we could improve assay sensitivity, and identified a total of 22,297 features that were differentially expressed (adjusted *P*-value <0.05) between normal mucosa and cancer, including several novel potential rectal cancer genes. We then used this comprehensive description of the rectal cancer transcriptome as the baseline for identifying *KRAS*-dependent alterations. The presence of activating *KRAS* mutations is significantly correlated to an upregulation of 13 genes (adjusted *P*-value <0.05), among them *DUSP4*, a MAP-kinase phosphatase, and *SMYD3*, a histone methyltransferase. Inhibition of the expression of both genes has previously been shown using the MEK1-inhibitor PD98059 and the antibacterial compound Novobiocin, respectively. These findings suggest a potential approach to overcome resistance to treatment with antibodies against the epithelial growth factor receptor in patients with *KRAS*-mutant rectal carcinomas.

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INTRODUCTION

The introduction of therapeutic antibodies for cancer treatment was a first step towards the implementation of targeted therapies, and, consequently, an important milestone towards the realization of individualized treatment. The most heralded target for a rational therapy of patients with colorectal cancer was an antibody against the EGF receptor, Cetuximab. The gene that encodes this protein maps to 7p, which is subject to recurrent genomic amplification in CRC (Platzer et al., 2002). Treatment with Cetuximab leads to higher response rates and to a significant prolongation of the progression-free interval in metastatic colorectal cancer. However, recent evidence strongly suggests that treatment failure in patients receiving chemotherapy in combination with anti-EGFR antibodies is caused by activating mutations of the *KRAS* proto-oncogene (Lievre et al., 2006, 2008; Di Fiore et al., 2007; Karnoub and Weinberg, 2008). Mutations of this gene occur in 35-45% of all colorectal cancers (Brink et al., 2003; Baldus et al., 2010), and result in the continuous activation of the *KRAS* signaling pathway, now independent of EGFR-dependent stimulation. Therefore, targets other than EGFR are currently pursued for the treatment of patients with *KRAS* mutated colorectal cancer. Alternatively, one could envision that drugs that counteract the effect of mutant *KRAS* or its downstream targets and would thus overcome the resistance of *KRAS* mutant tumors to *EGFR* inhibitors, could evolve as valuable treatment options.

We therefore aimed to analyze systematically and comprehensively the influence of *KRAS* mutations on the rectal cancer transcriptome. Towards this goal, we performed whole genome expression profiling of locally advanced rectal cancers, for which the respective *KRAS* mutation status had recently been analyzed (Gaedcke et al., 2010). We focused exclusively on rectal carcinomas and normalized gene expression levels for all carcinomas to matched normal mucosa biopsies. We defined these two criteria in an attempt to reduce the noise induced by the idiosyncrasies of individual patient samples and by differences as a consequence of the anatomical location. We hypothesized that the delineation of a "*KRAS* signature", and with it a comprehensive and definitive description of the rectal cancer transcriptome will lead to the identification of novel critical pathways and potential target genes, and hence unexplored potential alternative therapeutic strategies.

MATERIALS AND METHODS

Selection of Patients, Sample Ascertainment and RNA Isolation

Sixty-five patients with rectal adenocarcinomas were included in this study (Supplementary Table 1). All tumors were located within 12 cm from the anocutaneous verge, and diagnosed as locally advanced stages of the disease (UICC II/III). From each patient we collected pretreatment tumor biopsies adhering to the guidelines set by the local ethical review board. Biopsies were immediately stored in RNAlater (Qiagen, Hilden, Germany). Using a second forceps normal rectal mucosa biopsies were obtained from all 65 patients at a minimum distance of 3 cm from the tumor site.

Subsequently, RNA was isolated using TRIzol (Invitrogen, Carlsbad, CA) following standard procedures as previously described (Grade et al., 2006, 2007). Nucleic acid quantity, quality and purity were determined using a spectrophotometer (Nanodrop, Rockland, DE) and a 2100 Bioanalyzer (Agilent Technologies, Palo Alto, CA). RNA samples with an RNA Integrity Number (RIN) of > 5 were included.

Gene Expression Profiling

Expression profiling was performed as previously described (Grade et al., 2010). Briefly, 1 μg of total RNA was labeled with Cy3 using the Low RNA Input Fluorescent Linear

Amplification Kit according to the manufacturer's recommendations (Agilent Technologies, Santa Clara, CA). Quantity and efficiency of the labeled amplified cRNA were determined using the NanoDrop ND-1000 UV-VIS Spectrophotometer version 3.2.1. Subsequently, 1.5 μg of Cy3-labeled cRNA was hybridized to an oligonucleotide-based Whole Human Genome Microarray (4×44K, Agilent Technologies) and incubated at 65°C for 17 h. Slides were washed and scanned using an Agilent G2565BA scanner. Raw data were extracted using the Feature Extraction software version 9.1 (Agilent Technologies).

Data Normalization and Processing

Statistical analyses were performed with the free software R (version 2.8, www-r-project.org). The R-package 'limma' (www.bioconductor.org) was used for data normalization and identification of differentially expressed genes. Raw expression data from all 130 microarrays were log_2-transformed and quantile normalized (Bolstad et al., 2003). Features that showed in 90% of all arrays an expression that was lower than the average "Dark Corner" values were removed.

Statistical Analysis and Pathway Information

Genes with significantly different expression level ratios between tumor and mucosa samples were identified using the Limma method (Smyth, 2004). To control for multiple testing, raw p-values were adjusted using the method of Benjamini and Hochberg (Benjamini and Hochberg, 1995). Genes were regarded as differentially expressed when the adjusted *P*-value was smaller than 0.05. For a more stringent assessment we applied additional filter criteria: a 2-fold change in expression and a "tumor marker" criterion (the lowest expression of a given feature in the tumor samples always had to be higher than the highest expression in all the matched normal mucosae, or vice versa (in the following referred to as Min/Max criterion)).

Both gene lists were screened for known interactions and involvement in biological networks using the software package Ingenuity Pathway Analysis (IPA; Ingenuity, Mountain View, CA). The genes showing a 2-fold change in expression were queried as to their enrichment at certain chromosomal locations.

From statistical theory it is anticipated that the analysis of paired tumor and mucosa samples from the same patients is more powerful than a similar analysis with unpaired tumor and mucosa samples from different patients (Fisher, 1925). To demonstrate further the superiority of a paired tumor and mucosa samples in our data we performed some random sampling experiments. In each run, 30 patients were randomly chosen from our studied collective and their tumor samples were compared to their related mucosa samples. In the same run the tumor samples from the 30 selected patients were also compared to 30 randomly chosen unrelated mucosa samples (Supplementary Fig. 1).

The potential of differentially expressed genes detected between tumors with and without a *KRAS* mutation to distinguish between those two groups was evaluated using discriminant analysis within a Leave-One-Out-Cross-Validation (LOOCV).

Semi-Quantitative Real-time PCR

The mRNA expression levels of distinct genes were validated by semi-quantitative real-time PCR (qPCR) using iQ™ SYBR® Green Supermix (BIO-RAD Laboratories, Hercules, CA). Gene-specific primers were designed using Primer3 (http://frodo.wi.mit.edu/) and obtained from MWG Biotech AG (Ebersberg, Germany). All nucleotides were optimized according to standard protocols and shown to produce single amplicons and no primer-dimer artifacts. The efficiency of amplification was validated using LinRegPCR (http://www.gene-

quantification.de/download.html#linregpcr). Corresponding primer sequences are listed in Supplementary Table 2.

Briefly, total RNA was reverse-transcribed into cDNA using Superscript III Reverse Transcriptase (Invitrogen, Carlsbad, CA) and subsequently diluted 1:5. Triplicate quantifications were performed for each gene in an iCycler (Bio-Rad Laboratories GmbH, Munich, Germany), and each data point was calculated as the median of the three measured CT values. Relative mRNA levels were calculated and normalized to the expression levels of *OTUB1*, *FBXL12* and *RAB35* using the ΔΔCt technique. These genes were specifically chosen because their expression levels were stable among all samples. A detailed protocol can be found at www.riedlab.nci.nih.gov/protocols.asp.

Analysis of *KRAS* Status

KRAS mutation status was assessed by Sanger sequencing of DNA extracted from tumor biopsies. Analysis included exons 1, 2 and 3 as reported previously (Gaedcke et al., 2010). Gene expression profiles and *KRAS* mutation status were analyzed from identical biopsies (Supplementary Table 1).

RESULTS

The signaling pathway governed by the oncogene *KRAS* is crucially involved in tumorigenesis. In addition, there is sound evidence that mutations in the *KRAS* oncogene determine response to treatments that target the MAP kinase pathway, a promising molecular target for individualized therapy.

In order to identify downstream pathways of mutated *KRAS* that could explain resistance to MAP-kinase pathway inhibition, we first created a baseline for the systematic exploration of the consequences of activated ras signaling by comprehensively cataloguing transcriptional alterations in 65 rectal carcinomas for which we had previously established *KRAS* mutation status. In order to account for potential differences between rectal and colonic carcinomas, including different therapeutic regimen, we concentrated in this study exclusively on rectal cancer, and we compensated for inter-patient transcriptional differences by normalizing changes in the tumor transcriptome to patient-matched normal mucosa.

The Rectal Cancer Transcriptome: Differentially Expressed Genes

We profiled a series of 65 locally advanced rectal cancers. In contrast to previously performed microarray analyses of rectal carcinomas (Alon et al., 1999; Zou et al., 2002; Friederichs et al., 2005; Bianchini et al., 2006) matched normal rectal mucosa samples were used for comparison, to increase the power of the tests due to likely smaller variances. As expected using paired samples yielded in significantly more differentially expressed genes than using unpaired samples (P<0.01, Supplementary Fig. 1). Data were normalized and filtered as described in Materials and Methods. Of the 29,149 remaining features 22,297 were differentially expressed according to the FDR-adjusted P-values; they allowed a clear separation between tumors and matched normal mucosa samples (Fig. 1). To increase further the biological relevance of differentially expressed genes we applied the additional filter criteria of 2-fold difference in expression which reduced the number to 3,174 genes.

Since we have previously shown that a disproportional number of deregulated genes maps to specific chromosomes (Grade et al., 2007), we now explored whether this observation holds true when individual tumors were compared to matched normal mucosa. Of the 3,174 differentially expressed genes (false discovery rate adjusted P value <0.05 and a >2-fold difference in expression), 3,136 had a defined chromosomal location. One thousand six hundred seventy one genes were down-regulated and 1,503 were up-regulated in the tumors.

In order to compare the observed percentage of differentially expressed genes per chromosome with the percentage of genes expected to be differentially expressed by chance, we calculated 1,000 random distributions of these 3,174 genes. In fact, chromosomes 4, 18 and 20 showed significantly more differentially expressed genes than expected by chance, and, interestingly, chromosome 19 showed fewer genes (Fig. 2). Most genes on chromosomes 13 and 20 were upregulated; in contrast, most genes on chromosomes 14, 15 and 18 were underexpressed in the tumors, which is consistent with the frequent gain of chromosomes 13 and 20, and losses that include chromosomes 4 and 18.

Of the 3,174 features, 1,481 were up-regulated and 1,693 were down-regulated in the tumors (Supplementary Table 3). To identify potential novel cancer genes, differentially expressed genes were filtered to be either always higher expressed in the tumors compared to the mucosa, or vice versa, our so called Min/Max criteria. Nineteen features fulfilled this criterion, representing 17 different genes (two of the genes were represented with two features). Eleven of these features (ten genes) were highly expressed in the tumors, while eight features (seven genes) were highly expressed in the normal mucosa (Table 1).

Validation of Gene Expression Levels Using Semi-quantitative Real-time PCR

To validate independently the gene expression measurements derived from the microarray experiments, semi-quantitative RT-PCR (qPCR) was performed for 13 out of the 17 different genes in 10 tumors and 10 matched mucosa samples. As shown in Figure 3, the differential expression levels were confirmed for all genes analyzed with both methods. To assess the correlation of microarray data and qPCR results Pearson's correlation coefficient R was calculated using the fold changes between tumor and matched mucosa. We found a highly significant correlation between both techniques (Pearson's R=0.98, P<0.01; Fig. 3).

The Rectal Cancer Transcriptome: Biological Networks

We then interrogated in which networks or pathways these 17 genes operate using the software package IPA. Strikingly, 14 of the genes clustered together in one particular network, which was connected through *CEBPA* and *NFkB* complex, which are transcription factors, *GDF 15* and *TNF*, both of which are BMP superfamily members, and *ERK* and *JNK* (also known as *MAPK1* and *MAPK8),* two components of the MAP Kinase pathway. Furthermore, *TGFB1* was a central gene within the network (Fig. 4).

For a more global analysis of the differentially expressed genes we expanded the IPA analysis using genes that passed the filter criteria based on a fold change larger than two (n=3,174). As expected a large number of networks emerged. The top five, based on *P*-value, were functionally associated to cell cycle, cell mediated immune response, cell-cell signaling, tumor and organ morphology, and, most prominently, cancer. The most outstanding intersections were centered on *IL-6* ($P=10^{-41}$), *MMP3* and *KRAS* ($P=10^{-38}$), *NR3C1* ($P=10^{-36}$), *BRCA1* and *CDKN2A* ($P=10^{-36}$), as well as *ERK* and *TRIB3* ($P=10^{-34}$). The most relevant functions described for the differentially expressed genes included tumorigenesis ($P=10^{-61}$), cancer ($P=10^{-58}$), neoplasia ($P=10^{-57}$), genetic disorders ($P=10^{-42}$) and colorectal cancer ($P=10^{-39}$) (Supplementary Fig. 2).

Effect of *KRAS* Mutation Status on the Rectal Cancer Transcriptome

After we had now carefully annotated the transcriptional changes associated with rectal cancer we aimed to identify the consequences of *KRAS* mutations on the rectal cancer transcriptome. This analysis is relevant because (i) activating mutations are known to play a fundamental role in carcinogenesis, (ii) *KRAS* status is used for stratification of anti-EGFR therapy with Cetuximab and, (iii) it is of clinical importance to identify strategies to overcome the resistance against such antibody-based treatment.

Unsupervised clustering did not result in separation according to the *KRAS* mutation status, however, we identified a set of 13 genes that were differentially expressed between the two groups, based on an adjusted *P*-value smaller than 0.05. These genes are: *COPZ1*, LEMD1, S100A14, RDHE2, WDR51B, SMYD3, MYBPC1, TEGT, DUSP4, SERPINB1, TCP10L, GOLPH3L, and *CACNA1C*. Interestingly, *KRAS* mutation caused upregulation of all of these genes (Fig. 5 and Table 1). The potential of these differentially expressed genes to distinguish tumors with and without mutations was evaluated using a Leave-One-Out-Cross-Validation (LOOCV). With that estimate we achieved a test accuracy of 96.9% (sensitivity 93.3%; specificity 97.1%). Of those 13 genes, only one, *DUSP4*, had been previously reported to be linked to *KRAS* and the MAPK pathway.

DISCUSSION

Activating mutations of the *KRAS* oncogene play an important role in colorectal carcinogenesis. Mutations of this gene result in the GTP-dependent activation of the MAPK pathway, which, in turn impairs cell differentiation and apoptosis, and increases cell proliferation.

Furthermore, *KRAS* mutations have implications above and beyond basic tumor biology because successful targeting of the *EGFR* axis using Cetuximab depends on the maintenance of wild type *KRAS* (Lievre et al., 2006, 2008; Di Fiore et al., 2007; De Roock et al., 2008; Karapetis et al., 2008). Nevertheless, nothing is known about the transcriptional differences between *KRAS* mutant and wild-type tumors in rectal carcinomas and their impact on the whole transcriptome. In an attempt to identify such differences, we assessed *KRAS* mutation status and its consequences on the cancer transcriptome by analyzing 65 locally advanced rectal cancers and their corresponding normal mucosa. With this considerably large dataset, we were in a position to screen for *KRAS* mutation dependent transcriptional consequences on downstream targets.

Impact of KRAS on the Rectal Cancer Transcriptome

Forty-seven percent of rectal carcinomas in our dataset revealed activating *KRAS* mutations (Gaedcke et al., 2010). Our data are therefore congruent with published data on the prevalence of the mutations. Comparison of *KRAS* mutant and wild-type rectal cancers revealed thirteen differentially expressed genes which were always, and with high-fold and high-significance differentially expressed between tumors with and without mutations. All genes were upregulated in the mutant tumors. Relatively little is known about most of these genes. Only for one of the upregulated genes an association to the MAPK pathway had been reported previously: MAP-2 kinase phosphatase *(DUSP4)* has previously been reported to be upregulated in various cancer types (Yip-Schneider et al., 2001; Wang et al., 2003). Our own data confirm the significant upregulation of DUSP4 in rectal cancer ($P=10^{-21}$).

Khambata-Ford and colleagues (2007) investigated the impact of *DUSP4* expression levels on outcome of patients with metastatic colorectal cancer. Gene expression profiling from 80 patients with metastatic colorectal carcinomas enrolled in a Cetuximab monotherapy trial revealed *DUSP4* as one of the top resistance markers. Since *KRAS* mutations are currently considered as some of the most relevant resistance markers for treatment failure, overexpression of *DUSP4* within the same group confirms the finding of a mutation dependent regulation. Lung cancers with EGFR mutations respond well to Cetuximab, and it was recently shown that *DUSP4* is downregulated in those tumors. The overexpression of *DUSP4* in rectal cancer in the presence of *KRAS* mutations which are resistant to Cetuximab is therefore a possible explanation for the mode of action. *DUSP4* expression levels could therefore serve as biomarkers for treatment stratification therapies with Cetuximab.

In cDNA microarray analysis, the gene *LEMD1* (LEM domain-containing 1) has previously been found to be upregulated in colorectal cancer and was shown to be a member of the cancer-testis antigens (Yuki et al., 2004). *TEGT* is a regulator of apoptosis (Grzmil et al., 2006), *SERPINB1* was reported to be upregulated in oral cancer (Tseng et al., 2009) and *SMYD3*, a histone methyltransferase, is involved in the proliferation of cancer cells (Hamamoto et al., 2004, 2006; Zou et al., 2009). Nine of the thirteen genes showed connections when analyzed with IPA which suggests a functional relationship between these genes and could explain why they are jointly deregulated as a consequence of *KRAS* mutation (Supplementary Fig. 3).

We queried the relevance of identifying *KRAS*-related genes for clinical considerations. For instance, if resistance to Cetuximab as a consequence of *KRAS* mutation depends on *KRAS* regulated genes one could hypothesize that transcriptional modification of these genes would restore the sensitivity of colorectal carcinomas to Cetuximab. *DUSP4* is a good example because low levels of *DUSP4* sensitize tumors to Cetuximab and decreasing *DUSP4* levels using the agent PD98059 could therefore be used in treatment of *KRAS* mutated tumors in combination with Cetuximab (Yip-Schneider et al., 2001). Another potential target for such an intervention would be *SMYD3*, another one of the differentially expressed genes in our dataset, because the drug Novobiocin lowers the expression level of this gene (Luo et al., 2009).

Identification of Novel Rectal Cancer Tumor markers

The most stringent criteria to select differentially expressed genes was introduced to reveal new tumor markers (Min >< Max rule). This rule filtered genes that are always higher expressed in any of the tumors compared to all mucosa samples, or vice versa. Of the 19 features identified eleven were higher and eight were lower expressed in the tumor. The expression levels of 13 of these genes were validated using qPCR. As in previous validation experiments, the results between arrays and qPCR were extremely reproducible (R=0.98) attesting to the robustness of either methodology. Within the validated genes *ETV4* (Liu et al., 2007), *ROR1* (Katoh, 2005) or *CLDN1* (Kinugasa et al., 2007; Huo et al., 2009), *C20orf20* (Cai et al., 2003; Carvalho et al., 2009) and *FUT1* (Hallouin et al., 1999) have already been linked to colorectal cancer. Others are known to play a role in carcinogenesis in general, such as *TRIB3* (Du et al., 2003), *ACAN* (Skandalis et al., 2006; Stylianou et al., 2008) and *CEP72* (Kang et al., 2008) but have not been directly associated with colorectal cancer whereas an involvement of *MYOT*, *ENDOD1* and *ANO5* in epithelial tumorigenesis is a novel finding. All genes that we previously found differentially expressed or overexpressed in a more limited dataset of colorectal cancer were confirmed to be deregulated in the same direction (Grade et al., 2006, 2007).

Interestingly, when we analyzed these 17 genes using IPA we found 14 of them operating in one network (Fig. 4). This network was connected through *TNF*, *TGFB1*, *ERK*, and the *NFkB* complex which highlights the central role that these signaling pathways assume in CRC (Glick, 2004; Fang and Richardson, 2005; Zhang et al., 2007; Balkwill, 2009). Expanding the numbers of genes for pathway analysis we used the differentially expressed genes based on a FC >2. The main interceptions within the networks like *MMP3*, *KRAS*, *p16* or *ERK* again confirm the relevance of the retrieved genes.

In summary, this is the most comprehensive and systematic gene expression study of rectal carcinomas and normal mucosa. Using matched samples rather than a normal reference pool was important to retrieve more differentially expressed genes. In addition, this is the first systematic exploration of gene expression changes that are a consequence of activating *KRAS* mutations in rectal cancer. We identified *DUSP4* and *SMYD3* as attractive targets for a potential combination therapy of patients with Cetuximab resistant tumors.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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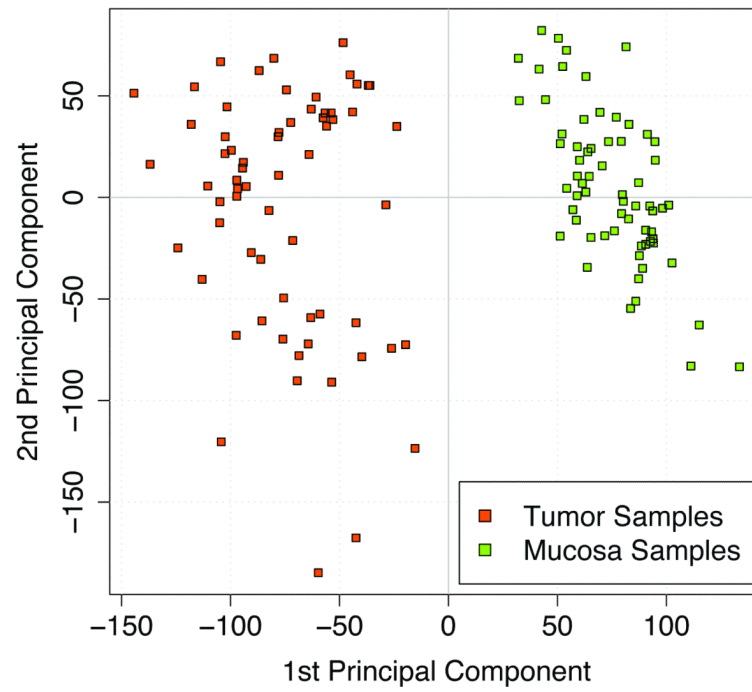
Figure 1.
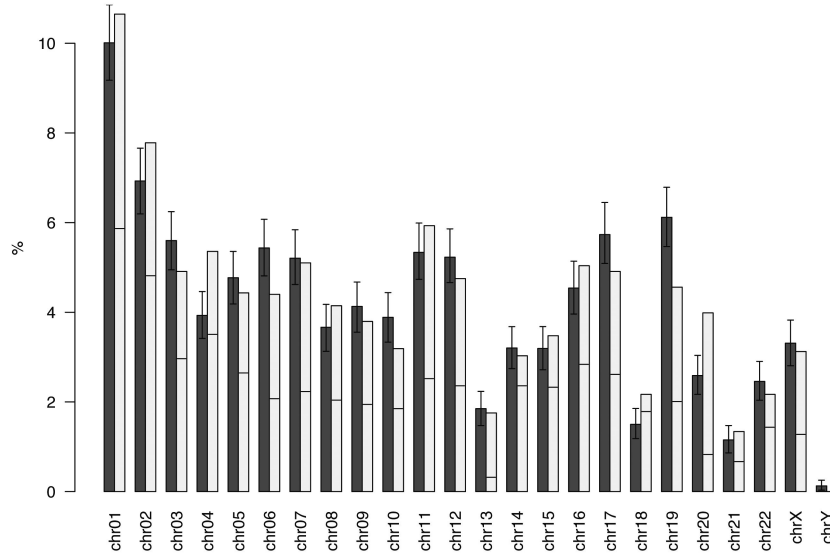Principal component plot representing tumor and mucosa samples from 65 patients.

Figure 2.
The dark bars display the expected percentage including the 95% confidence interval, the light bars display the observed percentages of DEGs per chromosome. Chromosomes 4, 18 and 20 show significantly more DEGs than expected; chromosome 19 shows less DEGs. The horizontal line in the light bar indicates the proportion of up- and downregulated genes displaying upregulation of most of the genes on chromosome 13 and 20 and downregulation on chromosomes 14, 15 and 18. (DEG, differentially expressed genes)
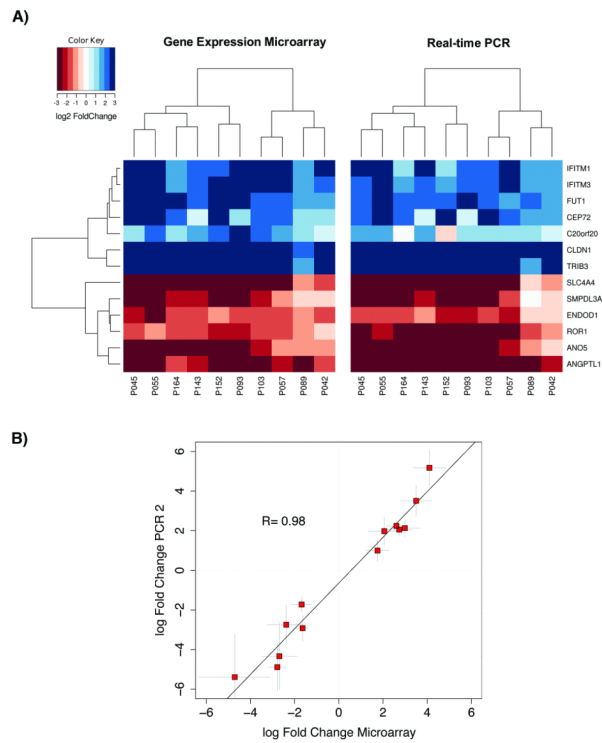
Figure 3.
(A) Comparison of log2 FC between qPCR and gene expression array (B) Correlation between log fold changes of qPCR measurements versus those of microarray features. Plot represents 13 of the detected tumor markers. Microarray fold changes deviate from those in Tab. 1 because they were derived from only 9 patients.
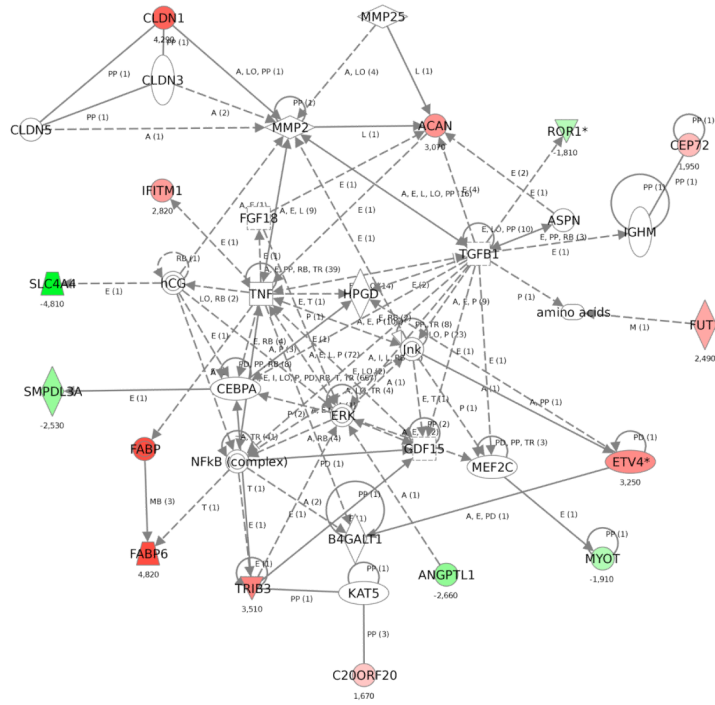
Figure 4.
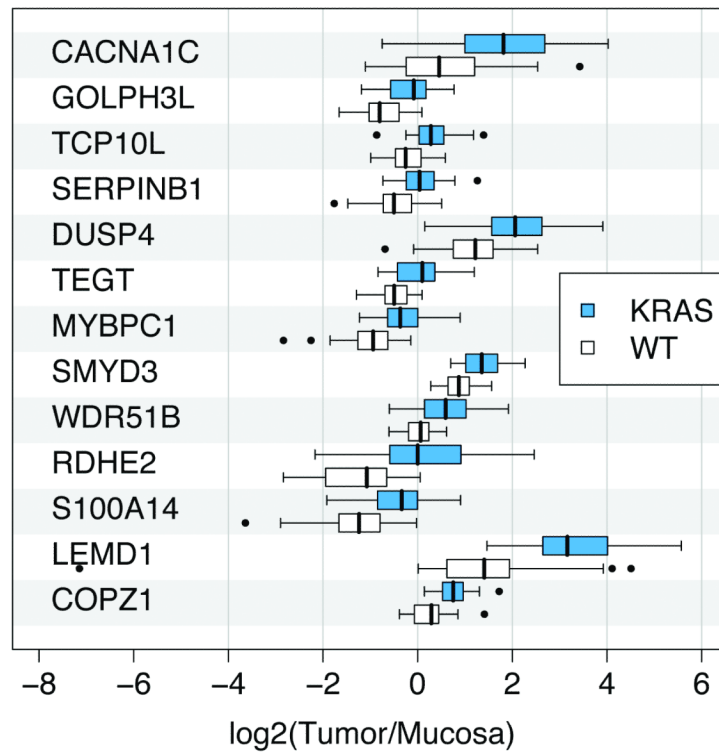Ingenuity pathway analysis reveals the close relationship between 14 of 17 of most relevant genes in rectal cancer

Figure 5.
Differentially expressed genes between *KRAS* wild type and mutant rectal carcinomas

TABLE 1

Expression Ratio for Genes of Interest

a) Features fulfilling the Min >< Max criteria

Systematic name	Gene name	Description	log2 FC tumor vs. mucosa	P	Map
NM_013227	ACAN	Aggrecan	3.07	6.60E-36	15q26.1
NM_004673	ANGPTL1	Angiopoietin-like 1	−2.66	1.22E-37	1q25.2
NM_018270	ANO5	Anoctamin 5	−2.9	3.78E-32	11p14.3
NM_018270	C20orf20	Chromosome 20 open reading frame 20	1.67	1.05E-33	20q13.33
NM_018140	CEP72	Centrosomal protein 72kDa	1.95	5.92E-35	5p15.33
NM_021101	CLDN1	Claudin 1	4.29	5.01E-48	3q28-q29
NM_015036	ENDOD1	Endonuclease domain containing 1	−1.91	6.00E-37	11q21
NM_001079675	ETV4	Ets variant 4	3.25	1.26E-41	17q21
NM_001079675	ETV4	Ets variant 4	2.97	9.72E-39	17q21
NM_001445	FABP6	Fatty acid binding protein 6, ileal	4.82	4.94E-43	5q33.3-q34
NM_000148	FUT1	Fucosyltransferase 1	2.49	2.00E-35	19q13.3
NM_003641	IFITM1	Interferon induced transmembrane protein 1 (9-27)	2.82	1.36E-38	11p15.5
NM_021034	IFITM3	Interferon induced transmembrane protein 3 (1-8U)	2.68	2.72E-38	11p15.5
NM_006790	MYOT	Myotilin	−1.91	3.97E-41	5q31
NM_005012	ROR1	Receptor tyrosine kinase-like orphan receptor 1	−1.67	9.35E-38	1p32-p31
NM_005012	ROR1	Receptor tyrosine kinase-like orphan receptor 1	−1.81	1.32E-35	1p32-p31
NM_003759	SLC4A4	Solute carrier family 4, sodium bicarbonate cotransporter, member 4	−4.81	8.58E-30	4q21
NM_006714	SMPDL3A	Sphingomyelin phosphodiesterase, acid-like 3A	−2.53	3.09E-34	6q22.31
NM_021158	TRIB3	Tribbles homolog 3 (Drosophila)	3.51	3.07E-41	20p13-p12.2

b) Genes being differentially expressed between *KRAS* WT and *KRAS* mutant.

Systematic name	Gene name	Description	log2 FC WT vs. mutant	*P*	Map
NM_000719	CACNA1C	Calcium channel, voltage dependent, L type, alpha 1C subunit	1.2	2.16E-05	12p13.3
NM_003217	TEGT	Testis enhanced gene transcript (BAX-inhibitor-1)	0.54	4.75E-06	12q12-q13
NM_016057	COPZ1	Coatomer protein complex, subunit zeta 1	0.52	7.25E-07	12q13.2-q13.3
NM_172240	WDR51B	WD repeat domain 51B	0.6	2.21E-06	12q21.33
NM_206819	MYBPC1	Myosin binding protein C, slow type	0.68	3.86E-06	12q23.2
NM_020672	S100A14	S100 calcium binding protein A14	0.94	1.02E-06	1q21.3
NM_018178	GOLPH3L	Golgi phosphoprotein 3 like	0.57	1.73E-05	1q21.3
NM_001001552	LEMD1	LEM domain containing 1	2.02	7.58E-07	1q32.1
NM_022743	SMYD3	SET and MYND domain containing 3	0.49	3.40E-06	1q44
NM_144659	TCP10L	T-complex 10 (mouse)-like	0.52	1.57E-05	21q22.11
NM_030666	SERPINB1	Serpin peptidase inhibitor, clade B (ovalbumin), member 1	0.56	1.32E-05	6p25
NM_001394	DUSP4	Dual specificity phosphatase 4	0.9	1.10E-05	8p12-p11
NM_138969	RDHE2	Epidermal retinal dehydrogenase 2	1.26	1.22E-06	8q12.1

FC, Fold Change