Comprehensive Analysis of R-Spondin Fusions and *RNF43* Mutations Implicate Novel Therapeutic Options in Colorectal Cancer

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ABSTRACT

Purpose: Gene fusions involving R-spondin (*RSPOfp*) and *RNF43* mutations have been shown to drive Wnt-dependent tumor initiation in colorectal cancer. Herein, we aimed to characterize the molecular features of *RSPOfp/RNF43* mutated (mut) compared with wild-type (WT) colorectal cancers to gain insights into potential rationales for therapeutic strategies.

Experimental Design: A discovery cohort was classified for *RSPOfp/RNF43* status using DNA/RNA sequencing and IHC. An independent cohort was used to validate our findings.

Results: The discovery cohort consisted of 7,245 colorectal cancer samples. *RSPOfp* and *RNF43* mutations were detected in 1.3% ($n = 94$) and 6.1% ($n = 443$) of cases. We found 5 *RSPO* fusion events that had not previously been reported (e.g., *IFNGR1–RSPO3*). *RNF43*-mut tumors were associated with right-sided primary tumors. No *RSPOfp* tumors had *RNF43* mutations. In comparison with WT colorectal cancers, *RSPOfp* tumors were characterized by a higher frequency of *BRAF*, *BMPR1A*, and *SMAD4* mutations. *APC* mutations were observed in only a minority of *RSPOfp*-positive compared with WT cases (4.4% vs. 81.4%). Regarding *RNF43* mutations, a higher rate of *KMT2D* and *BRAF* mutations were detectable compared with WT samples. Although *RNF43* mutations were associated with a microsatellite instability (MSI-H)/mismatch repair deficiency (dMMR) phenotype (64.3%), and a tumor mutation burden ≥10 mt/Mb (65.8%), *RSPOfp* was not associated with MSI-H/dMMR. The validation cohort replicated our genetic findings.

Conclusions: This is the largest series of *RSPOfp/RNF43*-mut colorectal cancers reported to date. Comprehensive molecular analyses asserted the unique molecular landscape associated with *RSPO/RNF43* and suggested potential alternative strategies to overcome the low clinical impact of Wnt-targeted agents and immunotherapy.

Introduction

Colorectal cancer remains one of the major causes of cancer-specific morbidity and mortality worldwide (1, 2). Despite therapeutic improvements, the prognosis of patients with metastatic disease remains poor with a 5-year overall survival (OS) rate of approximately 14% (1). Thus, new therapeutic strategies are urgently needed to improve survival.

Activation of the Wnt/β-catenin pathway, mostly facilitated by genetic mutations encoding for the adenomatous polyposis coli (APC) protein, can initiate tumorigenesis in colorectal cancer (3, 4). *In vitro* experiments have determined that the restoration of functional *APC* leads to tumor regression even in colorectal cancer cells with additional oncogenic mutations (i.e., *TP53* or *KRAS*; ref. 5). Therefore, Wnt/β-catenin signaling represents a major oncogenic driver in colorectal cancer. Over the last years, different genetic alterations activating the Wnt signaling pathway have been discovered. Seshagiri and colleagues (6) described previously chromosomal rearrangements involving members of the R-spondin family (*RSPO*) in colorectal cancer for the first time, which can be observed in up to 8% of colorectal cancers.

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Translational Relevance

To provide meaningful rationales to develop new impactful targeted approaches for patients with colorectal cancer, we comprehensively described previously the mutational landscape of R-spondin fusion proteins (*RSPOfp*) and *RNF43* mutations, which are known to induce Wnt signaling. Using a cohort of 7,245 colorectal cancer samples, we could identify five new *RSPO* rearrangements and could describe the unique molecular portrait of *RSPOfp* and *RNF43* mutations in colorectal cancers. The genetic profile of *RSPOfp*-positive tumors is similar to *RNF43*-mutated colorectal cancer and is characterized by a higher frequency of *BRAF*, *SMAD4*, and *KMT2D* mutations in comparison with *RSPOfp/RNF43*-negative cases. Of note, a subgroup of *RNF43*-mutated tumors is associated with microsatellite instability. Our data could support clinical and preclinical research developing treatments targeting the Wnt pathway and could also provide a rationale for combinational approaches to overcome primary resistance to immunotherapy in colorectal cancer.

Studies suggest that such *RSPO* translocations alone are sufficient to initiate carcinogenesis (7), as are mutations in *RNF43*, a negative feedback regulator of the Wnt/β-catenin pathway. *RSPO* molecules bind to the G-protein coupled receptor (LGR) family (LGR4/5/6) that contains a leucine-rich repeat segment resulting in an upregulation of the Wnt/β-catenin pathway by sequestering the E3 ubiquitin ligase *RNF43* (8). Mutations in *RNF43* have been described previously in a variety of malignancies, including colorectal cancer and gastric cancer, with a frequency of up to 20% (9–15). Interestingly, the frequency of *RNF43* mutations was noted to be even higher in microsatellite-unstable cancers (11). Most of the loss-of-function (LOF) mutations in *RNF43* have been determined to lead to an increased cell surface abundance of the Wnt receptor Frizzled, rendering the cells dependent upon Wnt/β-catenin signaling (16). Therefore, these cells are suggested to be more sensitive to inhibition of the porcupine homolog (PORCN) protein (16), a posttranslational modificator of the Wnt protein (17).

RSPOfp-positive/*RNF43*-mutated (mut) tumors represent a distinct genetic subgroup of colorectal cancers. However, gene alterations co-occurring in this subgroup are largely unknown. Thus, we set up this study to define the molecular profile of *RSPO/RNF43*-positive colorectal cancer that may provide important insights how Wnt/β-catenin pathway deregulation drives tumor growth in colorectal cancer. For this, we performed extensive genomic and transcriptomic sequencing, as well as IHC, to compare molecular profiles of *RSPO/RNF43*-positive versus wild-type (WT) cases, and detected clusters of gene mutation associations as well as several relations with microsatellite instability (MSI-H) and tumor mutation burden (TMB).

Materials and Methods

Sample characterization of the discovery cohort

Colorectal carcinoma specimens of 7,245 patients were submitted to Caris Life Sciences for genomic profiling. These cases were retrospectively reviewed, and gene sequencing, amplification, and protein expression data were analyzed. The pathology report was included with the specimens and hematoxylin and eosin slides were prepared for each tumor sample to be reviewed by board-certified pathologists to confirm the diagnosis of colorectal cancer. Tumors with a histologic diagnosis that was not concordant with the diagnosis of colorectal cancer were excluded from this analysis. During the recruitment period, tests have varied because there were different requests by the treating physicians and the testing technologies continuously evolved over time. The next-generation sequencing (NGS) platform for tumors tested in 2015 or earlier used the MiSeq platform (45 genes included) whereas those tested after 2015 were sequenced with the NextSeq platform (592 genes included). In keeping with 45 CFR 46.101(b), this study was performed using retrospective, de-identified clinical data. Therefore, this study is considered IRB exempt and no patient consent was necessary from the subjects. Thus, only basic demographic information was available. Patients were stratified into *RSPOfp* or *RNF43*-positive and negative cases. *RNF43* mutations included only pathogenic or presumed pathogenic mutations. Tumors with benign *RNF43* mutations, presumed benign *RNF43* mutations, or *RNF43* variants of unknown significance were categorized as *RNF43*-WT. Germline testing could not be performed because of the lack of access to germline DNA.

Samples of the validation cohort

A total of 816 cases of colorectal cancers were recruited between January 2016 and December 2017 at the Singapore General Hospital, Singapore. A local Ethics Committee approval was obtained. Molecular profiling was analyzed for *RNF43* mutations (excluding the specific G569fs variant) and co-mutations in Wnt and MEK signaling pathways as well as MSI-H or mismatch repair deficiency (dMMR; MSI-H/dMMR). *RSPO* fusions were not characterized.

Analyses performed

IHC was performed on 1,258 tumor samples on formalin-fixed paraffin-embedded (FFPE) sections on glass slides for the discovery cohort. Four micrometer sections were mounted on slides and stained using an automated system (Benchmark, Ventana Medical Systems; Autostainer, DAKO) according to the manufacturer's instructions, and were optimized and validated per CLIA/CAP and ISO requirements. All proteins of interest were evaluated on tumor cells. An intensity score (0 = no staining; 1+ = weak staining; 2+ = moderate staining; 3+ = strong staining) and a proportion score to determine the percentage of cells staining positive (0%–100%) was used. The primary antibody used to detect PD-L1 expression was SP142 (Spring Biosciences). The staining was deemed positive if its intensity on the membrane of the tumor cells was ≥2+ and the percentage of positively stained cells was ≥5%. Results were classified as positive or negative by using previously defined thresholds specific to each marker, based on published clinical literature that associates biomarker status to specific treatment response. The primary antibody used for PD-L1 testing was MRQ-22 (Ventana) and staining was scored as positive if the number of PD-L1–positive cells was >1 cell per high power field. A single board-certified pathologist independently evaluated immunohistochemical results.

NGS was performed on FFPE tumor samples using the NextSeq platform (Illumina, Inc.). A custom-designed SureSelect XT assay was used to enrich 592 whole-gene targets (Agilent Technologies). All variants were detected with >99% confidence based on allele frequency and amplicon coverage with an average sequencing depth of coverage of >500 and with an analytic sensitivity of 5%. Genetic variants identified were interpreted by board-certified molecular geneticists and categorized as "pathogenic," "presumed pathogenic," "variant of unknown significance," "presumed benign," or "benign," according to the American College of Medical Genetics and Genomics (ACMG) standards. When assessing mutation frequencies of individual genes,

"pathogenic," and "presumed pathogenic," were defined as mutations whereas "benign" or "presumed benign" variants and "variants of unknown significance" were defined as WT.

A combination of multiple test platforms was used to determine the MSI or MMR status of the tumors profiled, including fragment analysis (Promega), IHC [MLH1, M1 antibody; MSH2, G2191129 antibody; MSH6, 44 antibody; and PMS2, EPR3947 antibody (Ventana Medical Systems, Inc.)], and NGS (for tumors tested with NextSeq platform, 7,000 target microsatellite loci were examined and compared with the reference genome hg19 from the University of California).

Statistical analysis

Statistical comparisons were performed with the χ^2 test and the Mann–Whitney *U* test when appropriate. A two-sided *P* value of <0.05 was considered as statistically significant. *P* values were further corrected for multiple comparisons using the Benjamini–Hochberg method to avoid type I error, and an adjusted *P* value (*q* value) of <0.05 was considered as a significant difference.

Real-world OS information was obtained from insurance claims' data in an updated larger cohort (incorporating the initially described discovery cohort) and calculated from first specimen collection to last contact. Kaplan–Meier estimates were calculated for the molecularly defined patient cohorts.

Availability of data and materials

The deidentified sequencing data are owned by Caris Life Sciences. The datasets generated during and analyzed during the current study are available from the authors upon reasonable request and with permission of Caris Life Sciences. Qualified researchers may contact the corresponding author with their request.

Results

Patients' characteristics and prognosis

In total, 7,245 patients with colorectal cancer were tested for alterations in *RSPO* and *RNF43* (see **Table 1**). Of those, 443 (6.1%) and 94 patients (1.3%) showed an *RNF43* mutation or an *RSPOfp*, respectively. *RSPO3* fusions were more frequently detected than *RSPO2* translocations (89 vs. 5 cases). Patients with an *RSPOfp* were younger than patients harboring an *RNF43* mutation (61 vs. 69 years, $P = 0.0003$). No difference in distribution by gender was noted between *RSPOfp* and WT cases (P = n.s.). For *RNF43* mutations, a significant female predominance was observed compared with male patients ($P < 0.001$). Furthermore, we found a higher percentage of cases with *RNF43* mutations in right-sided than in left-sided colorectal cancer (14.3 vs. 3.1%, $P < 0.001$). However, no site-specific difference was observed for *RSPOfp*.

Table 1. Characteristics of the discovery cohort.

Characteristic		*RSPO* fusion positive	*RNF43*-mut	*RNF43* and *RSPO* wild-type
Total, no. (%)		94 (1.3)	443 (6.1)	6,708 (92.6)
Age, y	Median age	61	69	62
	Range	36–90	18–93	15–98
Sex, no. (%)	Female	46 (49)	263 (59)	2,922 (44)
	Male	48 (51)	180 (41)	3,786 (56)
Tumor location, no. (%)	Left	23 (25)	66 (15)	2,156 (32)
	Rectal	29 (31)	39 (9)	1,640 (24)
	Right	24 (26)	232 (52)	1,612 (24)
	Transverse	8 (9)	46 (10)	293 (4)
	Unclear	10 (11)	60 (13.5)	1,007 (15)

The most frequently detected *RSPOfp* was the *PTPRK–RSPO3* fusion protein ($n = 89$). Of note, we detected 5 fusion partners (*CPSF1*, *CDH17*, *MATN2*, and *ADAM9*) that had not been described before (see Supplementary Table S1). The most frequently detected point mutations in *RNF43* were G659fs, followed by R117fs and P660fs (see Supplementary Table S2).

Until now, the prognostic relevance of *RNF43* mutations and *RSPOfp* remains largely unclear. Therefore, we performed survival analyses using real-world data obtained from insurance claims. Patients with colorectal cancer harboring an *RNF43* mutation or an *RSPOfp* are associated with a poor survival compared with WT cases (**Fig. 1A** and **B**). Moreover, in the MSS sub-cohort patients harboring *RSPOfp* or *RNF43* mutations were characterized by poor survival [*RSPOfp* vs. WT: HR, 0.61, 95% confidence interval (CI), 0.47–0.79, $P < 0.001$; *RNF43*-mut vs. WT: HR, 0.65; 95% CI, 0.57–0.75; $P < 0.001$].

Molecular landscape of *RSPO* fusion proteins and *RNF43* mutations

RSPOfp-positive colorectal cancers were associated with a higher rate of co-incident mutations in *BRAF* (35.9 vs. 6.3%), *SMAD4* (30.0 vs. 13.5%), *BMPR1A* (5.4 vs. 0.2%), *AKT1* (3.3 vs. 0.4%), and *ERBB3* (5.4 vs. 1.6%, all $q < 0.05$) compared with WT cases (**Fig. 2A**).

Compared with *RNF43*-mut cancers, co-incident mutations in *TP53* (79.1%), *KRAS* (53.3%), and *SMAD4* (30.0%) occurred more frequently in *RSPOfp*-positive cancers (*RNF43*: 54.1%, 18.8%, and 15.3%, respectively; all $q < 0.05$). Importantly, in *RSPOfp*-positive colorectal cancers we discovered no concomitant *RNF43* mutations. In contrast, tumors containing *RNF43* mutations exhibited a different molecular landscape as compared with *RSPOfp*-positive tumors: *ARID1A* (75.6% vs. 35.7%), *ASXL1* (65.8 vs. 6.3%), *BRAF* (53.6 vs. 35.9%), *KMT2D* (43.3 vs. 2.5%), and *PTEN* (18.2 vs. 4.3%) gene alterations were more frequently detected (all $q < 0.05$). Of note, *APC* mutations were observed in 19.3% of *RNF43*-mut cases, in 4.4% of *RSPOfp*-positive tumors and in 81.4% of WT cases (all $q < 0.05$). Regarding *BRAF* mutations, the most prevalent genetic variant was the V600E mutation (78.8%).

Copy-number alterations (CNA) in *MYC* and *AKT2* genes were differently distributed between *RSPOfp*-positive tumors compared with *RNF43*-mut tumors (4.4 vs. 1.1%, and 2.2 vs. 0.0%, respectively; all $q < 0.05$). Among others, CNAs in *CDX2* gene were found more often in WT cases (11.3%) than in *RSPOfp*-positive (3.3%) or *RNF43*-mut (2.3%) samples (all $q < 0.05$; **Fig. 2B**).

Validation cohort

An independent validation cohort was used to confirm our findings in terms of *RNF43* mutations. The retrospective use of a NGS panel without analyses on fusions prohibited further validation of the findings generated in the *RSPOfp* subset of the discovery cohort. The validation cohort consisted of 816 patients with colorectal cancer (**Table 2**). This cohort was obtained from a time period between 2016 and 2017 and was retrospectively analyzed. The data were mined for molecular status of *RNF43* and other mutations, including *APC*, *KRAS*, *BRAF*, *NRAS*, and other genes. MSI-H/dMMR was also included in this analysis. In line with the findings from our discovery cohort, the incidence of *RNF43* mutations was similar (7.97% vs. 6.1%, P = n.s.). Moreover, the co-activation of Wnt and MAPK signaling (including, *APC*, *KRAS*, *BRAF*, and *NRAS*) was strongly associated

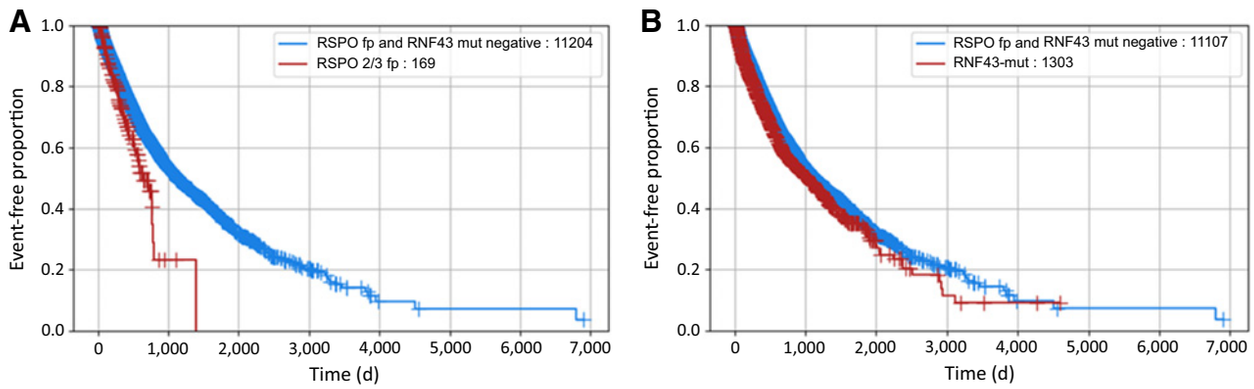

Figure 1.
Real-world overall survival stratified by *RSPO/RNF43* status. **A,** Comparison of *RSPOfp* versus *RNF43/RSPOfp*-WT patients (*RSPOfp* vs. WT: HR, 0.62; 95% CI, 0.48–0.81; $P < 0.001$). **B,** Comparison of *RNF43*-mut versus *RNF43/RSPOfp*-WT patients (HR, 0.86; 95% CI, 0.78–0.94; $P < 0.001$).

with *RNF43* mutations (in total: 88%); 12% had no detectable coincident mutations. Of the *RNF43*-mut cases, 11% showed an MSI-H/dMMR status, 64% showed an MSS/pMMR status, whereas 25% had no data for MSI-H/dMMR status available.

RNF43 mutations are associated with MSI-H

Next, we analyzed biomarkers associated with a predictive value for response to immune checkpoint inhibitors. In samples harboring an *RSPO fusions*, no individual with an MSI-H/dMMR genotype was

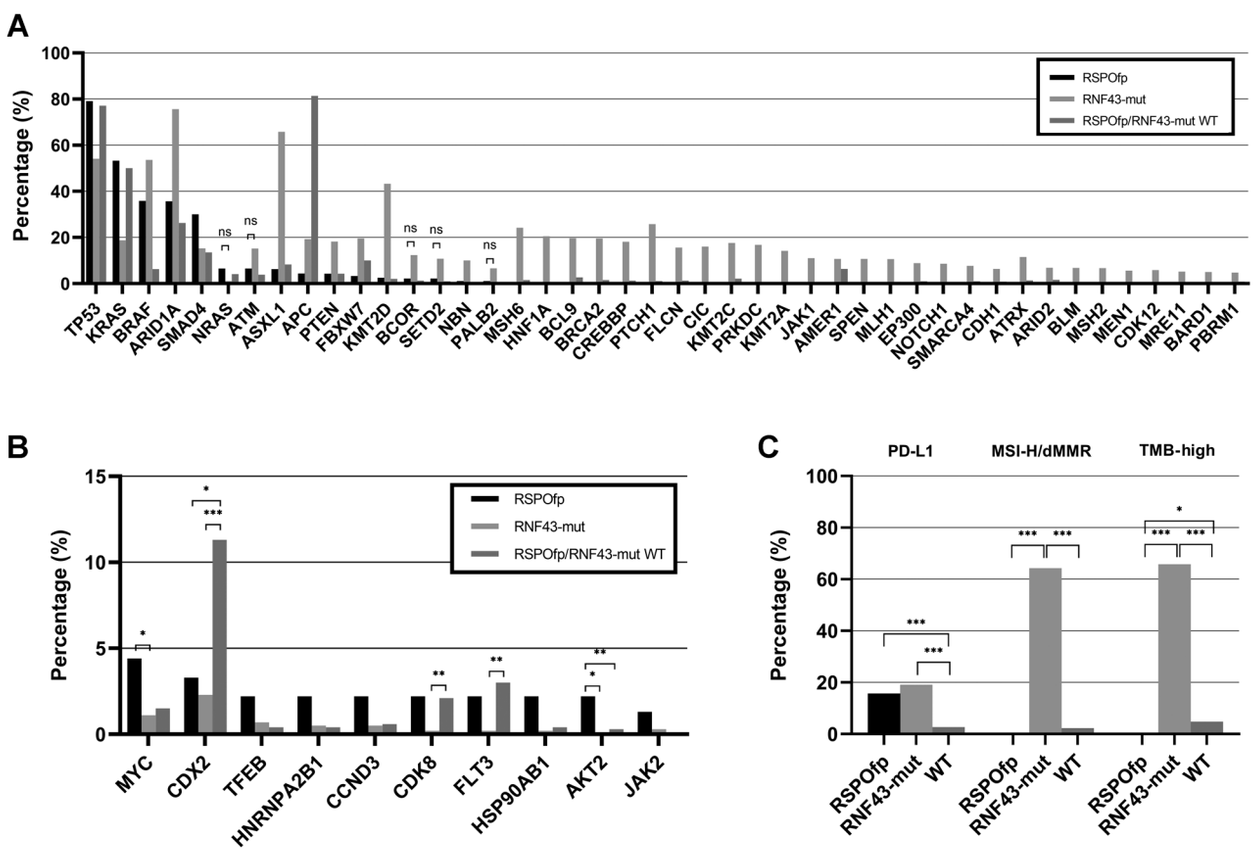

Figure 2.
Molecular landscape of the discovery cohort. **A,** Comparison of the genetic landscape of *RNF43*-mut, *RSPOfp*, and *RNF43/RSPOfp*-WT tumors. Shown are mutations that are significantly different between *RSPOfp* and *RNF43*-mut tumors (all $q < 0.05$; ns: $P < 0.05$, but $q < 0.05$ was not reached). **B,** Copy-number alterations in *RNF43*-mut, *RSPOfp*, and *RNF43/RSPO*-WT tumors. *, $q < 0.05$; **, $q < 0.01$; and ***, $q < 0.001$. **C,** MSI, TMB, and PDL-1 status in *RNF43*-mut, *RSPOfp* and *RNF43/RSPOfp*-WT tumors. None of the *RSPOfp* patients showed a TMB >10 mt/Mb or an MSI-H/dMMR status.*, $q < 0.05$; **, $q < 0.01$; and ***, $q < 0.001$.

Table 2. Characteristics of the validation cohort.

Characteristics	No. (%)
Colorectal cancer **cases**	816
***RNF43* mutation status**	
Mutated	65 (7.97)
Wild-type	751 (92.03)
Comutations in *APC*, *KRAS*, *BRAF*, and *NRAS*	57 (88)
No comutation in the respective genes	8 (12)
Microsatellite status	
MSI-H/dMMR (%)	7 (11)
MSS/pMMR (%)	42 (64)
Not reported (%)	16 (25)

detected (0.0%), compared with an MSI-H/dMMR rate of 64.3% in *RNF43*-mut samples ($q < 0.001$), and 2.3% in WT tumors ($q < 0.001$; **Fig. 2C**). Moreover, in *RSPOfp*-positive tumors no case presented with a TMB of ≥10 mt/Mb. However, in *RNF43*-mut samples, 65.8% had a TMB ≥10 mt/Mb ($q < 0.001$), which was also higher than for WT cases (4.8%, $q < 0.001$). Positive staining for PD-L1 was detected in 15.7% of *RSPOfp*-positive specimens, 19.1% of *RNF43*-mut samples, and 2.7% of WT cases ($q < 0.001$ for *RSPOfp* vs. WT, and *RNF43*-mut vs. WT).

Because MSI-H/dMMR status may trigger secondary mutations, we performed a subgroup analysis in MSS cases. A higher prevalence of females and right-sided primary locations in the MSS subset of patients harboring an *RNF43* mutation was observed. Comparing the molecular profile of the *RSPOfp*-positive and the MSS/*RNF43*-mut cases, no differences in the frequency of *TP53* mutations (79.1% vs. 85.2%, P = n.s.) and *BRAF* mutations (35.9% vs. 43.7%, P = n.s.) were observed. However, there were more *KRAS* mutations in the *RSPOfp*-positive group than in the MSS/*RNF43*-mut group (53.3% vs. 24.2%, $q < 0.001$). Moreover, the rate of *APC* mutations in the MSS/*RNF43*-mut subgroup was only 11.5%, compared with 81.6% in MSS/WT cases ($q < 0.01$; **Fig. 3A**). Interestingly, in the MSS/*RNF43*-mut subgroup, *ARID1A* and *ASXL1* mutations were identified in 22.7% and 2.2%, respectively, compared with 75.6% and 65.8% in the overall *RNF43*-mut cohort.

In the MSS/*RNF43*-mut subgroup ($n = 158$) and MSS/*RNF43*/*RSPOfp* WT cases ($n = 6{,}533$), only 6.4% of the *RNF43*-mut samples and 2.6% of the WT samples had a TMB ≥10 mt/Mb ($q < 0.001$). Furthermore, PD-L1–positive staining was observed in 12.9% of the MSS/*RNF43*-mut subgroup and in 2.4% of the MSS WT samples ($q < 0.001$; **Fig. 3B**). In terms of CNA within the MSS subgroup, we observed more frequent CDX2 CNAs within the *RNF43/RSPO* WT (11%) compared with *RSPOfp*-positive (3%) and *RNF43*-mut (6%) cancers (all, $q<0.05$). In contrast, CNAs in *TFEB*, *AKT2*, *HNRNPA2B1* as well as in *HSP90AB1* were frequently less detected in *RNF43/RSPO* WT compared with *RNF43/RSPO*-positive tumors (all, $q < 0.05$; **Fig. 3C**).

Regarding the MSI-H/dMMR subcohort, it revealed that patients harboring *RNF43* mutations are characterized by increased frequencies of *BRAF*, *KMT2D*, *HNF1A*, and *BRCA2* mutations (all, $q < 0.001$). In contrast, a lower prevalence of *APC*, *KRAS*, *CTNNB1*, and *PIK3CA* mutations compared with *RNF43* WT patients was observed (all, $q < 0.05$; Supplementary Fig. S1).

Because literature is conflicting regarding the functional loss of the specific *RNF43* G659fs variant we evaluated the subset of *RNF43* G659fs patients. Of note, virtually all of these cases showed an MSI-H/dMMR (99.2%) and a high TMB (99.6%) status. A comparison of *RNF43* non-G569fs variants and *RNF43/RSPO* WT cases is displayed in Supplementary Fig. S2.

Discussion

Inappropriate activation of Wnt/β-catenin signaling is a key oncogenic event in a significant subset of colorectal cancers (18) and is associated with tumor cell proliferation and drug resistance (19, 20). Although the most frequent LOF mutation in the Wnt/β-catenin pathway, namely *APC*, has been very well studied (21), genetic alterations in the Wnt receptor complex emerged only recently as a potential new therapeutic target (21, 22). LOF mutations in *RNF43* and *RSPO* fusion proteins were described previously to occur in a small subgroup of colorectal cancers (15, 23, 24). However, the molecular landscape of these genetic alterations in colorectal cancer remains previously unexplored. Herein, we studied the molecular profile of patients with colorectal cancer harboring an *RNF43* mutation or an *RSPOfp*. Our study revealed that the molecular landscape of *RNF43*-mut colorectal cancer substantially differs from the genetic portrait of *RSPOfp* colorectal cancer. In fact, a higher rate of MSI-H/dMMR was observed in *RNF43*-mut compared with *RSPOfp*-positive tumors. This is in line with findings previously reported in the literature, that *RNF43* mutations are more frequently encountered in patients with MSI-H/dMMR cancers (15), both in sporadic cases, and, to a lesser extent, in patients with a Lynch syndrome (25). However, when focusing on the subgroup of MSS/*RNF43*-mut tumors, the genetic profile exhibited greater similarity to that observed in *RSPOfp*-positive tumors. From this first perspective this finding might indicate that a part of *RNF43* mutations might be a secondary mutation effect triggered by MSI. However, when analyzing the subset of MSI-H patients, distinct differences of the molecular landscape according to *RNF43* status were observed. Hence, it remains elusive to which extent the genomic landscape is altered either due to MSI-H/dMMR status or *RNF43* mutations.

Up to now, conflicting data exist regarding the pathogenicity of specific *RNF43* mutations. In 2019, Tu and colleagues (26) reported that the G659fs mutation does not seem to have an impact on carcinogenesis and seems to be fully functional. In contrast, two studies published in 2020 were not able to corroborate this finding (27). In particular, Yu and colleagues (16) could show that the G659fs mutation induces LOF. The current uncertainty whether the G659fs mutation represents a LOF is also reflected in our analyzed cohorts. In the discovery cohort, the G659fs mutational variant was considered pathogenic whereas this specific mutation was excluded in the analyses of the validation cohort. Of note, we observed that virtually all patients harboring an *RNF43* G659fs mutation were characterized by an MSI-H/dMMR and a TMB-high phenotype. Up to now, the impact of the G659fs mutation on WNT activation remains elusive. Therefore, further mechanistic studies are highly desirable to unravel the pathogenic interplay between MSI-H/dMMR and different *RNF43* mutations.

To date, only limited data are available regarding prognostic significance of the respective alterations. Matsumoto and colleagues (28) reported that *RNF43* mutations are associated with an aggressive phenotype in *BRAF*-mut colorectal cancer leading to poor outcome. In line with this finding, survival analysis of the discovery cohort showed that patients harboring *RNF43* mutations are characterized by inferior overall survival. In addition, for the first time we observed that *RSPO* fusions represent a poor prognostic factor.

Anatomic location, or "sidedness," of colorectal cancer has emerged over the past several years as an important predictive and

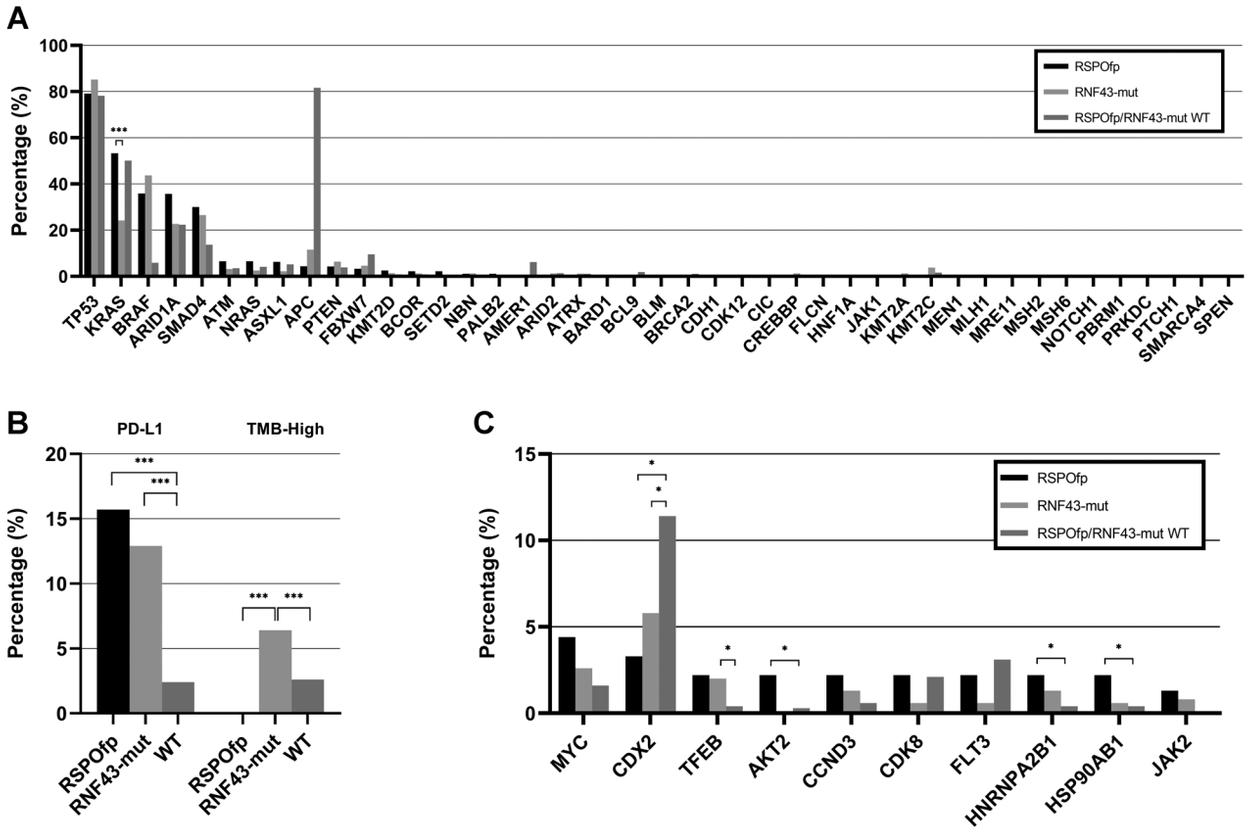

Figure 3.

Molecular landscape of the MSS subcohort. **A,** Genetic landscape comparison between *RSPOfp* and *RNF43*-mut tumors in the MSS subgroup. *KRAS* mutation was the only statistically different genetic alteration. ***, $q < 0.001$. **B,** TMB and PDL-1 status in *RNF43*-mut, *RSPOfp* and *RNF43/RSPOfp*-WT colorectal cancers. None of the *RSPOfp* patients showed a TMB >10 mt/Mb or an MSI-H/dMMR status; *, $q < 0.05$; ***, $q < 0.001$. **C,** Copy-number alterations in *RNF43* mutations, *RSPO* rearrangements, and *RNF43/RSPO*-WT samples; *, $q < 0.05$.

prognostic biomarker in this cancer entity (29, 30). In particular, enrichment of mutations in *BRAF*, and also co-association with MSI-H/dMMR in right-sided colorectal cancer tumors is associated with a worse prognosis (31, 32), and many of the additional molecular factors associated with this worse outcome are under active investigation. Thus, we hypothesized that *RNF43* and/or *RSPOfp* are associated with this genomic signature. In pursing this hypothesis, we detected a higher prevalence of *RNF43* mutations in right-sided colorectal cancer primaries compared with tumors originating in left-sided locations irrespective of MSI status. This observation opens further options to combinational treatment approaches in this subset of patients with colorectal cancer. Indeed, in patients with MSI-H/dMMR tumors immune checkpoint inhibition has been proven to be efficacious (33, 34). To date, the reasons why patients with MSS cancers do not respond to immunotherapy have not been fully elucidated at the cellular and molecular levels, so far. Besides the hypothesis of reduced neoantigen formation in MSS tumors (35), other authors have reported that T cells are actively excluded from the tumor (36). One possible pathway that modulating T-cell activity is the Wnt pathway, whose activation has been shown to prevent antitumor response in melanoma (37). Hence, inhibition of Wnt signaling seems to activate the immune system by activating dendritic cells as well as T cells (38, 39).

Many studies reported, that *RSPOfp* alterations do not occur in tumors with *APC* mutations (6, 15), although it is not clear if *RSPOfp* mutations have a functional redundancy with *APC* mutations. However, in both (experimental and validation) cohorts, we observed that some *RNF43*-mut/*RSPOfp*-positive tumors harbor co-mutations in *APC*, which represents a novel finding.

Furthermore, despite the observation that Wnt/β-catenin activation is one of the key drivers of tumorigenesis in colorectal cancer, inhibition of the Wnt/β-catenin pathway has not been proven to be an efficacious therapeutic strategy to date (40). However, new attempts are being made to efficiently target the Wnt/β-catenin signaling pathway. One strategy could consist of inhibiting ligand-mediated activation of the Wnt/β-catenin cascade by PORCN inhibitors in patients with colorectal cancer carrying *RSPO* rearrangements (17). For the *RNF43* G659fs mutation as a predictive marker for a Wnt/β-catenin inhibiting treatment is still inconclusive, as some authors suggest that this mutation does not alter the protein's function (26, 41). However, others provide evidence that this frameshift mutation leads to a responsiveness to PORCN inhibition (16). Other strategies may include to target the DKK-1, a modulator of Wnt/β-catenin activity (42), for which the monoclonal antibody DKN-01 is currently under clinical investigation in several gastrointestinal malignancies (e.g., NCT04057365 or NCT04166721) or targeting the Wnt co-receptor LRP5/6 for which the inhibitor BI905677 is currently under early

clinical investigation (NCT03604445). Moreover, drugs directly blocking the interaction of β-catenin and CREB are currently being investigated in clinical trials (43). Taken together, it is tempting to speculate that the emergence of effective Wnt/β-catenin inhibitors, such as the PORCN inhibitors LGK974 (44), ETC-159 (45), or CGX1321 (41) might reshape the immunologic sensitivity of a subset of colorectal cancers overcoming resistance to immunotherapeutical approaches, especially in the MSS subcohorts.

Several limitations apply to our study: (i) Validation of our findings regarding *RSPO* rearrangements was not feasible, because in the validation cohort no fusion panel analysis was performed. (ii) Because of the retrospective study design, a potential selection bias might have existed. (iii) Lacking the option of prospective longitudinal analyses, we were not able to account for the possibility of sub-clonal *RNF43* mutations. (iv) Because of limited availability of tissue and specific restrictions, no additional IHC stainings, depicting a variety of immunogenic markers and immune cell infiltration, and respective correlation with *RNF43/RSPO* status, could be conducted. Future prospective trials using sequential analyses during the molecular patient journey and further techniques (i.e., liquid biopsy, single-cell analysis) are desirable to dismantle the above mentioned limitations.

Taken together, in this large cohort of patients with colorectal cancer whose tumors underwent molecular profiling, we have identified a significant subset of colorectal cancers harboring an *RNF43* mutation or an *RSPO* fusion protein that are characterized by a distinct genetic landscape. Thus, these detectable gene alterations represent a potential new therapeutic target and several clinical trials are currently ongoing to prove the efficacy of different Wnt/β-catenin signaling inhibitors in *RNF43/RSPO*-positive tumors. Furthermore, MSI-H/dMMR were observed in a subgroup of *RNF43*-mutated tumors suggesting that immune checkpoint inhibition with and without Wnt/β-catenin signaling inhibitors may be a reasonable combinational therapeutic approach that should be tested in prospective trials.

Authors' Disclosures

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Authors' Contributions

A. Seeber: Conceptualization, writing–original draft. **F. Battaglin:** Writing–original draft. **K. Zimmer:** Writing–original draft. **F. Kocher:** Formal analysis. **Y. Baca:** Methodology, writing–review and editing. **J. Xiu:** Resources. **G. Spizzo:** Conceptualization. **V. Novotny-Diermayr:** Validation. **D. Rieder:** Software. **A. Puccini:** Project administration. **J. Swensen:** Resources. **M. Ellis:** Data curation. **R.M. Goldberg:** Supervision. **A. Grothey:** Investigation. **A.F. Shields:** Writing–original draft. **J.L. Marshall:** Project administration. **B.A. Weinberg:** Conceptualization. **P.E. Sackstein:** Visualization. **K.H. Lim:** Validation. **G.S. Tan:** Validation. **C. Nabhan:** Methodology. **W.M. Korn:** Methodology. **A. Amann:** Project administration. **Z. Trajanoski:** Software, formal analysis. **M.D. Berger:** Supervision. **E. Lou:** Project administration, writing–review and editing. **D. Wolf:** Supervision, investigation. **H.-J. Lenz:** Funding acquisition, project administration.

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