Tgfbr1 Haploinsufficiency Is a Potent Modifier of Colorectal Cancer Development

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Abstract

Transforming growth factor-β (TGF-β) signaling is frequently altered in colorectal cancer. Using a novel model of mice heterozygous for a targeted null mutation of *Tgfbr1* crossed with $Apc^{Min/+}$ mice, we show that $Apc^{Min/+}$;$Tgfbr1^{+/-}$ mice develop twice as many intestinal tumors as $Apc^{Min/+}$;$Tgfbr1^{+/+}$ mice, as well as adenocarcinoma of the colon, without loss of heterozygosity at the *Tgfbr1* locus. Decreased Smad2 and Smad3 phosphorylation and increased cellular proliferation are observed in the colonic epithelium crypts of $Apc^{Min/+}$;$Tgfbr1^{+/-}$ mice. Smad-mediated TGF-β signaling is preserved in both $Apc^{Min/+}$;$Tgfbr1^{+/+}$ and $Apc^{Min/+}$;$Tgfbr1^{+/-}$ intestinal tumors, but cyclin D1 expression and cellular proliferation are significantly higher in $Apc^{Min/+}$;$Tgfbr1^{+/-}$ tumors. These results show that constitutively reduced Tgfbr1-mediated TGF-β signaling significantly enhances colorectal cancer development and results in increased tumor cell proliferation. These findings provide a plausible molecular mechanism for colorectal cancer development in individuals with constitutively altered TGFBR1 expression, a recently identified common form of human colorectal cancer. [Cancer Res 2009;69(2):678–86]

Introduction

There is growing evidence that constitutive and somatically acquired alterations in transforming growth factor-β (TGF-β) signaling are associated with colorectal cancer risk and disease progression. Germ-line mutations of the *SMAD4* and *BMPR1A* genes are associated with juvenile polyposis (1), and common and functionally relevant alleles of *SMAD7* influence colorectal cancer risk (2). There is also evidence that loss of SMAD signaling in human colorectal cancer is associated with advanced disease and poor prognosis (3). Analysis of 13,023 genes in human colorectal cancers has shown that four of the 69 most frequently mutated genes are constitutive elements of the TGF-β signaling pathway: *TGFBR2, SMAD2, SMAD3*, and *SMAD4* (4).

The central role of impaired TGF-β and bone morphogenic protein (BMP) signaling in colon cancer development and progression was first shown in animal experiments by the use of *cis-*$Apc^{+/\Delta 716}$ $Smad4^{+/-}$ compound mutant mice (5). In the compound mutant mice, complete loss of Smad4-dependent TGF-β signaling causes intestinal adenomas to develop into adenocarcinomas. Other animal experiments have shown that complete loss of *Tgfbr2* in intestinal epithelial cells promotes the invasion and malignant transformation of tumors (6). Complete *Smad3* deficiency promotes tumorigenesis in the distal colon of $Apc^{Min/+}$ mice (7), and complete loss of Smad4-dependent signaling in T cells has been shown to increase spontaneous gastrointestinal tumorigenesis (8). Whereas increased gastrointestinal tumor susceptibility has not yet been reported in $Tgfbr1^{+/-}$, $Tgfbr2^{+/-}$, $Smad2^{+/-}$, or $Smad3^{+/-}$ mice, $Smad4^{+/-}$ mice are predisposed to the development of late-onset polyps in the upper gastrointestinal tract (9–11). Whether haploinsufficiency of any of the TGF-β genes contributes to colorectal cancer development is unknown.

We have previously identified *TGFBR1**6A, which encodes a common human TGFBR1 variant (12) and transduces TGF-β signaling less effectively than TGFBR1 (13, 14). Cancer risk is higher for *TGFBR1**6A homozygotes than for *TGFBR1**6A heterozygotes among patients with hereditary colorectal cancer and no evidence of mismatch repair deficiency, which suggests that constitutively decreased TGF-β signaling modifies cancer risk (15, 16). These findings led us to hypothesize that decreased Tgfbr1-mediated TGF-β signaling may be a modifier of cancer susceptibility (17). Here we report on a novel $Tgfbr1^{+/-}$ mouse model generated to test the hypothesis that constitutively decreased Tgfbr1 signaling is causally involved in colorectal cancer development. When $Tgfbr1^{+/-}$ mice in mixed 129Svlm/C57BL/6 background were crossed with $Apc^{Min/+}$ mice, a significantly higher number of tumors was observed in $Apc^{Min/+}$;$Tgfbr1^{+/-}$ mice than in $Apc^{Min/+}$;$Tgfbr1^{+/+}$ mice. These findings confirmed our hypothesis and prompted us to investigate the relevance of these findings in humans. We considered *TGFBR1* to be a notable candidate for a gene that, when mutated, causes predisposition to colorectal cancer or acts as a modifier of other genes resulting in a predisposition. This led to the discovery that 12% of patients with colorectal cancer and 1.5% of healthy controls have evidence of germ line decreased TGFBR1 expression (18). Thus, this novel phenotype likely accounts for a significant proportion of human colorectal cancers (18). This report describes new mechanistic insights into the role of Tgfbr1 signaling in colorectal cancer development both in mixed 129Svlm/C57BL/6 and pure C57BL/6 backgrounds with significant implications for human colorectal cancer.

Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

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Materials and Methods

Generation of a targeted Tgfbr1 mouse model. Using mouse genomic DNA as a template, we designed *Tgfbr1* primers amplifying a 491-bp fragment spanning from position 27 (exon 1) to position 517 (exon 3). Using an isogenic 129SvIm genomic library (Stratagene), we picked several clones, grew them, and excised the insert by *Not*I cleavage. Two overlapping clones were obtained that spanned this genomic region. We found a *Not*I site 5 bp downstream of the ATG start codon. The targeting vector has been designed to insert the neomycin resistance cassette (*Neo*) into the *Not*I site, thus interrupting the *Tgfbr1* open reading frame and removing a 1.1-kb mouse genomic sequence immediately upstream of this *Not*I site (Fig. 1*A*). Following transfection and selection of 129SvIm embryonic stem cells, knockout clones were karyotyped and injected into C57BL/6 blastocysts. Germ-line transmission from the resulting chimeras was obtained and a colony established. F3 $Tgfbr1^{+/-}$ mice were backcrossed into the C57BL6/J background using speed congenics markers. Briefly, a minimum of eight $Tgfbr1^{+/-}$ animals from each generation of backcrossing were genotyped for 152 markers by the Jackson Laboratory (Supplementary Table S1). Mice with the highest percentage of the host genome were used to backcross to the host for the next generation. Two fully congenic F6 males (99.9% C57BL6/J) were confirmed using a full genome-wide panel of 150 SNP markers (Jackson laboratory). These two males were crossed with C57BL6/J females to obtain pure $Tgfbr1^{+/-}$ mice in the C57BL6/J background.

$Tgfbr1^{+/-}$ genotype was confirmed by PCR analysis using the following set of three primers: 5′-AGACCCCAGCTCTTAGCCCCCA-3′, 5′-GAGACGCTCCA-CCCACCTTCCC-3′, and 5′-GAAGCTGACTCTAGAGGATCCC-3′. PCR amplification results in two bands in $Tgfbr1^{+/-}$ mice (240 and 314 bp, corresponding to the knockout and wild-type *Tgfbr1* allele, respectively; Fig. 1*B*).

Pure $Tgfbr1^{+/-}$ female mice in C57BL6/J were mated with C57BL/6J $Apc^{Min/+}$ male mice to generate pure C57BL6/J animals harboring $Tgfbr1^{+/-}$ or $Tgfbr1^{+/+}$. The $Apc^{Min/+}$ locus was detected by PCR with the primers 5′-TTCCACTTTGGCATAAGGC-3′ and 5′-TTCTGAGAAAGACAGAAGTTA-3′. PCR amplification results in a band of 340 bp (Supplementary Fig. S1). There was no evidence of expression of the Neo cassette in the germ line of $Tgfbr1^{+/-}$ mice (Supplementary Fig. S2).

Histopathology of intestinal polyps and polyp scoring. The number and size of polyps were scored by two examiners. Tissue specimens were prepared according to standard protocols. Polyps from seven randomized mice from each group were sectioned and stained with H&E to differentiate tumors from lymphoid aggregates.

Mouse embryonic fibroblasts. Mouse embryonic fibroblasts (MEF) were collected at embryonic day 12.5 according to standard protocol (19) and cultured in DMEM (Invitrogen) supplemented with 10% fetal bovine serum (Hyclone), 2 mmol/L L-glutamine, and 100 units/mL penicillin/streptomycin (20).

Spontaneous cell proliferation assays. MEFs were seeded in normal growth medium at a concentration of 5×10^4 per well in six-well plates on

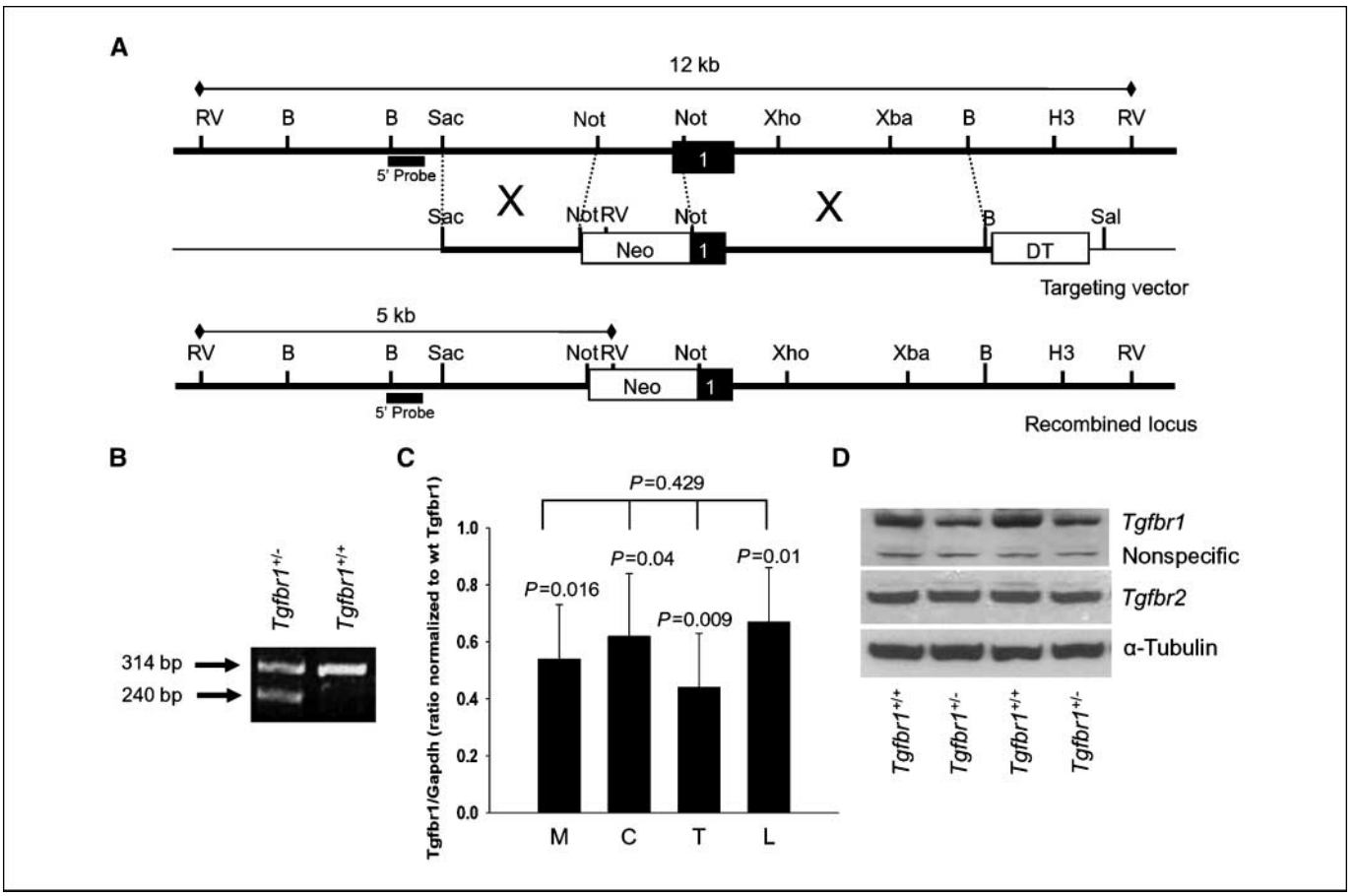

Figure 1. Generation of a novel Tgfbr1 exon 1 knockout mouse model. *A,* strategy for interrupting the *Tgfbr1* open reading frame by insertion of a Neo cassette. A classic targeting vector was generated by inserting a Neomycin resistance cassette (*Neo*) into a *Not*I site located immediately after the start codon and removing 1.1 kb of mouse genomic sequence immediately upstream of this *Not*I site. *B,* PCR genotyping of $Tgfbr1^{+/-}$ mice using three primers reveals a band at 240 bp, corresponding to the knocked out allele, and the wild-type *Tgfbr1* band at 314 bp. *C,* quantitative reverse transcription-PCR assessment of Tgfbr1 expression levels in MEFs (*M*), colon intestinal tissue (*C*), tail (*T*), and peripheral lymphocytes (*L*) of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ mice. Tissues were collected from three animals of each genotype. Each experiment was done at least three times in triplicates. Tgfbr1 levels in $Tgfbr1^{+/-}$ tissues are expressed as ratio of Tgfbr1/Gapdh compared to each corresponding $Tgfbr1^{+/+}$ tissue. *D,* Western blot analysis of Tgfbr1 and Tgfbr2 expression of two representative pairs of MEFs from $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ mice.

day 0. Cell number was determined by trypsinizing and counting cells on days 1, 2, and 3.

TGF-β–mediated cell proliferation assays. TGF-β–mediated cell growth inhibition was assessed by [^{3}H]thymidine incorporation assays as previously described (21).

Luciferase assays. The 3TP-Lux and SBE4-Lux reporter constructs were gifts from Dr. Joan Massagué (Sloan-Kettering Institute, Memorial Sloan-Kettering Cancer Center, New York, NY) and Dr. Bert Vogelstein (Johns Hopkins University, Baltimore, MD). The experiments were done as described before (22).

Immunoblotting and immunohistochemistry. Nuclear extracts from MEFs were obtained using a NE-PER nuclear and cytoplasmic extraction kit (Thermo Fisher Scientific, Inc.). Cell lysates were collected in lysis buffer [TNT buffer (10 mmol/L Tris pH 8.0, 1% Triton X-100, 1 mmol/L EDTA, 150 mmol/L NaCl) supplemented with phosphatase inhibitor cocktails 1 and 2 and protease inhibitor cocktail (Sigma)] and centrifuged at 14,000 × *g* for 15 min. All lysates were separated in SDS-PAGE gels (Invitrogen) and transferred onto nitrocellulose membrane (GE Healthcare). Immunoblotting was done using the following antibodies: rabbit anti-TGFBR1, anti–cyclin D1, anti-TGFBR2, anti-p15, anti–cyclin-dependent kinase (Cdk)-4, mouse anti-Cdk2, anti-Cdk6, anti-p21, anti-p27, and anti–histone 1 (Santa Cruz Biotechnology); rabbit anti-pSmad2 (Cell Signaling Technology); and rabbit anti-pSmad3 (a gift from Dr. Koichi Matsuzaki, Kanzai Medical University, Osaka, Japan). Signal detection was measured by SuperSignal West Femto Chemiluminescent Substrate (Thermo Fisher Scientific). Films were scanned and densitometry was done using Fujifilm LAS-3000 (Fuji Medical System).

Immunohistochemistry. Immunohistochemistry was done with the DAKO EnVision System. Percentage of positively stained cells was determined by assessing the number of strongly positive stained cells of the total number of cells in a field. Five representative fields in three different samples were assessed.

Loss of heterozygosity analyses. The SNaPshot method (PE Applied Biosystems) was used to identify each allele and to detect loss of heterozygosity (LOH) in tumor DNA.

Statistical analysis. Data were analyzed by Student's *t* test and are expressed as mean ± SE. $P < 0.05$ was considered significant. All tests were two-tailed. Data were transformed in logarithm scale when normality assumption was violated. One-way ANOVA was used for the analysis of Tgfbr1 expression in various tissues (Fig. 1*C*). Chi-square analysis was used to compare the proportion of intestinal tumors in $Tgfbr1^{+/-}$ and $Tgfbr1^{+/+}$ mice and the proportion of colonic tumors in $Apc^{Min/+};Tgfbr1^{+/-}$ and $Apc^{Min/+};Tgfbr1^{+/+}$ mice.

Results

Generation of a novel mouse model of targeted Tgfbr1 inactivation. A knockout mouse model of *Tgfbr1* generated by targeted deletion of exon 3 has been previously described (23). There is growing evidence that the signal sequence of human *TGFBR1**6A may have intrinsic biological effects, which are caused by mutations within the exon 1 GCG repeat sequence (21, 22). Whereas the exon 3 *Tgfbr1* knockout model does not result in the generation of functional Tgfbr1 (23), the generation of a functionally active signal sequence cannot be excluded. To circumvent this potential problem, we designed a classic knockout vector to insert a Neo cassette into a *Not*I site located immediately after the start codon and removing 1.1 kb of mouse genomic sequence immediately upstream of this *Not*I site (Fig. 1*A*). This approach precludes the generation of any signal sequence, which is encoded by part of the removed sequence. The $Tgfbr1^{+/-}$ mice were viable and fertile and appeared normal in their morphology and behavior. A total of 50 pups from the heterozygous intercrosses were genotyped and no $Tgfbr1^{-/-}$ pups were found, with only the wild-types and the heterozygotes at a ratio of 1:2. Dead $Tgfbr1^{-/-}$ embryos were found at a ratio of 1:4 at the time of collection of MEFs. These findings are consistent with the previous report of targeted disruption of *Tgfbr1* exon 3 in which mice lacking *Tgfbr1* die at midgestation (23). We did not therefore attempt to determine the stage of lethality. At 16 months, follow-up of 10 $Tgfbr1^{+/-}$ mice does not suggest increased mortality as compared with 10 wild-type littermates.

Tgfbr1 expression levels in different tissues were first compared by real-time PCR. Tgfbr1 expression in $Tgfbr1^{+/-}$ tissues ranged from 54% in embryonic fibroblasts to 62% in colonic epithelium, 44% in tail, and 67% in blood lymphocytes when compared with corresponding expression levels in $Tgfbr1^{+/+}$ mice (Fig. 1*C*). Tissue-specific differences between $Tgfbr1^{+/-}$ and $Tgfbr1^{+/+}$ mice were significant for each corresponding tissue: $P = 0.016$ for embryonic fibroblasts, $P = 0.04$ for colonic epithelium, $P = 0.009$ for tail, and $P = 0.01$ for blood lymphocytes. The differences in Tgfbr1 expression levels between the various $Tgfbr1^{+/-}$ tissues were not statistically significant, $P = 0.429$. To assess the functional consequences of *Tgfbr1* haploinsufficiency, we measured Tgfbr1 and Tgfbr2 protein expression in MEFs. Tgfbr1 expression levels were lower in the $Tgfbr1^{+/-}$ MEFs than in $Tgfbr1^{+/+}$ MEFs (Fig. 1*D*). As expected, Tgfbr2 levels were similar (Fig. 1*D*).

***Tgfbr1* haploinsufficiency enhances tumor formation.** Because the gastrointestinal tract is a common site of cancer in humans with constitutively altered TGF-β signaling (1, 16), we tested the effect of *Tgfbr1* haploinsufficiency on $Apc^{Min/+}$-mediated intestinal tumorigenesis. $Apc^{Min/+}$ mice harbor a premature stop codon in one allele of the *Apc* tumor suppressor gene ($Apc^{Min/+}$). These mice develop multiple intestinal adenomas and mimic human familial adenomatosis polyposis coli (24, 25). $Tgfbr1^{+/-}$ female mice on the 129SvIm background were backcrossed into the C57BL/6 background. F2 $Tgfbr1^{+/-}$ females were crossed with $Apc^{Min/+}$ male mice (C57BL/6). Mice were sacrificed at 12 weeks and examined for intestinal tumors. The tumors counted were verified by histology. We did not observe any tumors in the small and large bowels of eight $Tgfbr1^{+/+}$ and nine $Tgfbr1^{+/-}$ mice in wild-type *Apc* background. A total of nine $Apc^{Min/+};Tgfbr1^{+/+}$ mice developed an average of 5.4 ± 1.7 tumors (mean ± SE), whereas the number of tumors observed in 10 $Apc^{Min/+};Tgfbr1^{+/-}$ mice was almost three times higher, 14.5 ± 1.1 tumors (Fig. 2*A*). The difference in the number of tumors between the two groups was highly significant, 9.8 tumors (95% confidence interval, 4.8–13.4; $P = 0.0004$). The majority of tumors was small (<3 mm) and predominantly scattered in the small intestine. Five $Apc^{Min/+};Tgfbr1^{+/-}$ mice (50%) had an average of 2.4 ± 0.2 colonic tumors whereas only two $Apc^{Min/+};Tgfbr1^{+/+}$ mice (22%) had one colonic tumor each, a nonsignificant difference, $P = 0.437$. The identity of each lesion as tumor rather than lymphoid aggregates was confirmed in seven mice from each group by histopathology.

To determine the reproducibility of our initial findings obtained in a mixed 129SvIm × C57BL/6 background in 2006, we repeated these experiments with $Tgfbr1^{+/-}$ mice, which were fully back-crossed into the C57BL/6 using speed congenics markers (Supplementary Table S1). As seen in Fig. 2*B*, there was an average of 30.2 ± 0.9 tumors in 12 $Apc^{Min/+};Tgfbr1^{+/+}$ mice and 61.4 ± 3.4 tumors in 7 $Apc^{Min/+};Tgfbr1^{+/-}$ mice (mean ± SE). The difference in the number of tumors between the two groups was highly significant, 31.2 tumors (95% confidence interval, 25.3–37.2; $P = 4.8 \times 10^{-5}$). Importantly, the number of colonic tumors was higher among $Apc^{Min/+};Tgfbr1^{+/-}$ mice (4.9 ± 0.3) than among $Apc^{Min/+};Tgfbr1^{+/+}$ mice (3.0 ± 0.4), $P = 0.0005$.

Six $Apc^{Min/+};Tgfbr1^{+/-}$ mice (three in the mixed background and three in the pure C57BL/6 background) exhibited large colonic tumors with a maximal diameter >7 mm (Fig. 2*C*). Histologic analysis of these polypoid and ulcerated colonic tumors revealed the presence of carcinoma (Fig. 2*D*; Supplementary Fig. S3) as evidenced by the presence of distinct cytologic and nuclear atypia. The largest tumors in the $Apc^{Min/+};Tgfbr1^{+/+}$ mice in either the mixed 129SvIm/C57BL/6 or the pure C57BL/6 background were 3 mm in size, and none of them harbored carcinoma. Among all mice examined at 12 weeks, the proportion of $Apc^{Min/+};Tgfbr1^{+/-}$ mice with colonic tumors >7 mm (35.3%) harboring carcinoma was significantly higher than that of $Apc^{Min/+};Tgfbr1^{+/+}$ mice (0%; $P = 0.018$).

***Tgfbr1* haploinsufficiency modifies TGF-β–mediated signaling and cell proliferation but does not alter hematopoiesis.** Next, we studied the effects of *Tgfbr1* haploinsufficiency on cell proliferation using MEFs from $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ mice. In the absence of TGF-β, the growth of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs was identical (Fig. 3*A*). In the presence of exogenously added TGF-β, the proliferation of $Tgfbr1^{+/-}$ MEFs decreased by 38.32 ± 3.44% whereas that of $Tgfbr1^{+/+}$ MEFs decreased by 58.24 ± 5.74% (Fig. 3*B*), $P = 0.0005$. To directly analyze the signaling activity of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs, we used as readouts the TGF-β reporter 3TP-lux (26) and the TGF-β reporter SBE4-Lux (27). As seen in Fig. 3*C*, following addition of TGF-β to the cell culture medium, induction of TGF-β signaling was significantly higher for $Tgfbr1^{+/+}$ than $Tgfbr1^{+/-}$ MEFs for 3TP-Lux (3.62-fold versus 2.73-fold; $P = 0.02$) and SBE4-Lux (5.76-fold versus 4.47-fold; $P = 0.04$). The differences between $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ with respect to the induction of SBE4-Lux and 3TP-Lux on exposure to TGF-β were almost similar, 24.6% and 22.4%, respectively.

Because the TGF-β signaling pathway is a potent regulator of hematopoietic differentiation (28) and because alterations in lymphocyte TGF-β signaling have been implicated in colorectal tumor progression in mice (8, 29), we sought to determine whether *Tgfbr1* haploinsufficiency had any measurable effects on the hematopoietic compartment. Complete blood counts of five $Tgfbr1^{+/-}$ and five $Tgfbr1^{+/+}$ mice obtained at 12 weeks did not reveal any difference in the average RBC, WBC, or platelet numbers, thus indicating that *Tgfbr1* haploinsufficiency alone does not significantly alter hematopoiesis. The average lymphocyte count was 13.11 ± 0.31 and 12.73 ± 0.55 (mean ± SD) for $Tgfbr1^{+/-}$ and $Tgfbr1^{+/+}$ mice, respectively, a nonsignificant difference ($P = 0.181$).

***Tgfbr1* haploinsufficiency impairs Smad2 and Smad3 signaling.** We first assessed the levels of TGF-β–mediated generation of pSmad2 in $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs over 24 hours. Whereas pSmad2 levels were almost identical at 1 and 4 hours, pSmad2 levels decreased by ~50% at 8 hours and by 80% at 24 hours in $Tgfbr1^{+/-}$ MEFs, whereas they decreased only slightly in $Tgfbr1^{+/+}$ MEFs (Fig. 4*A*). It has been previously shown that phosphorylation of Smad3 is an essential step in signal transduction by TGF-β for inhibition of cell proliferation (30), and *Smad3*-deficient mice are prone to colon cancer development (7, 31). To assess the effect of *Tgfbr1* haploinsufficiency on the phosphorylation of Smad3, we used an antibody targeting the $Ser^{423/425}$ site on Smad3 (32, 33). As seen in Fig. 4*B*, following exposure to TGF-β,

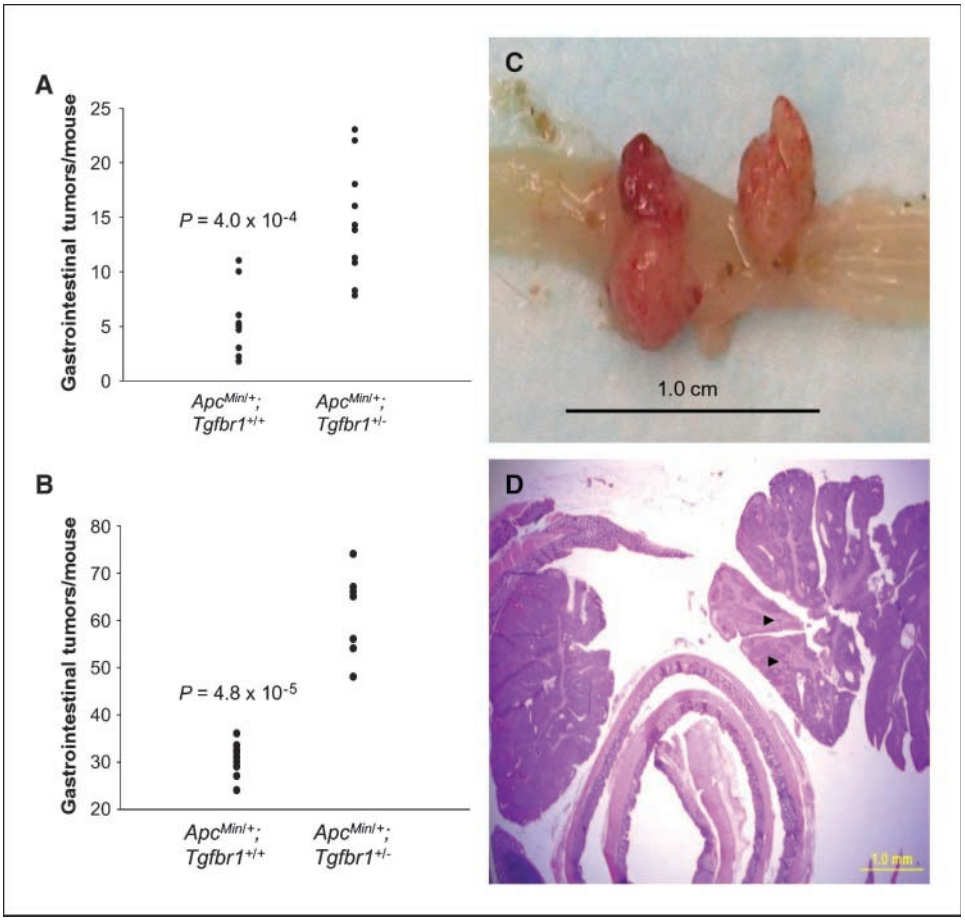

Figure 2. Tumorigenesis of $Apc^{Min/+};Tgfbr1^{+/+}$ and $Apc^{Min/+};Tgfbr1^{+/-}$ mice. *A* and *B*, number of gastrointestinal tumors per mouse at 12 wk of age for $Apc^{Min/+};Tgfbr1^{+/+}$ mice ($n = 9$) and $Apc^{Min/+};Tgfbr1^{+/-}$ littermates ($n = 10$) in mixed 129SvIm/C57BL/6 background (*A*) and in $Apc^{Min/+};Tgfbr1^{+/+}$ mice ($n = 12$) and $Apc^{Min/+};Tgfbr1^{+/-}$ littermates ($n = 7$) in C57BL/6 background (*B*). *Points*, no. of tumors in each individual mouse. *C*, large polyps arising from $Apc^{Min/+};Tgfbr1^{+/-}$ mouse colonic mucosa at 12 wk. *Bar*, 1 cm. *D*, histologic analysis of the large polypoid colonic tumor from the $Apc^{Min/+};Tgfbr1^{+/-}$ mouse shown in *C*. *Black arrowheads*, presence of carcinoma. *Bar*, 1 mm; 100 μm.

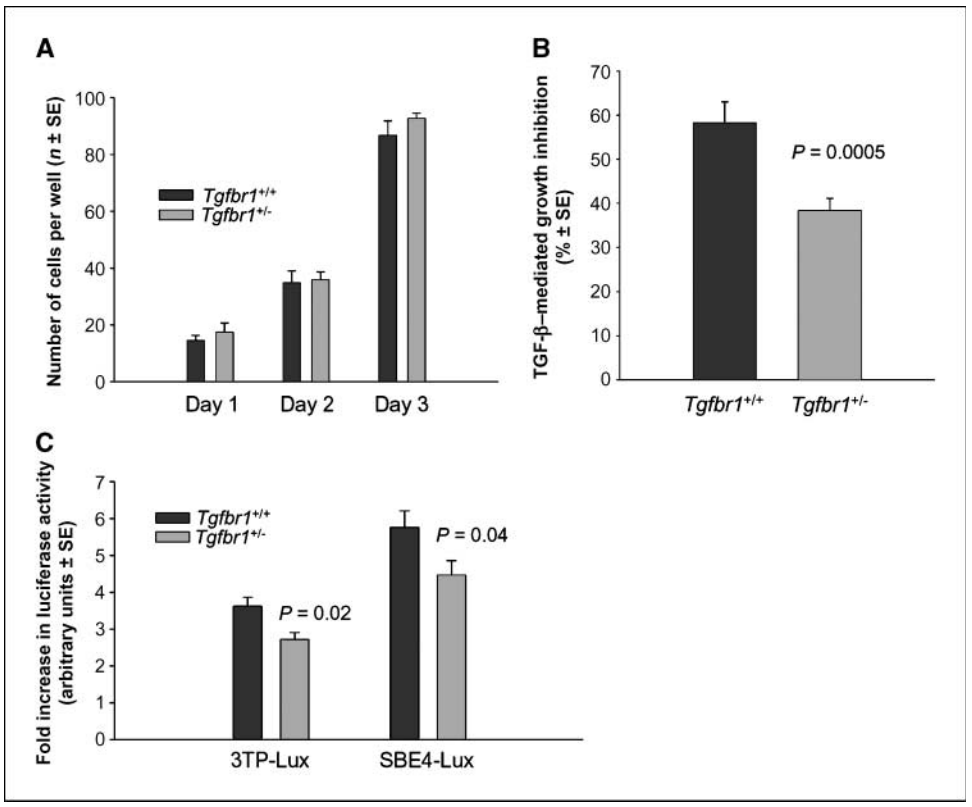

Figure 3. TGF-β–mediated cell proliferation of *Tgfbr1*$^{+/+}$ and *Tgfbr1*$^{+/-}$ MEFs. *A,* spontaneous cell proliferation of *Tgfbr1*$^{+/+}$ and *Tgfbr1*$^{+/-}$ MEFs. Cell proliferation was assessed daily for 3 d by counting cells. The experiments were done thrice in triplicates. *Columns,* mean cell count; *bars,* SE. *B,* TGF-β–mediated cell proliferation assays. TGF-β–mediated cell proliferation was assessed in *Tgfbr1*$^{+/-}$ and *Tgfbr1*$^{+/+}$ MEFs exposed to 100 pmol/L TGF-β1 for 24 h. Cell proliferation was assessed by thymidine incorporation. The experiments were done thrice in triplicates. *Columns,* mean percent TGF-β growth inhibition; *bars,* SE. *C,* direct measurement of TGF-β signaling using the 3TP-Lux and SBE4-Lux reporter assays in *Tgfbr1*$^{+/+}$ and *Tgfbr1*$^{+/-}$ MEFs following exposure to 100 pmol/L TGF-β. *Columns,* average fold increase (in arbitrary units) of three experiments done in triplicates; *bars,* SE.

pSmad3 levels were higher at 1 and 16 hours in *Tgfbr1*$^{+/+}$ MEFs than in *Tgfbr1*$^{+/-}$ MEFs. Hence, *Tgfbr1* haploinsufficiency was associated with a small but significant decrease in TGF-β signaling mediated by decreased phosphorylation of both Smad2 and Smad3.

Downstream effects of decreased Tgfbr1-mediated signaling *in vitro*. To dissect the downstream effects of decreased TGF-β signaling, we assessed the expression levels of selected mediators of the cell cycle and downstream effectors of TGF-β signaling. As seen in Fig. 4*C*, there was no difference in the levels of these mediators in the absence of TGF-β with the exception of mildly decreased baseline levels of Ccnd1 in *Tgfbr1*$^{+/+}$ MEFs when compared with *Tgfbr1*$^{+/-}$ MEFs. This differential expression pattern was significantly enhanced following exposure to TGF-β as exemplified by reduced Ccnd1 expression in *Tgfbr1*$^{+/+}$ MEFs after 4 hours, whereas Ccnd1 levels initially increased and remained elevated at 16 hours in *Tgfbr1*$^{+/-}$ MEFs (Fig. 4*C*). Levels of Cdkn2b remained unchanged on exposure to TGF-β in *Tgfbr1*$^{+/+}$ MEFs, whereas we observed a small decrease in Cdkn2b levels in *Tgfbr1*$^{+/-}$ MEFs. The emergence of differential expression of pSmad2 (Fig. 4*A*), pSmad3 (Fig. 4*B*), and Ccnd1 (Fig. 4*C*) levels occurred in parallel, which suggests that decreased Smad signaling results in persistently high Ccnd1 levels in *Tgfbr1*$^{+/-}$ MEFs.

Characterization of *Tgfbr1* haploinsufficiency effects on the intestinal epithelium. To characterize the *in vivo* consequences of constitutively decreased TGF-β signaling, we performed pSmad2 immunostaining of normal-appearing intestinal tissue and tumor sections. Whereas pSmad2 staining was homogeneous throughout the intestinal mucosa of *Apc*$^{Min/+}$;*Tgfbr1*$^{+/+}$ mice (Fig. 5*A*), we observed reduced pSmad2 staining in the crypts but not in the villi of *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice (Fig. 5*B*). To comprehensively assess the effect of *Tgfbr1* haploinsufficiency on Smad-mediated TGF-β signaling, we also performed pSmad3 immunostaining of the same tissues. As seen in Fig. 5*C*, we observed homogeneous pSmad3 staining in the crypts of *Apc*$^{Min/+}$;*Tgfbr1*$^{+/+}$ mice, whereas pSmad3 staining was markedly reduced in the crypts of *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice (Fig. 5*D*), mirroring the pSmad2 findings and showing that *Tgfbr1* haploinsufficiency results in decreased phosphorylation of both receptor Smads within the intestinal epithelial crypts, thus resulting in overall decreased Smad-mediated TGF-β signaling *in vivo*. To determine whether the differential expression of Smads within the intestinal crypts modifies cellular proliferation *in vivo*, we assessed the levels of proliferating cell nuclear antigen (PCNA) in the normal intestinal epithelium of *Apc*$^{Min/+}$;*Tgfbr1*$^{+/+}$ and *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice. PCNA staining was significantly more intense in *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice (62.2 ± 2.2% positive staining; Supplementary Fig. S4*B*) than in their wild-type counterpart (44.4 ± 2.8% positive staining; Supplementary Fig. S4*A*; $P = 0.008$), thus confirming *in vivo* the observed *in vitro* increased cellular proliferation of *Tgfbr1*$^{+/-}$ on exposure to TGF-β.

Characterization of *Tgfbr1* haploinsufficiency effects on intestinal tumors. Tumors arising from both *Apc*$^{Min/+}$;*Tgfbr1*$^{+/+}$ and *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice had uniform pSmad staining, reflecting preserved *in vivo* Smad signaling. However, we found focal areas of decreased pSmad2 staining among *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice tumors (Fig. 6*B*) but not in their wild-type counterparts (Fig. 6*A*). Consistent with the findings of preserved TGF-β signaling activity in the tumors of both *Apc*$^{Min/+}$;*Tgfbr1*$^{+/+}$ and *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice, we found no evidence of *Tgfbr1* LOH in six microdissected colonic tumors from three different *Apc*$^{Min/+}$;*Tgfbr1*$^{+/-}$ mice (Supplementary Table S2). The combined evidence from pSmad2 immunohistochemistry and LOH analysis of intestinal tumors shows that reduced dosage, rather than abrogation of Tgfbr1-mediated Smad signaling, is sufficient to enhance the *Apc*-mediated development of intestinal tumors and adenocarcinoma at 12 weeks.

The role of Ccnd1 as a mediator of colon cancer development and progression is reflected by the fact that decreased Ccnd1 expression reduces tumor formation in $Apc^{Min/+}$ mice (34). Conversely, the role of the Wnt pathway in promoting intestinal stem cell proliferation has been previously documented (35). Located in the intestinal crypts, stem cells constantly generate progeny that differentiate as they flow upward to the tip of the villi, where they die within days. T-cell factor–mediated induction of c-Myc, with secondary induction of Ccnd1, is thought to drive proliferation in these cells and their malignant derivatives (35). To assess the downstream effects of decreased Tgfbr1-mediated TGF-β signaling on Ccnd1 *in vivo*, we measured the levels of Ccnd1 by immunohistochemistry and found that Ccnd1 staining was significantly higher in the tumors of $Apc^{Min/+}$;$Tgfbr1^{+/-}$ mice (50.7 ± 4.1% positive staining; Fig. 5*D*) than in those of $Apc^{Min/+}$;$Tgfbr1^{+/+}$ mice (20.1 ± 5.7% positive staining; Fig. 5*C*; $P = 0.002$).

To determine whether *Tgfbr1* haploinsufficiency modifies tumor proliferation *in vivo*, we assessed the levels of PCNA in tumors of $Apc^{Min/+}$;$Tgfbr1^{+/+}$ and $Apc^{Min/+}$;$Tgfbr1^{+/-}$ mice. PCNA staining was significantly more intense in $Apc^{Min/+}$;$Tgfbr1^{+/-}$ tumors (82.0 ± 2.9% positive staining; Supplementary Fig. S5*B*) than in their wild-type counterpart (48.2 ± 3.8% positive staining; Supplementary Fig. S5*A*; $P = 0.0003$), thus establishing *in vivo* that decreased but not abrogated Tgfbr1-mediated signaling confers a selective growth advantage to tumor cells.

Discussion

The significant difference in the number of intestinal tumors observed in both mixed 129SvIm × C57BL/6 and pure C57BL/6 backgrounds provides strong support for the novel concept that decreased Tgfbr1-mediated signaling results in the enhanced cell proliferation of normal-appearing intestinal epithelial cells within the crypts as well as tumor cells in the presence of preserved TGF-β signaling. Similarly to what was originally observed with the *cis*-$Apc^{+/\Delta 716}$ $Smad4^{+/-}$ mice in which TGF-β signaling is completely abrogated (5), we found essentially the same results with the F3 (C57BL/6) backcross generation and the fully backcrossed (C57BL/6) generation, except for higher intestinal polyp numbers. It has been previously hypothesized that the reduced polyp numbers in mice with a mixed 129SvIm × C57BL6 background is presumably due to the background gene(s) brought in from the 129SvIm strain (5). Immunohistochemistry analysis shows that PCNA levels were inversely correlated with pSmad2 and pSmad3 levels in the intestinal crypts, providing strong support for the notion that increased cellular proliferation is a direct consequence of decreased pSmad2/pSmad3–mediated signaling.

Existing mouse intestinal tumor models based on somatic *Apc* inactivation display mainly small intestinal lesions, and carcinomas are rare (36, 37). Inactivation of one copy of the *Smad4* gene accelerated tumor progression from intestinal polyps to adenocarcinoma in compound heterozygous *cis*-$Apc^{+/\Delta 716}$ $Smad4^{+/-}$ mice, whereas control *cis*-$Apc^{+/\Delta 716}$ mice developed adenomas but not adenocarcinomas (5). However, tumor epithelial cells in *cis*-$Apc^{+/\Delta 716}$ $Smad4^{+/-}$ mice carry homozygous mutations in both *Apc* and *Smad4*, and there is no evidence of Smad4 protein expression in the colorectal tumor cells (38). This results in complete abrogation of Smad-mediated TGF-β signaling within intestinal tumors. Similar results have been reported in mice in which the *Tgfbr2* allele was knocked out in the intestinal epithelium (6). In both models, complete abrogation of TGF-β signaling was required to induce malignant transformation of

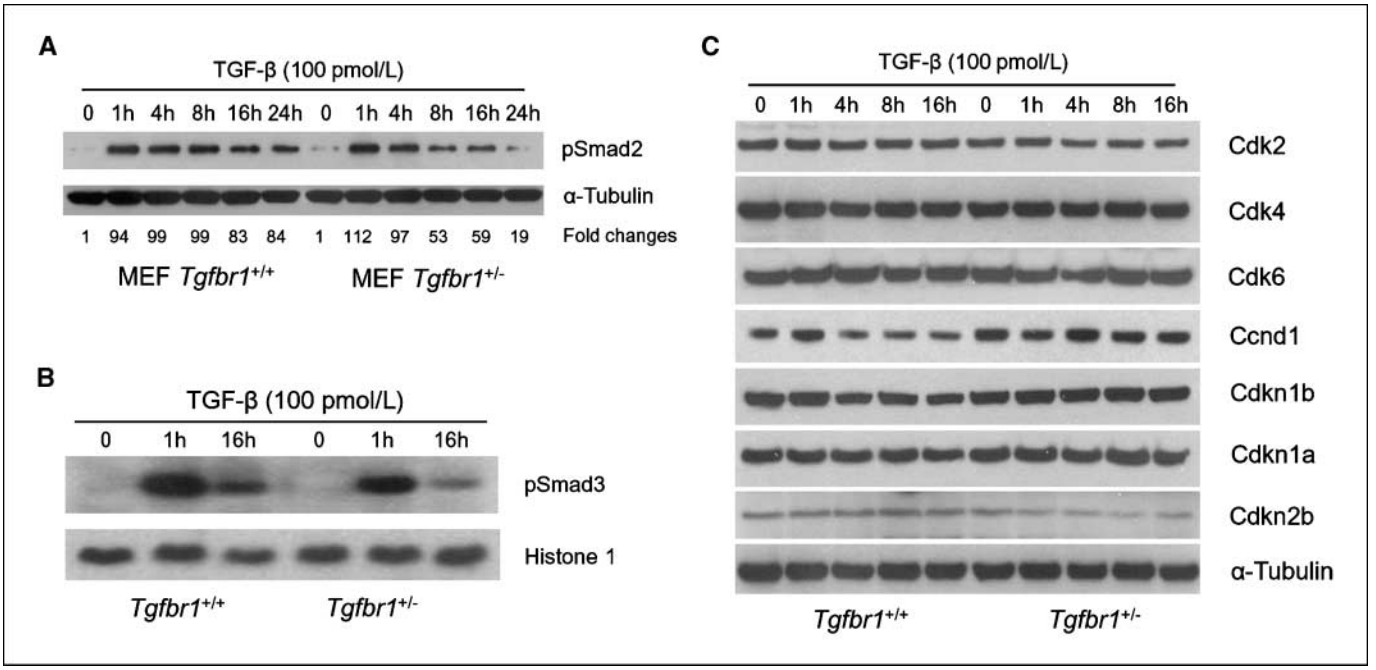

Figure 4. TGF-β–mediated Smad signaling of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs. *A,* assessment of pSmad2. Levels of phosphorylated Smad2 (*pSmad2*) following exposure of MEFs to TGF-β1 were assessed in three pairs of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs from six different mice. The MEF pair presented is representative of the three pairs of MEFs. *B,* assessment of pSmad3. Levels of phosphorylated Smad3 (*pSmad3*) following exposure of MEFs to TGF-β1 were assessed in three pairs of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs. MEF nuclear extracts were used for Western blot analysis probed with pSmad3 antibodies. Histone 1 is a loading control for nuclear protein extracts. The MEF pair presented is representative of the three pairs of MEFs. *C,* differential regulation of cell cycle mediators: Western blot analysis of $Tgfbr1^{+/+}$ and $Tgfbr1^{+/-}$ MEFs in the absence (time 0) and in the presence of 100 pmol/L TGF-β1 for 1, 4, 8, and 16 h. The MEF pair presented is representative of the three pairs of MEFs.

intestinal neoplasms initiated by *Apc* mutation. Our findings constitute the first report of decreased but not abrogated TGF-β signaling, resulting in adenocarcinoma formation at 3 months. It is also the first report of constitutively altered but not abrogated TGF-β signaling upstream of Smad4 associated with increased colorectal tumor development. These results provide strong evidence that constitutively altered Tgfbr1-mediated TGF-β signaling is a potent modifier of colorectal carcinogenesis. Our initial results with mice bred in a mixed background prompted us to investigate the relevance of this novel concept in human colorectal carcinogenesis. This led to the discovery that germ-line decreased expression of TGFBR1 is a quantitative trait that occurs in 10% to 20% of patients with microsatellite instability-negative colorectal cancer and in 1% to 3% of healthy controls (18). This trait is dominantly inherited, segregates in families, and confers a substantially increased risk of colorectal cancer (18).

Decreased Tgfbr1 signaling leads to decreased levels of phosphorylated Smad2 and Smad3 in MEFs, in *in vitro* experiments, and *in vivo* in the normal-appearing colonic epithelium, thus resulting in a global decrease of Smad-mediated signaling. This was observed *in vitro* on addition of exogenous TGF-β but was only observed in the intestinal crypts and in patches within tumors *in vivo*. Interestingly, the same pattern of decreased SMAD signaling, as well as evidence of constitutively decreased expression of TGFBR1, was observed in the lymphocytes of patients with colorectal cancer (18). This highlights the critical role of Tgfbr1 as a potentially limiting factor with respect to the activation of the Smad signaling cascade at sites of high TGF-β secretion and/or high cellular proliferation. The absence of effective down-regulation of Ccnd1 in $Tgfbr1^{+/-}$ MEFs and the observed increased Ccnd1 levels within the tumors of $Apc^{Min/+};Tgfbr1^{+/-}$ mice provide the first evidence of the downstream effects of decreased Smad-mediated TGF-β signaling. The TGF-β responses in epithelial cells involve the induction of Cdkn2b by means of the Smads (39). Increased Cdkn2b levels are an important aspect of the TGF-β cytostatic program leading to decreased Ccnd1 expression (40). The decreased Cdkn2b levels observed in $Tgfbr1^{+/-}$ MEFs provide a plausible link between decreased Smad-mediated signaling and increased Ccnd1 expression. The absence of any obvious phenotype in $Tgfbr1^{+/-}$ mice as well as the absence of phenotypic traits in human beings with constitutionally reduced *TGFBR1* expression (18) suggests that decreased Tgfbr1-mediated TGF-β signaling does not affect normal development. One potential explanation is that decreased Tgfbr1 signaling only becomes a limiting factor when persistently decreased phosphorylation of Smad2 and Smad3 leads to decreased TGF-β signaling, which in turn results in higher cell proliferation. As mutations of the *APC* gene are among the most commonly encountered genetic hallmarks of human colorectal cancer (4, 41), altered Tgfbr1 signaling is emerging as a potent modifier of colorectal cancer development. The effect of decreased Tgfbr1-mediated signaling leading to decreased Smad2 and Smad3 signaling is further highlighted by the recent discovery that both *SMAD2* and *SMAD3* are among the most commonly mutated genes in human colorectal cancer (4), acting as crucial mediators of colon carcinogenesis.

Thorough histologic review of the normal-appearing colorectal epithelium and tumor tissues did not reveal any difference in the numbers of inflammatory cells in either mouse strain. Together with the findings of comparable lymphocyte counts in $Apc^{Min/+};Tgfbr1^{+/-}$ and $Apc^{Min/+};Tgfbr1^{+/+}$ mice at 12 weeks, this argues against a major role of inflammation as a contributor to the tumor phenotype observed in $Apc^{Min/+};Tgfbr1^{+/-}$ mice. Nonetheless, TGF-β in tumor infiltrating lymphocytes has been shown to control the growth of dysplastic epithelial cells in experimental

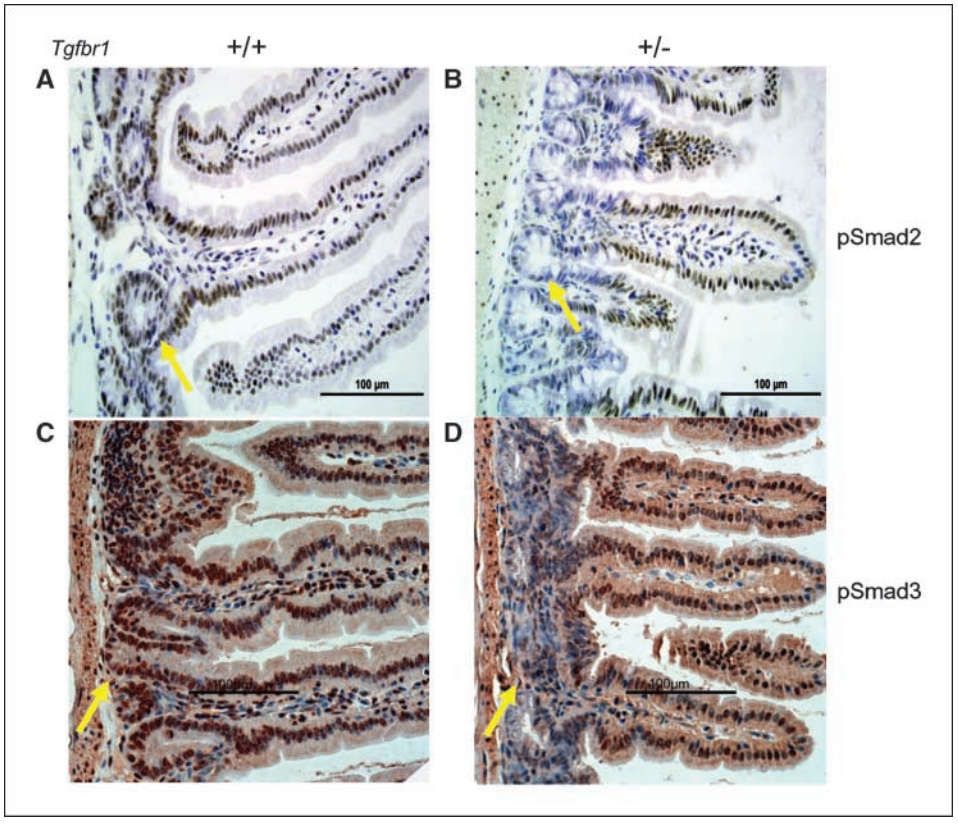

Figure 5. Immunohistochemistry staining patterns of normal-appearing small bowel tissues from $Apc^{Min/+};Tgfbr1^{+/+}$ and $Apc^{Min/+};Tgfbr1^{+/-}$ mice. *A* and *B,* normal-appearing small intestine stained with pSmad2 shows identical staining pattern throughout the villi of both $Apc^{Min/+};Tgfbr1^{+/+}$ mice (*A*) and $Apc^{Min/+};Tgfbr1^{+/-}$ mice (*B*). However, pSmad2 staining within the intestinal crypts of $Apc^{Min/+};Tgfbr1^{+/-}$ mice (*arrow*) is reduced when compared with that of their wild type counterparts (*arrow*). *C* and *D,* normal-appearing small intestine stained with pSmad3 shows identical staining pattern throughout the villi of both $Apc^{Min/+};Tgfbr1^{+/+}$ mice (*C*) and $Apc^{Min/+};Tgfbr1^{+/-}$ mice (*D*). However, pSmad3 staining within the intestinal crypts of $Apc^{Min/+};Tgfbr1^{+/-}$ mice (*arrow*) is reduced when compared with that of their wild type counterparts (*arrow*).

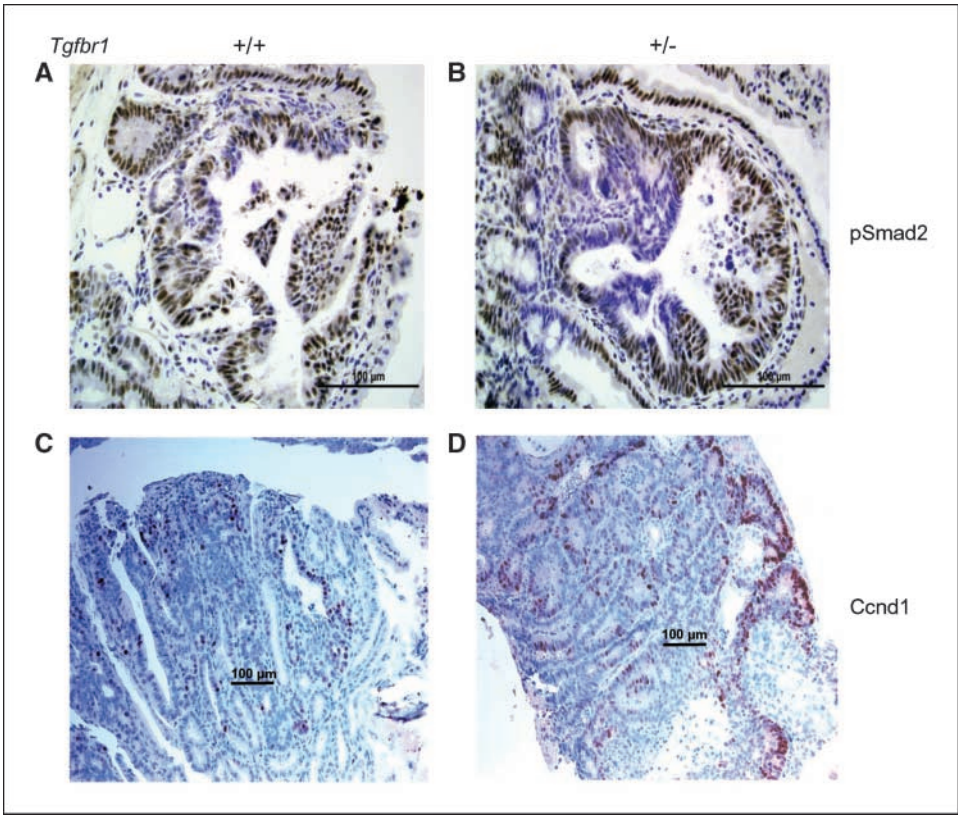

Figure 6. Characterization of Tgfbr1 haploinsufficiency on molecular signaling within tumors. *A* and *B,* pSmad2 staining is patchy within tumors arising from $Apc^{Min/+};Tgfbr1^{+/-}$ mice, which reflects focally decreased Smad-mediated TGF-β signaling (*B*), whereas tumors arising from $Apc^{Min/+};Tgfbr1^{+/+}$ mice have uniform pSmad2 staining showing preserved Smad-mediated TGF-β signaling (*A*). *C* and *D,* Ccnd1 (cyclin D1) expression is significantly higher in the tumors of $Apc^{Min/+};Tgfbr1^{+/-}$ mice (*F*, 50.7 ± 4.1% positive staining) than in those of $Apc^{Min/+};Tgfbr1^{+/+}$ mice (*E*, 20.1 ± 5.7% positive staining), $P = 0.002$.

colon cancer (29). Furthermore, abrogation of TGF-β signaling within T cells by means of *Smad4* inactivation leads to gastrointestinal cancer development (8). These findings suggest that alterations in lymphocyte-mediated TGF-β signaling may contribute to colorectal cancer development in $Apc^{Min/+};Tgfbr1^{+/-}$ mice through a "landscaping" effect (42). Additional studies will be needed to clarify the role of decreased Tgfbr1-mediated signaling and assess potential qualitative differences between $Tgfbr1^{+/-}$ and $Tgfbr1^{+/-}$ lymphocytes and stromal cells.

In summary, our data provide a strong rationale and a plausible mechanism for the novel concept that *Tgfbr1* haploinsufficiency has a causative role in intestinal carcinogenesis. $Apc^{Min/+};Tgfbr1^{+/-}$ mice may therefore emerge as a valuable human-based mouse model for studying colorectal cancer development and progression.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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