TITLE:
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CITATION:

ISSUE DATE:
2015-01-01

URL:
http://hdl.handle.net/2433/218587

RIGHT:
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RESEARCH ARTICLE

Id2 deletion attenuates Apc-deficient ileal tumor formation

Kyoko Biyajima1,4, Fumihiko Kakizaki2, Xiaodong Shen1, Kentaro Mori1, Manabu Sugai1, M. Mark Taketo2 and Yoshifumi Yokota1,*

ABSTRACT

The expression level of inhibitor of DNA binding 2 (Id2) is increased in colorectal carcinomas and is positively correlated with poor prognosis. However, the functional significance of Id2 in intestinal tumorigenesis has not been fully defined using genetic approaches. Here, we show that Id2 promotes ileal tumor initiation in Apc-deficient mice. Expression of Id2 was stimulated by Wnt signaling through the enhancer region of the Id2 promoter at the early stage of tumorigenesis in ApcΔ716 (ApcΔ716) mice. Genetic depletion of Id2 in ApcΔ716 mice caused ~80% reduction in the number of ileal polyps, but had little effect on tumor size. Notably, the lack of Id2 increased the number of apoptotic cells in the normal crypt epithelium of the mice. Furthermore, DNA microarray analysis revealed that the expression level of Max dimerization protein 1 (Mxd1), known as a c-Myc antagonist, was specifically increased by Id2 deletion in the ileal intestinal epithelium of ApcΔ716 mice. In contrast, the protein level of c-Myc, but not the mRNA level, was decreased by loss of Id2 in these mice. These results indicate that loss of Id2 inhibits tumor initiation by up-regulation of Mxd1 and down-regulation of c-Myc in ApcΔ716 mice.

KEY WORDS: Apc, c-Myc, Id2, Mxd1, ileal tumor initiation

INTRODUCTION

Somatic mutation of the adenomatous polyposis coli (APC) tumor suppressor gene occurs in most colorectal cancers, and is an early event in the development of sporadic colorectal cancer (Powell et al., 1992). A germ-line mutation of APC is also responsible for the genetic disorder familial adenomatous polyposis (FAP) (Kinzler and Vogelstein, 1996; Taketo and Edelmann, 2009). Mutation of APC leads to activation of Wnt signaling via β-catenin stabilization. The accumulated β-catenin then translocates to the nucleus where it stimulates the expression of Wnt target genes through interaction with T-cell factor/lymphocyte enhancer factor (TCF/LEF) transcription factors (Fodde et al., 2001).

Id2, a member of the Id family, has a helix-loop-helix (HLH) motif but lacks a DNA-binding domain. Therefore, Id2 proteins prevent bHLH proteins from interacting with DNA in a dominant negative manner (Ruzinova and Benezra, 2003; Yokota and Mori, 2002). Since bHLH transcription factors play an important role in multiple processes of cell differentiation and proliferation, Id2 is also involved in these processes (Ruzinova and Benezra, 2003; Yokota, 2001). The expression level of Id2 is generally low in normal adult tissues. However increased expression of Id2 is observed in various human cancers including colorectal cancer, and often correlates with poor prognosis (Gray et al., 2008; Perk et al., 2005; Rockman et al., 2001; Wilson et al., 2001). Interestingly, previous studies have shown that transcription from the ID2 promoter is increased by overexpression of β-catenin (Rockman et al., 2001). Electrophoretic mobility shift assays have also revealed that the ID2 promoter contains a functional TCF-4 binding site (Rockman et al., 2001). Furthermore, knockdown of Id2 expression not only inhibits proliferation but also induces apoptosis in colorectal cancer cells that have mutations in components of the Wnt signaling pathway (Gray et al., 2008). On the other hand, overexpression of Id2 increases anchorage-independent survival of colon cancer cells (Rockman et al., 2001). These circumstantial evidences suggest that Id2 is likely to be important for colorectal tumorigenesis in vivo. However, the functional significance of Id2 in intestinal tumorigenesis has not been fully defined using genetic approaches.

To elucidate the physiological role of Id2 in intestinal tumorigenesis using a genetic approach, we introduced an Id2 null mutation into ApcΔ716 mice, a model for human FAP (Oshima et al., 1995a; Yokota et al., 1999). We have demonstrated here that Id2 plays an essential role in ileal tumor initiation in ApcΔ716 mice.

RESULTS

Expression of Id2 is stimulated at early stages of polyp formation in ApcΔ716 mice

To investigate the potential role of Id2 in intestinal tumorigenesis, we first determined the mRNA levels of Id2 in the tumor epithelium of ApcΔ716 mice by qRT-PCR analysis. The tumor and adjacent normal epithelia were collected by laser microdissection. As shown in Fig. 1A, the level of Id2 in the microadenoma epithelium (≤0.5 mm in diameter) was 5 times higher than that in normal crypts in ApcΔ716 mice. We also found that tumor epithelial cells from adenomas larger than 0.5 mm in diameter showed essentially the same level of Id2 mRNA as that in microadenomas (Fig. 1A). Consistent with the qRT-PCR data, the levels of Id2 protein in ApcΔ716 adenomas were 3 times higher than that in the adjacent normal intestinal tissues (Fig. 1B). It has been reported that ID2 is a downstream target gene of Wnt signaling in human colon cancer cell lines (Rockman et al., 2001). To determine if mouse Id2 is also a target gene of Wnt signaling, we performed ChIP-PCR analysis of the binding of Tcf4 to the promoter region of the Id2 gene. Sequencing analysis revealed ten putative Tcf/Lef-binding consensus sequences in the Id2 promoter region spanning from −4000 to −1 (Fig. 1C; supplementary material Fig. S1). As expected, Tcf4 bound to the DNA region spanning from −3300 to −3146 of the Id2 distal promoter (Fig. 1D). We also confirmed the binding of Tcf4 to the promoter region of the known β-catenin target gene Id2.
Fig. 1. Expression of Id2 is increased in the intestinal tumor epithelial cells of Apc\(^{Δ716}\) mice. (A) Expression level of Id2 mRNA determined by qRT-PCR. Epithelial cells were collected by laser-microdissection from intestinal polyps and adjacent normal crypts (crypt epithelial cells) of Apc\(^{Δ716}\) mice. Microadenomas (mAd) and adenomas 1 mm, 2 mm and >2 mm in diameter were analyzed. The results are given as means±s.d. (n=3). **P<0.01. (B) Expression level of the Id2 protein in intestinal polyps and adjacent normal tissues of Apc\(^{Δ716}\) and Apc Id2 mice was analyzed by western blotting. N, normal tissue; P, polyp. Open arrowhead, nonspecific band; closed arrowhead, endogenous Id2. β-actin, loading control. (C) Schematic representation of the locus of the Id2 enhancer region (Id2 enh) in the Id2 promoter. The gray rectangle indicates the first exon of Id2. The numbers indicate the distance from the Id2 transcriptional start site. The open arrowheads indicate Tcf/Lef binding consensus sequences. (D,E) ChIP assays. Chromatin from small intestinal polyps of Apc\(^{Δ716}\) mice was immunoprecipitated with antibodies against Tcf4 or IgG as a control, followed by qPCR using (D) primer pairs (#1–#3) spanning the mouse Id2 promoter locus shown in C or (E) primers specific for the Axin2 promoter. The results are presented as percentage immunoprecipitated over input and are representative of three independent experiments. N.D., not detected. The results are given as means±s.d. (F) Schematic representation of the luciferase (Luc) expression constructs containing the Id2 enhancer with/without a CMV-minimal promoter (mPro). (G) Luciferase reporter gene assays for active β-catenin mediated activation of the CMV-mPro. HCT116 (left) or SW480 (right) cells were transfected with a reporter construct and an expression vector for active β-catenin and TCF4. Bars indicate relative luciferase activities calibrated to those of the promoter-less luciferase construct. Error bars show standard deviation of triplicate samples. Empty, promoter-less luciferase construct; mPro, luciferase construct containing only CMV minimal promoter; Id2 Enh, luciferase construct containing the CMV minimal promoter and Id2 DNA fragment of –3641 to –3136. **P<0.01.
Apc and other hand, in mice developed 55±15 ileal polyps at the age of 16 weeks. On the tumorigenesis of To determine the role of increased Id2 expression in the Loss of Id2 inhibits ileal tumor initiation of C57BL/6 background was transferred to the 129/Sv genetic and ileum caused by loss of Id2 (Russell et al., 2004), the mice became moribund around 16 weeks of age. We therefore polyp number in mice. Notably, loss of Id2 resulted in a markedly decreased ileal at 16 weeks of age. We therefore euthanized these mutant mice at this age. Since the mice became moribund around 16 weeks of age. We therefore euthanized these mutant mice at this age. Since the Id2 mutation in the 129/Sv genetic background formed few polyps in the colon at this age, we therefore focused on small intestinal polyps in these mice. Notably, loss of Id2 resulted in a markedly decreased ileal polyp number in ApcΔ716 mice (Fig. 2A,B). Specifically, the ApcΔ716 mice developed 55±15 ileal polyps at the age of 16 weeks. On the other hand, in Apc Id2 mutant mice of the same age, the total ileal polyp number was significantly lower (8±4 polyps), showing an 80% reduction in the number found in the ApcΔ716 mice (P=0.0001

Loss of Id2 inhibits ileal tumor initiation of ApcΔ716 mice
To determine the role of increased Id2 expression in the tumorigenesis of Apc-deficient intestinal adenomas, we crossed the ApcΔ716 mice with Id2/−/− mice twice to generate ApcΔ716 Id2/−/− (Apc Id2) mice. Because Id2/−/− mice are perinatal lethal on a C57BL/6 background (Ghosh et al., 2014), the ApcΔ716 allele on the C57BL/6 background was transferred to the 129/Sv genetic background. As shown in Fig. 1B, expression of Id2 protein could not be detected in the normal intestinal tissues or intestinal polyps of the Apc Id2 mice. Due to intestinal distortion between the jejunum and ileum caused by loss of Id2 (Russell et al., 2004), the Apc Id2 mice became moribund around 16 weeks of age. We therefore euthanized these mutant mice at this age. Since the ApcΔ716 mice in the 129/Sv genetic background formed few polyps in the colon at this age, we therefore focused on small intestinal polyps in these mice. Notably, loss of Id2 resulted in a markedly decreased ileal polyp number in ApcΔ716 mice (Fig. 2A,B). Specifically, the ApcΔ716 mice developed 55±15 ileal polyps at the age of 16 weeks. On the other hand, in Apc Id2 mutant mice of the same age, the total ileal polyp number was significantly lower (8±4 polyps), showing an 80% reduction in the number found in the ApcΔ716 mice (P=0.0001

Fig. 2. Loss of Id2 attenuates ileal tumor formation in ApcΔ716 mice.
(A) Representative Swiss rolls of the ileum from ApcΔ716 and Apc Id2 mice stained with H&E. Arrowheads indicate polyps. Scale bars, 1 mm. (B) Total number of polyps in the ApcΔ716 and Apc Id2 mice at 16 weeks of age as assessed using a dissecting microscope. The results show the mean number of polyps/mouse±s.d. (n=7–8). **P<0.01.
(C) Size distribution of the polyps. Polyps were classified according to their diameter in millimeters. The results are shown as percentages for the respective size classes (n=7–8). Φ indicates polyp diameter.
detected in Id2 loss-induced epithelial tumor cells (supplementary material Fig. S3F). Because of these differences, Apc-deficient adenomas can be distinguished from Id2 loss-induced polyps in Apc Δ716 mice. β-catenin staining revealed that the percentage of Apc-deficient adenomas was ~96% in Apc Δ716 mice (supplementary material Table S1). This result suggests that the tumors derived from Id2 loss are negligible in number in this analysis.

The Id2 protein is specifically expressed in the intestinal crypt epithelium

It has been reported that polyp formation is initiated by LOH at the Apc locus in the proliferative zone cells of the intestinal crypts of Apc Δ716 mice (Oshima et al., 1995a). To determine if Id2 is expressed in intestinal crypts, we assessed its protein expression level along the crypt-villus axis of the intestinal epithelium in these mice. We first separated the normal villus and crypt epithelium from the surrounding tissue. H&E staining showed that villi and crypts were successfully isolated (Fig. 3A). Western blotting showed prominent Id2 expression in the crypt epithelium but not in the villus epithelium within the normal epithelial compartment of the Apc Δ716 mice (Fig. 3B).

Because the loss of Id2 specifically suppresses ileal tumor initiation in Apc Δ716 mice, we confirmed the expression patterns of Id2 and other Id-family members (Id1 and Id3) along the proximal-distal axis of the small intestine. The expression levels of Id1, Id2, and Id3 remained unchanged throughout the small intestine, although the levels of Id1 and Id3 were increased by Id2 deletion (supplementary material Fig. S4A-C). These results indicate that the ileal specific phenotype is not attributable to different expression patterns among Id-family members along the proximal-distal axis of the small intestine.

It is known that an additional mutation in the Cdx2 gene in Apc Δ716 mice reverses polyp localization, shifting most polyps to the colon (Taketo and Edelmann, 2009). It has also been reported that a conditional mutation in the Gata4 gene in the jejunum of adult mice results in a partial jejunal-to-ileal transformation (Bosse et al., 2006). We therefore evaluated the expression of the Gata4, Cdx1, and Cdx2 genes. However, the expression levels of Gata4, Cdx1, and Cdx2 were not altered by the loss of Id2 (supplementary material Fig. S5). These results suggest that Id2 promotes ileal tumor initiation in the proliferating crypt epithelium of Apc Δ716 mice without the effect on the location of the polyps.

Id2 promotes ileal tumor initiation through inhibition of apoptosis in intestinal crypts of Apc Δ716 mice

To analyze the mechanism of Id2-mediated tumor initiation, we next investigated the effect of Id2-deficiency on the proliferation and apoptosis of normal crypt cells of Apc Δ716 mice. Immunohistochemistry of cleaved caspase-3, which is a marker of apoptosis, revealed that the rate of apoptotic cells per 100 crypts in Apc Δ716 mice was 3.7 times higher than that in Apc Δ716 mice. (Apc Δ716, 2.6±1.5 versus Apc/Id2, 9.7±3.8; P=0.04; Fig. 4A, B). On the other hand, loss of Id2 did not affect apoptosis of villus epithelial cells in Apc Δ716 mice (Fig. 4C,D). Furthermore, there was no difference in the percentage of Ki67 positive cells in normal crypt epithelium between Apc Δ716 and Apc Id2 mice. (Apc Δ716, 82±4.1 versus Apc/Id2, 84±5.7; P=0.15; Fig. 4E,F). In addition, the absence of Id2 in ileal tumor epithelium did not alter the proliferative capacity or the apoptosis rate in Apc Δ716 mice (supplementary material Fig. S6). These data suggest that Id2 promotes tumor initiation with inhibition of apoptosis in the intestinal crypt cells of Apc Δ716 mice.

Loss of Id2 reduces the protein level of c-Myc and increases the mRNA level of its antagonist Mxd1 in ileal crypt epithelium of Apc Δ716 mice

To investigate the genes that could be involved in the inhibition of ileal tumor formation in Apc Δ716 mice, we next performed DNA microarray analysis of ileal crypts that were isolated from Apc Δ716 and Apc Δ716 mice. We then applied the following criteria to select such genes. First, the expression of the candidate gene was up- or down-regulated by more than 8-fold in the microarray analysis. Second, the expression levels of the candidate genes are changed in the ileal crypt, yet not in the duodenum or jejunum. Third, the candidate-genes have been implicated in tumor initiation.
Although 183 and 57 genes were up- and down-regulated, respectively, by the Id2 loss (supplementary material Table S2), *Max dimerization protein 1* (*Mxd1*) was the only candidate gene that met the three criteria. It is known that *Mxd1* antagonizes c-Myc function by competing with c-Myc for interaction with Max (Ayer et al., 1993). It has been also reported that c-Myc is one of the most important downstream targets of Wnt signaling (He et al., 1998) and functions as a mediator of polyp growth and intestinal cancer initiation (Ignatenko et al., 2006; Sansom et al., 2007; Yekkala and Baudino, 2007). As shown in Fig. 5A, loss of Id2 increased the mRNA level of *Mxd1* by ∼8 fold in the crypt epithelium of the ileum but not in that of the duodenum or jejunum. Induction of *Mxd1* expression by Id2 deletion was also observed at protein level, as shown by western blot (Fig. 5B). To analyze the functional interaction between c-Myc and Mxd1, we next determined the expression levels of c-Myc in the intestinal crypt. Lack of Id2 did not affect the level of c-Myc mRNA throughout the small intestinal tract (Fig. 5C). Importantly, loss of Id2 down-regulated the protein level of c-Myc in the ileum but not in the duodenum of *Apc<sup>Δ716</sup>* mice (Fig. 5D). According to these results, Id2 ablation also affects translation or stabilization of c-Myc protein as well as transcription of Mxd1 mRNA. These results
We have shown here direct genetic evidence that Id2 plays a crucial role in ileal tumor initiation in Apc\textsuperscript{Δ716} mice. Although Apc-deficient mice have been widely analyzed, this study is the first report to show ileum-specific reduction of tumor multiplicity in these mice.

Id2 is highly expressed in the intestinal crypt epithelium and its expression level is further increased in Apc-deficient adenoma (Figs 1 and 3). It is known that Wnt signaling is activated in the intestinal crypt and adenoma epithelial cells (Reya and Clevers, 2005). Consistent with these findings, our results have shown that Tcf4 binds directly to the enhancer region of the Apc\textsuperscript{Δ716} mouse; Al, Apc Id2 mouse. β-actin, loading control. (C) Expression of c-Myc mRNA determined by qRT-PCR. Total RNA was prepared from isolated crypts in the normal duodenum, jejunum and ileum of Apc\textsuperscript{Δ716} and Apc Id2 mice. The results are given as means±s.d. (n=5). (D) Expression of c-Myc protein determined by western blotting. Protein samples were prepared from isolated crypts, as shown in Fig. 3A. The open and closed arrowheads indicate nonspecific bands and specific Mxd1 bands. A, Apc\textsuperscript{Δ716} mouse; Al, Apc Id2 mouse. β-actin, loading control.

Earlier studies have shown that Id2 contributes to tumor proliferation. Overexpression of Id2 increases anchorage-independent proliferation of both SW480 and HT29 colon cancer cells (Rockman et al., 2001), and knockdown of Id2 decreases cell proliferation of HCT116 cells (Gray et al., 2008). On the other hand, we have demonstrated here that loss of Id2 inhibits tumor initiation rather than tumor expansion in Apc\textsuperscript{Δ716} mice (Fig. 2B,C). Of note, adenoma epithelial cells of Apc\textsuperscript{Δ716} mice do not carry additional mutations other than Apc (Oshima et al., 1995a). In contrast, human colon cancer cell lines that have been used in previous reports have several mutations such as K-ras, p53 and transforming growth factor (TGF)-β type II receptor (Gayet et al., 2001; Ijichi et al., 2001). It is therefore conceivable that Id2 is involved in the proliferation of adenocarcinoma epithelium beyond the stage examined here.

O’Brien et al. have reported that Id1 and Id3, other Id family members, are expressed in colon cancer initiating cells and function together with p21 to regulate their self-renewal capacity through cell cycle restriction and DNA damage accumulation (O’Brien et al., 2012). A more recent study has also shown that loss of Id1 inhibits tumor initiation but does not affect tumor expansion in Apc\textsuperscript{Min/−} mice (Zhang et al., 2015). These findings and our study show that Id2 plays an important role in intestinal tumor initiation in addition to Id1 and Id3. This raises the possibility that Id1 and Id3 compensate for the function of Id2 in the duodenal- and jejunal-tumor initiation that is not affected by the loss of Id2.

Our results suggest the possibility that the enhanced expression of Mxd1 suppresses ileal-tumor initiation in Apc Id2 mice (Fig. 5A,B). Mxd1 belongs to the Max dimerization protein (Mxd) family of proteins, which function as potent antagonists of c-Myc. It is currently understood that Mxd1 competes with c-Myc for the
transcription factor Max and for their recognition sequence E-box (Cascón and Robledo, 2012; D’Ioriati et al., 2015). The Mxd1–Max heterodimer then functions as a transcriptional repressor at E-box containing promoters and antagonizes the c-Myc–Max functions. Consistently, overexpression of Mxd1 inhibits c-Myc/Ha-Ras mediated co-transformation in rat embryo cells (Cerni et al., 1995). In addition, loss of Mxd2, a member of the Mxd family, resulted in susceptibility to tumorigenesis in squamous cell carcinoma of the skin and malignant lymphoma (Schreiber-Agus et al., 1998). It is therefore possible that Mxd1 contributes to the tumor initiation of various tissues including ileum.

c-Myc is a critical mediator of adenoma initiation following Apc loss (Ignatenko et al., 2006; Sansom et al., 2007; Yekkala and Baudino, 2007). It was reported that targeted c-myc deletion in the intestinal epithelium reduced the tumor number of Apc heterozygotic (Apc^{Min}−/) mice with increases in apoptosis (Ignatenko et al., 2006). Consistent with those studies, our results show that down-regulation of c-Myc is accompanied by increases in apoptosis in the intestinal crypt epithelium of Apc Id2 mice (Figs 4A,B and 5B). However, it has also been reported that conditional Myc gene ablation decreases the number of apoptotic cells in the intestinal epithelium of Apc homozygotic (AbCre Apc^{Δ/Δ}) mice (Sansom et al., 2007). This discrepancy in the apoptotic phenotypes may be attributable to the number of Apc mutant alleles in the normal intestinal epithelium. Further studies are required to understand the precise roles of Id2, c-Myc and Apc in apoptosis of intestinal epithelial cells.

Curiously, Id2 deletion decreased c-Myc protein levels, but not mRNA levels, in the small-intestinal ileal crypt (Fig. 5C,D). Importantly, it is known that Mxd1 can inhibit c-Myc function by prevention of c-Myc–Max heterodimerization (Ayer et al., 1993). This raises a possibility that inhibition of c-Myc–Max heterodimer formation by enhanced expression of Mxd1 is involved in destabilizing c-Myc protein. Thus, it is likely that Id2 promotes tumor initiation through inhibition of the Mxd1–Max network and activation of the c-Myc–Max.

In conclusion, we have demonstrated that Id2 is transcriptionally controlled by Wnt signaling and contributes to the cell survival of distal-intestinal crypt epithelium, which is accompanied by the suppression of Mxd1 and stabilization of c-Myc.

MATERIALS AND METHODS

Mice

The knockout alleles of the Apc and Id2 genes have been described previously (Oshima et al., 1995a; Yokota et al., 1999). The Apc^{716} allele on the C57BL/6 background was transferred to the 129/Sv genetic background by backcrossing for more than 5 generations. Female Apc^{716} mice on the 129/Sv background were then crossed twice with the 129/Sv background mice (N货ly et al., 1995). Mouse Id2 allele on the 716 allele on the C57BL/6 background was transferred to the 129/Sv genetic background. Id2 mice were then crossed twice with the 129/Sv background mice (N货ly et al., 1995). The knockout alleles of the Apc and Id2 genes were previously described (Sato et al., 2009). Total RNA was purified using the RNeasy Micro Kit (Qiagen). Gene expression profiles were analyzed using the Affymetrix Mouse GeneChip Gene 2.0 Plus 3’ microarray (Affymetrix, Santa Clara, CA, USA) according to the manufacturer’s instructions.

Cell culture

HCT116 and SW480 cells were obtained from the American Type Culture Collection. The cells were grown at 37°C in 5% CO2 using DMEM (Wako, Osaka, Japan) supplemented with 10% fetal bovine serum (Thermo Fisher Scientifics, Waltham, MA, USA) and penicillin/streptomycin (Wako).

RT-PCR

The levels of specific mRNAs were determined by quantitative reverse-transcription polymerase chain reaction (RT-PCR) using a StepOnePlus Real Time PCR system (Life Technologies, Foster, CA, USA). This analysis was adapted from the previous study (Kakizaki et al., 2010). Primers used were as follows: mouse Actb (forward, 5′-TGACAGGATGCAGAAGG-AGA-3′; reverse, 5′-GCTGGAAGGTGGCAGTGA-3′); mouse Id2 (forward, 5′-ACTCGACTCCACTCGTCAGC-3′; reverse, 5′-TGCT- ATCCATCCGACATAAGCTCAGA-3′), mouse Id1 (forward, 5′-GGGAC-TGAAACTCCGAGTCTGAA-3′; reverse, 5′-GATGCTCGTGCTGAA- CACA-3′), mouse Id3 (forward, 5′-GAAATCGCAGCCGTTCATA- 3′; reverse, 5′-GAGATCCACAGTTCCGGAGTGA-3′), mouse c-Myc (forward, 5′-CGAGCTTGTGAAAGCCTGGA-3′; reverse, 5′-GTCGCC- AGATGAAATAGGGCTGT-3′), mouse Mxd1 (forward, 5′-GAGACGC- GTGGCTCTGGT-3′; reverse, 5′-CTGTGCTCCTACATCAC-3′), mouse Cdx1 (forward, 5′-ACAGCCTCGACTCATTAC-3′; reverse, 5′-CTGTGGAGGCTGGTGT- TGCT-3′), and mouse Gata4 (forward, 5′-CCGCGCTGTCATCCTAC- TAT-3′; reverse, 5′-CGACAGCCTGACTGGTAGT-3′).

Western blotting

Dissected tissue samples were homogenized in RIPA lysis buffer containing 50 mM Tris-HCl, pH 7.4; 150 mM NaCl; 1 mM NaF; 1% NP-40; 0.25% sodium deoxycholate; 1 mM sodium orthovanadate; 1 mM EDTA and a protein protease inhibitor cocktail (Nacalai Tesque, Kyoto, Japan). Lysates containing 10–40 μg of protein were separated by SDS-PAGE and transferred to Hybond ECL Nitrocellulose membranes (GE Healthcare, Buckinghamshire, UK). The membranes were blocked with Blocking One (Nacalai Tesque) for 1 h at room temperature. The membranes were then probed with the following antibodies: rabbit polyclonal anti-Id2 (sc-489; Santa Cruz Biotechnology, Dallas, TX, USA), rabbit monoclonal anti-Id3 (D39E8, #3431; Cell Signaling Technology, Beverly, MA, USA), rabbit polyclonal anti-Mxd1/Mad1 (sc-222; Santa Cruz Biotechnology), rabbit monoclonal anti-c-Myc (D94C12, #5605; Cell Signaling Technology) and mouse monoclonal anti-β-actin (Sigma-Aldrich, Saint Louis, MO, USA) antibodies. After incubation with horseradish peroxidase-conjugated secondary antibodies, bound proteins were detected by incubation with an Immobilon chemiluminescent substrate (Millipore, Billerica, MA, USA).

Polypl number scoring

Dissected intestinal tissues were fixed with 4% paraformaldehyde. The number of polyps was scored as described previously (Oshima et al., 1995a).

Histological analysis

Dissected intestinal tissues were fixed with 4% paraformaldehyde, embedded in paraffin wax and sectioned at a thickness of 4 μm. These sections were stained with H&E or were processed for further immunostaining as described previously (Oshima et al., 1995b). Antibodies used in this study were rabbit polyclonal anti-cleaved caspase3 (Asp175, #9661; Cell Signaling Technology), anti-Ki67 (RM-9106; Thermofisher Scientifics) were used as primary antibodies.

Classification of polyps

Dissected intestinal tissues were fixed with 4% paraformaldehyde, embedded in paraffin wax and sectioned at a thickness of 4 μm at 40 μm intervals throughout the tissue block and stained with anti-β-catenin (c2206; Sigma-Aldrich) antibodies. Polyps were categorized as β-catenin-positive or β-catenin-negative and scored for numbers.

DNA microarray

Normal ileal crypts were isolated from the Apc^{716} and Apc Id2 mice as previously described (Sato et al., 2009). Total RNA was purified using the RNeasy Micro Kit (Qiagen). Gene expression profiles were analyzed using the 3D-Gene Mouse Oligo Chip 24k (Toray Industries, Kanagawa, Japan).

ChIP-PCR

ChIP assays were performed using the ChIP-it high sensitivity kit (Active Motif, Carlsbad, CA, USA) according to the manufacturer’s instructions.
Intestinal polyps from ApcΔ716 mice were fixed with 1% formaldehyde for 15 min at room temperature. Isolated nuclei from the mouse intestinal polyps were sonicated using a Biorupter (Cosmo Bio Co., Ltd., Tokyo, Japan). After centrifugation to remove debris, chromatins were incubated with rabbit monoclonal anti-TCF4 antibody (C48H11, #2569; Cell Signaling Technology) or normal rabbit IgG (#2729; Cell Signaling Technology) overnight at 4°C. The qPCR analysis of immunoprecipitated DNA fragments was performed using KOD SYBER qPCR Mix (TOYOBO, Osaka, Japan) with the following primer set: mouse Axin2 promoter (forward, 5′-CTGCATACCTCTCCTCTCC-3′; reverse, 5′-TTCCACAGTCATGAGGCACG-3′), mouse Id2 promoter-1 (forward, 5′-GGGTGCTGAAATGATTCAAAA-3′; reverse, 5′-GTGGCAGAATGTGAGTAT-3′); mouse Id2 promoter-2 (forward, 5′-TCAGTACCAGAGATGACAAG-3′; reverse, 5′-GCCGAGCAGTTTGTGTTGGA-3′); mouse Id2 promoter-3 (forward, 5′-TTGGAGTCAAAGCCATCC-3′; reverse, 5′-AGACCTTGCCAAAGCAGAAGG-3′). Results are presented as percentage immunoprecipitated over input and are representative of three independent experiments.

**Vector construction and site-directed mutagenesis**

The full-length, TCF4/TCF7L2 cDNAs were isolated by PCR-based cloning techniques using the following primer sets: TCF4/TCF7L2 (forward, 5′-CTCCTTCCTCTCATTCTTTTCT-3′; reverse, 5′-CAATGAGAC-TGGATAAACATC-3′). The TCF4/TCF7L2 cDNAs was inserted into pcDNA6/V5-HisA (Invitrogen, Grand Island, NY, USA) for transient expression. The putative Id2 enhancer region was cloned by PCR amplification from the genomic DNA from mouse tail using the forward primer 5′-CGGTTCAGGCTGGTACTAC-3′ and the reverse primers 5′-AGACCTTGCCAAAGCAGAAGG-3′, and inserted into pGL4.10 luciferase vector (Promega; Madison, WI, USA) to generate the reporter construct (Fig. 1C). The pCMV6-XLS expression vector carrying the CTNNB1 was obtained from T. Akiyama (The University of Tokyo). Site-directed mutagenesis for mutating the CTNNB1 was performed using PrimeSTAR mutagenesis Basal kit (TaKaRa, Shiga, Japan) with the CTNNB1 construct (Fig. 1C). The pCMV6-XLS expression vector carrying the CTNNB1 was obtained from T. Akiyama (The University of Tokyo). Site-directed mutagenesis for mutating the CTNNB1 was performed using PrimeSTAR mutagenesis Basal kit (TaKaRa, Shiga, Japan) with the CTNNB1 construct (Fig. 1C). The pCMV6-XLS expression vector carrying the CTNNB1 was obtained from T. Akiyama (The University of Tokyo). Site-directed mutagenesis for mutating the CTNNB1 was performed using PrimeSTAR mutagenesis Basal kit (TaKaRa, Shiga, Japan) with the CTNNB1 construct (Fig. 1C).

**Luciferase reporter gene assay**

The luciferase assay protocol was adapted from a previous study (Kakizaki et al., 2010). HCT116 or SW480 cells were seeded into MP-24 tissue culture plates at a density of 5×10⁵ cells per well. The cultures were transfected with 100 ng of luciferase reporter gene constructs, 200 ng of a pcDNA6/V5-HisA expression vector carrying the CTNNB1 S33A mutant encoding the active form of β-catenin and TCF4, and 2 ng of the hRLuc-CMV vector (Promega), using LipofectaminLTX (Life Technologies). After 24 h of incubation, the cultures were washed once with ice-cold PBS and then lysed in 100 μl of Passive lysis buffer (Promega) according to the manufacturer’s protocol. Firefly and Renilla luciferase activities were determined using the Dual-Luciferase Reporter Assay System (Promega) with a MITHORAS LB 940 (Berthold Biolumat, Bad Wildbad, Germany). Firefly luciferase activities were normalized against the Renilla luciferase activities.

**Statistical analysis**

The values are shown as means±s.d. Data were analyzed using a Student’s t-test or ANOVA. P-values smaller than 0.05 were considered statistically significant.

**Accession numbers**

Microarray hybridization data have been deposited in the GEO database with accession code GSE66480.

**Acknowledgements**

The authors thank Hisanori Kurooka, Koji Aoki, Yoshitaka Aoki, Hiroko Shigemi, and Kyoko Okezaki for helpful discussions; Yukie Matsui for her technical assistance; Tetsu Akiyama for human CTNNB1 cDNA.

**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**

K.B., K.M. and Y.Y. conceived and designed experiments and also designed experiments together with F.K.; K.B. and X.S. conducted experiments; M.M.T. provided ApcΔ716 mice; K.B. and F.K. analyzed and interpreted data; K.M., M.S. and M.M.T. provided advice on the manuscript; K.B., F.K. and Y.Y. wrote the manuscript.

**Funding**

This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports and Technology of Japan (K.B.: #24793079, Y.Y.: #21390092, #24390077).

**Supplementary material**

Supplementary material available online at http://bio.biologists.org lookup/supplid=10.1242/bio.012252/D1

**References**


