

Nicotine enhances the stemness and tumorigenicity in intestinal stem cells via Hippo-YAP/TAZ and Notch signal pathway

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Abstract

Summary

Cigarette smoking is a well-known risk factor inducing the development and progression of various diseases. Nicotine (NIC) is the major constituent of cigarette smoke. However, knowledge of the mechanism underlying the NIC-regulated stem cell functions is limited. In this study, we demonstrate that NIC increases the abundance and proliferative activity of intestinal stem cells (ISCs) in vivo and ex vivo. Moreover, NIC induces Yes-associated protein (YAP)/Transcriptional coactivator with PDZ-binding motif (TAZ) and Notch signaling in ISCs via $\alpha 7$ -nicotinic acetylcholine receptor (nAChR) and protein kinase C (PKC) activation; this effect was not detected in Paneth cells. The inhibition of Notch signaling by dibenzazepine (DBZ) nullified the effects of NIC on ISCs. NIC enhances in vivo tumor formation from ISCs after loss of the tumor suppressor gene *Apc*, DBZ inhibited NIC-induced tumor growth. Hence, this study identifies a NIC-triggered pathway regulating the stemness and tumorigenicity of ISCs and suggests the use of DBZ as a potential therapeutic strategy for treating intestinal tumors.

eLife assessment

This study presents a **valuable** finding on a potential signaling pathway responsible for the direct effects of nicotine on intestinal stem cell growth and tumorigenesis. However, the evidence supporting the authors' claims remains **incomplete**. Additional analysis on how stem cells uniquely respond to nicotine could provide more definitive evidence and strengthen the study. This research will be of interest to medical biologists specializing in intestinal tumors.

Introduction

All tissues and organs are generated from stem cells. Abnormal stem cell functions are significantly associated with age-related organ dysfunction and carcinogenesis¹. Intestinal epithelial turnover is sustained by intestinal stem cells (ISCs) and adjacent Paneth cells. Paneth cells constitute the niche for ISCs that reside at the bottom of the crypts. Most of the ISCs are leucine-rich repeat-containing G-protein-coupled receptor 5 (Lgr5)⁺ ones that regulate intestinal homeostasis in response to dietary signals^{2,3}. In the intestine, Lgr5⁺ ISCs are possibly the origin of precancerous adenomas⁴. For instance, long-term high-fat diet (HFD)-induced obesity enhances the self-renewal potential of ISC and promotes in vivo formation of tumors via the induction of peroxisome proliferator-activated receptor delta in ISCs⁵.

Moreover, cigarette smoking has emerged as a potential major risk factor associated with colon cancer, along with metabolic risk factors such as diet and obesity. Previous studies indicate that cigarette smoking is significantly associated with colon cancer and mortality in humans⁶ and animal models⁷.

Cigarette smoke contains a wide range of compounds that are harmful to human health; nicotine (NIC) derivatives 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) and N'-nitrosonornicotine (NNN) are highly carcinogenic^{8,9}, which can induce mutations in tumor suppressive genes like Ras, p53, and Rb¹⁰. Although NIC itself, the addictive component in cigarette smoke, is generally considered to have a limited ability to initiate cancer, it can stimulate several effects crucial for cancer development independently¹¹. However, knowledge of the mechanism underlying the NIC-regulated ISC functions and intestinal tumorigenicity is limited.

In this study, we aimed to demonstrate the effects of NIC treatment on the functions of murine ISCs ex vivo and in vivo. Moreover, we explored the molecular factors and signaling cascades prospectively associated with the regulation of the effects of NIC on ISCs. This study can potentially contribute to the comprehensive knowledge on the pathway by which stem cells respond to NIC, a major component of cigarette smoke, and suggest an effective new strategy for the treatment of smoking-related colon cancer.

Results

NIC treatment enhances the frequency of ISC in the intestine

Histological analyses of the small intestine in C57BL/6 mice treated with 200[μg/ml NIC (which emulates active smoking) revealed that NIC exposure decreased villus length without affecting crypt size (Figure S1A), which was consistent with NIC-induced decrease in the number of differentiated cells, including absorptive enterocytes (Figure S1B) or chromogranin A⁺ enteroendocrine cells (Figure S1C), in the gut.

We investigated the effect of NIC on the population of proliferative cells in the crypts using Ki67 labeling to mark proliferative stem and progenitor cells in the crypts. NIC exposure increased abundance of Ki67-positive cells in the small and large intestine (**Figures 1A and B**). Consistently, the number of proliferative olfactomedin-4 (Olfm4)-positive ISCs significantly increased in the small intestine of NIC-treated mice (**Figure 1C**). Moreover, the number of Lgr5⁺ colonic stem cells (CSCs) was increased in NIC-treated *Lgr5-EGFP-IRES-CreERT2* mice expressing EGFP under the control of the Lgr5 promoter (**Figure 1D**). Paneth cells support the proliferation of ISCs. However, we did not observe any changes in the number of Paneth cells in NIC-treated mice (**Figure 1E**). These results indicate that the self-renewal of ISCs in NIC-treated mice increased with a reciprocal decrease in the number of differentiated cells.

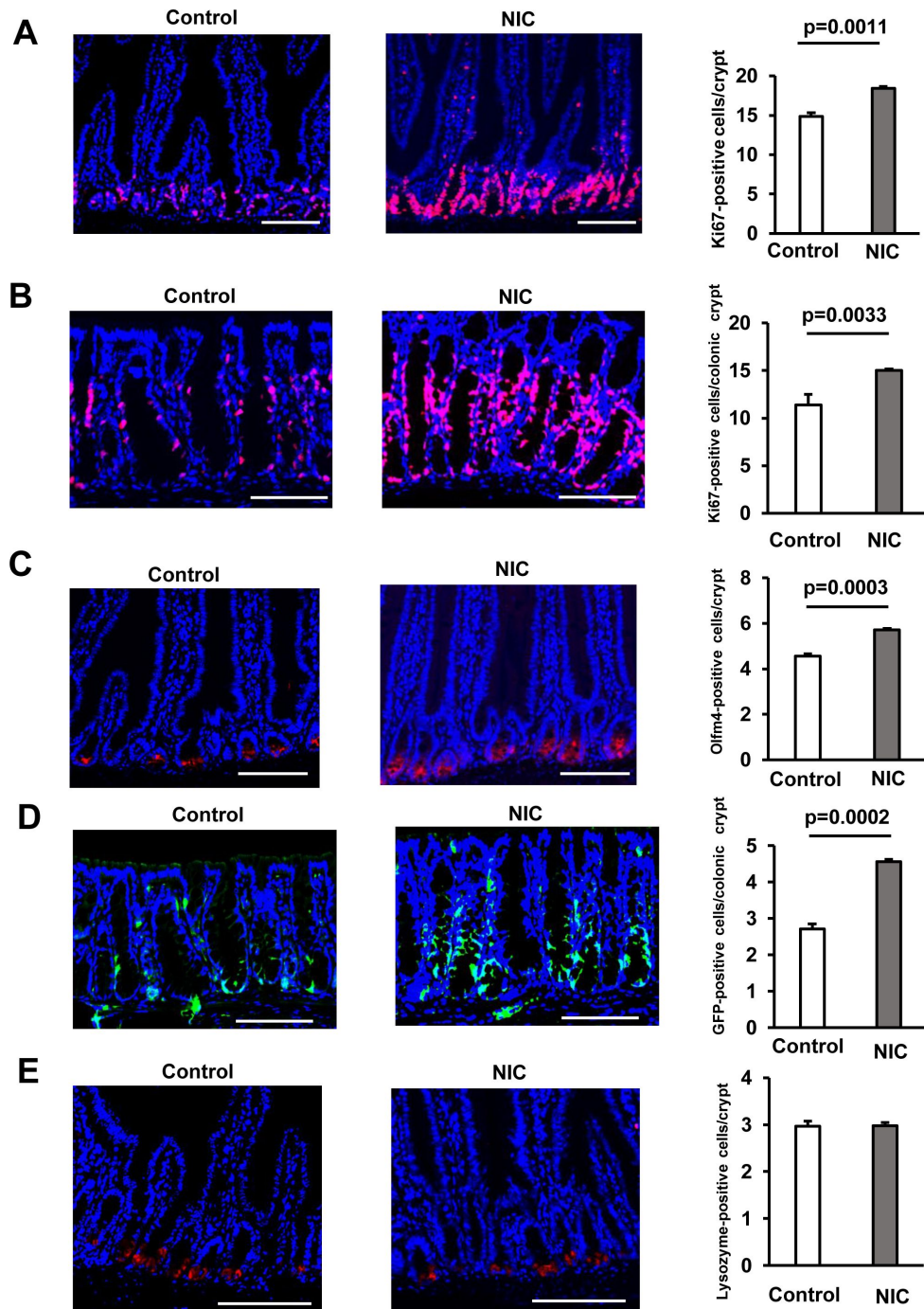


Figure 1.

Nicotine (NIC) treatment increases the number of ISCs in the Intestine

(A and B) Image of Ki67-positive cells (Red: Ki67, Blue: DAPI) and their quantification at the crypt base of proximal jejunum (A) or colon (B) of NIC-treated and untreated mice (A:3–4 mice per group, B: 3 mice per group). (C) Olfm4 staining image (Red: Olfm4, Blue: DAPI) and the quantification of Olfm4-positive cells at the crypt base of proximal jejunum with or without NIC treatment (3–4 mice per group). (D) GFP staining image (Green: GFP, Blue: DAPI) and the quantification of Lgr5-GFP-positive cells at the crypt base of the colon in NIC or control-treated *Lgr5-EGFP-IRES-CreERT2* mice (3 mice per group). (E) Lysozyme staining image (Red: Lysozyme, Blue: DAPI) and the quantification of Lysozyme-positive Paneth cells with or without NIC treatment (3–4 mice per group). Original magnifications: 200× (A–E). Scale bar: 100 μm (A–E). Values represent the mean ± standard error of the mean (SEM). Significant differences are denoted by p values (Student's t-test). See also Figure S1.

NIC treatment enhances the formation of intestinal organoids from ISCs

Our ISC proliferation analysis using intestinal crypts of wild-type mice revealed that a range of nicotine concentrations (100nM, 1 μ M, and 10 μ M) promoted the organoid formation from crypts from the small intestine (**Figure 2A**). This was consistent with the *in vivo* data (**Figures 1A and C**). However, the same dose of cotinine, a minor tobacco alkaloid, and a major metabolite of NIC¹² did not exhibit similar effects (**Figure 2A**). Furthermore, the addition of 1 μ M NIC promoted the organoid formation from colonic crypts (**Figure 2B**). Next, to address how ISCs and Paneth cells interact functionally, we isolated *Lgr5*-positive ISCs and Paneth cells from control or NIC-treated *Lgr5-EGFP-IRES-CreERT2* mice as described previously². ISCs and Paneth cells were co-cultured in the culture media containing glycogen synthase kinase 3 β (GSK3 β) inhibitor CHIR99021, which induces β -catenin and thus stimulates organoid formation^{2,13}. *Lgr5*-positive ISCs isolated from NIC mice formed more organoid colonies than those isolated from control mice when cultured with or without Paneth cells (**Figure 2C**). Consistently, the addition of 1 μ M NIC to control ISCs stimulated the organoid colony formation (**Figure 2D**). However, Paneth cells exhibited no significant difference in function (organoid formation) between control and NIC-treated groups, with or without CHIR99021 (**Figures 2C** and **S2A**). Therefore, this *ex vivo* assay for ISC function and ISC–Paneth cell interaction demonstrated that NIC affects ISCs rather than Paneth cells.

The $\alpha 7$ subunits of nAChR control the effects of NIC on ISC proliferation

We investigated the pathway underlying the NIC-regulated proliferation of ISCs. NIC interacts with nicotinic acetylcholine receptors (nAChRs), which are heterodimers of nine types of α subunits ($\alpha 2$ – $\alpha 10$) and three types of β subunits ($\beta 2$ – $\beta 4$)¹⁴. We validated the significance of nAChR signal transduction using ISCs, isolated wild-type mice cultured in the presence of NIC, and the nonselective nAChR antagonist Mecamylamine, which indicated that Mecamylamine treatment completely abolishes the NIC-mediated formation of ISC-derived organoids (**Figure 3A**). We further explored the nAChR subtypes. Considering that NIC has a high affinity for the nAChR comprised of $\alpha 4$ and $\beta 2$ subunits¹⁵, we cultured ISCs in the presence of NIC and Adiphenine, a non-competitive inhibitor of nAChR ($\alpha 1$, $\alpha 3\beta 4$, $\alpha 4\beta 2$, and $\alpha 4\beta 4$). However, Adiphenine exhibited no effect on the NIC-induced organoid formation from ISCs, indicating that the effect of NIC was not mediated by these nAChRs (**Figure 3B**). As some cancer stem cells are known to express $\alpha 7$ -nAChR^{16,17}, we further analyzed the role of $\alpha 7$ -nAChR. The existence of $\alpha 7$ -nAChR in ISCs was detected by immunoblotting and RT-PCR, respectively (**Figures 3C and D**). Interestingly, NIC treatment significantly upregulated $\alpha 7$ -nAChR in ISCs rather than Paneth cells (**Figure 3D**). Moreover, addition of the $\alpha 7$ -selective nAChR agonist PNU282987 increased organoid colony formation from ISCs (**Figure 3E**), which was consistent with the effects of NIC. Furthermore, α -Bungarotoxin, an $\alpha 7$ -selective nAChR antagonist, completely inhibited the NIC-induced increase in organoid formation (**Figure 3F**). These outcomes indicate the effect of nicotine is mediated via the $\alpha 7$ subunits of nAChR.

NIC induces a Hippo-YAP/TAZ and notch signaling in ISCs

As NIC can activate protein kinase C (PKC) or cAMP-dependent protein kinase A (PKA) via $\alpha 7$ -nAChR activation^{17,18}, we cultured isolated ISCs in the presence of NIC combined with Go6983, a pan-PKC inhibitor, or H89, a selective PKA inhibitor. H89 did not suppress NIC-induced organoid formation, however, Go6983 completely abolished this effect of NIC (**Figures 4A and B**). Consistently, the PKC activator Ingenol-3-angelate stimulated the formation of organoid colonies from ISCs (**Figures 5E** and **5F**).

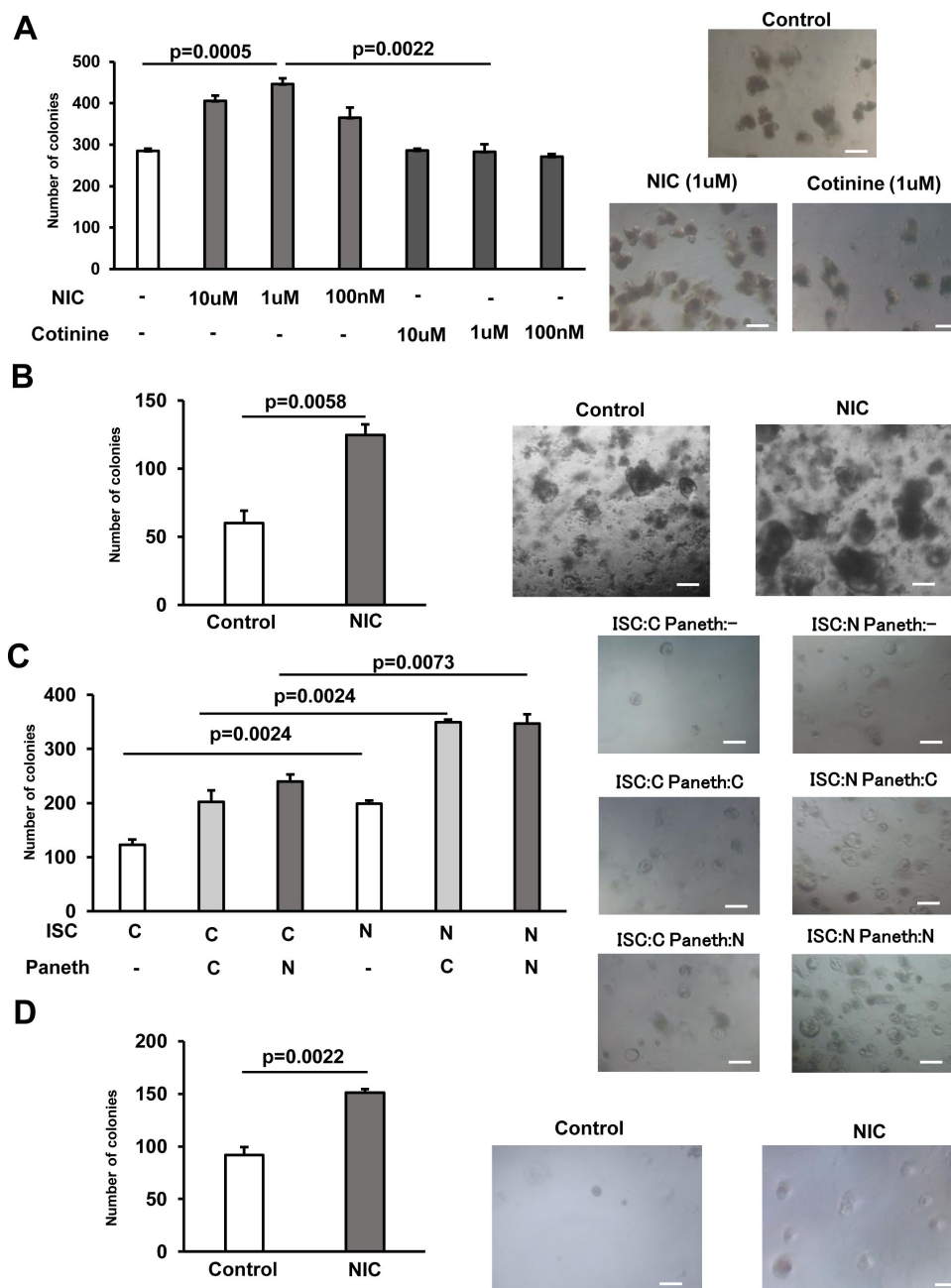


Figure 2.

NIC enhances the formation of intestinal organoids from ISCs

(A) Crypts from the proximal small intestine were cultured with 10 μ M, 1 μ M, and 100 nM NIC or cotinine to allow ISCs to form organoid colonies; the control set contained no NIC or cotinine. Representative images of the organoids and the quantification of organoids number at day 5 (3 wells/ group). (B) Colonic crypts were cultured with or without 1 μ M NIC to allow CSCs to form organoid colonies. Representative images of the organoids and the quantification of organoids number at day 5 are shown (3 wells/ group). (C) ISCs and Paneth cells were isolated from the small intestine of *Lgr5-EGFP-IRES-CreERT2* mice treated with or without NIC; 2×10^3 cells each were co cultured in the medium containing 10 μ M CHIR99021. Representative images of the organoids and the frequency of organoids at day 5 (3 wells/ group). (D) ISCs isolated from the small intestine of *Lgr5-EGFP-IRES-CreERT2* mice were cultured in the absence of Paneth cells using the medium containing 10 μ M CHIR99021, with or without 1 μ M NIC. Representative images of the organoids and the frequency of organoids number at day 5 (3 wells/ group). C: control, N: NIC. Original magnification: 40 $\times$. Scale bar: 100 μ m. Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t-test). See also Figure S2.

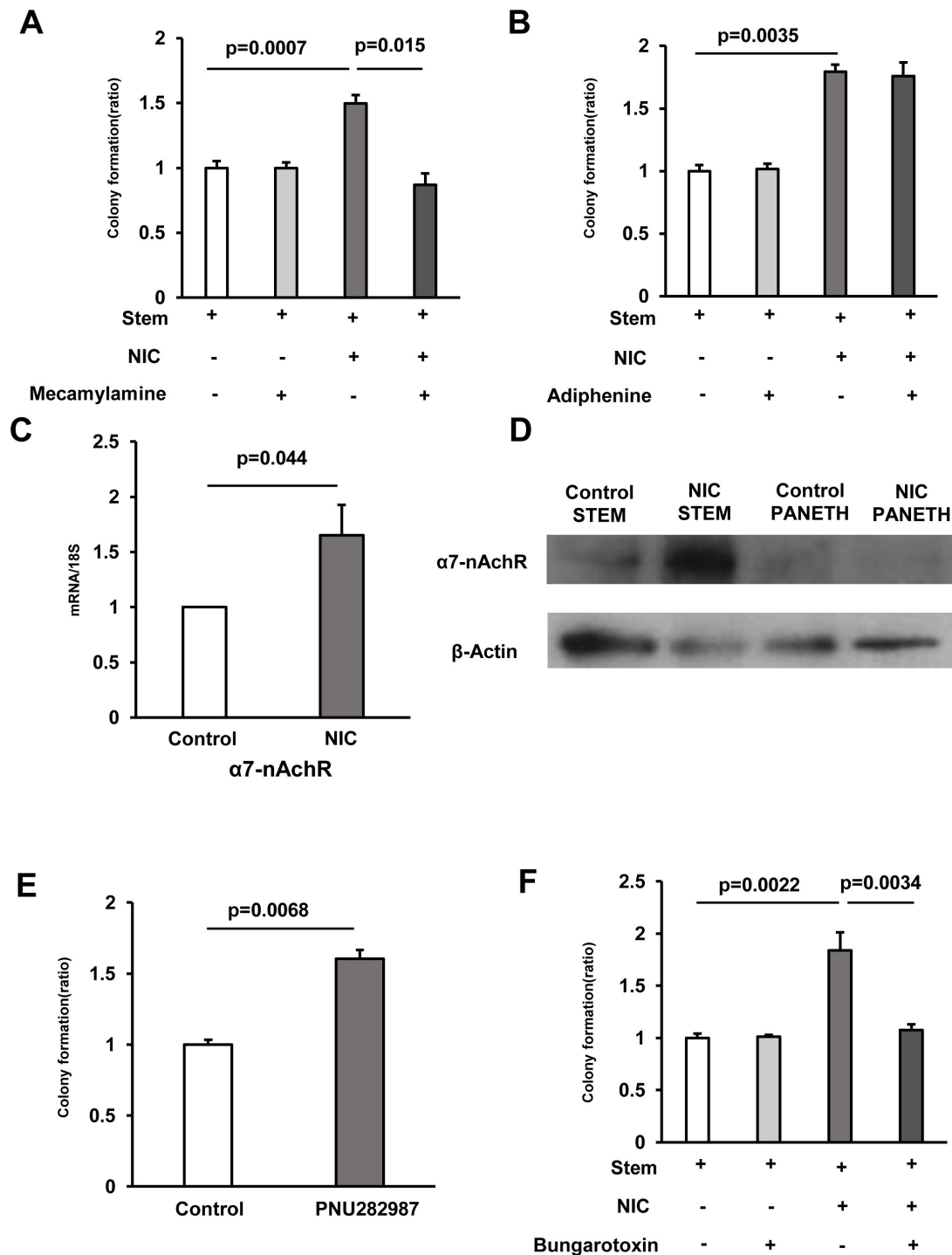


Figure 3.

The effect of NIC is mediated via the $\alpha 7$ subunits of $\alpha 7$ -nicotinic acetylcholine receptor (nAChR)

(A) Isolated ISCs were cultured in a medium with or without 1 μ M NIC and 10 μ M Mecamylamine (3 wells/group). (B) Isolated ISCs were cultured in a medium with or without 1 μ M NIC and 3 μ M Adiphenine hydrochloride (3 wells/group). (C) In ISCs isolated from control and NIC mice, nAChR mRNA levels were analyzed using quantitative real-time PCR (n = 5 per group). (D) ISC or Paneth cell lysates prepared from control and NIC mice were immunoblotted with antibodies against $\alpha 7$ -nAChR and β -actin. (E) Isolated ISCs were cultured in a medium supplemented with or without 10 μ M PNU 282987 (3 wells/group). (F) Isolated ISCs were cultured in a medium with or without 1 μ M NIC and 1 μ M Bungarotoxin (3 wells/group). Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t-test).

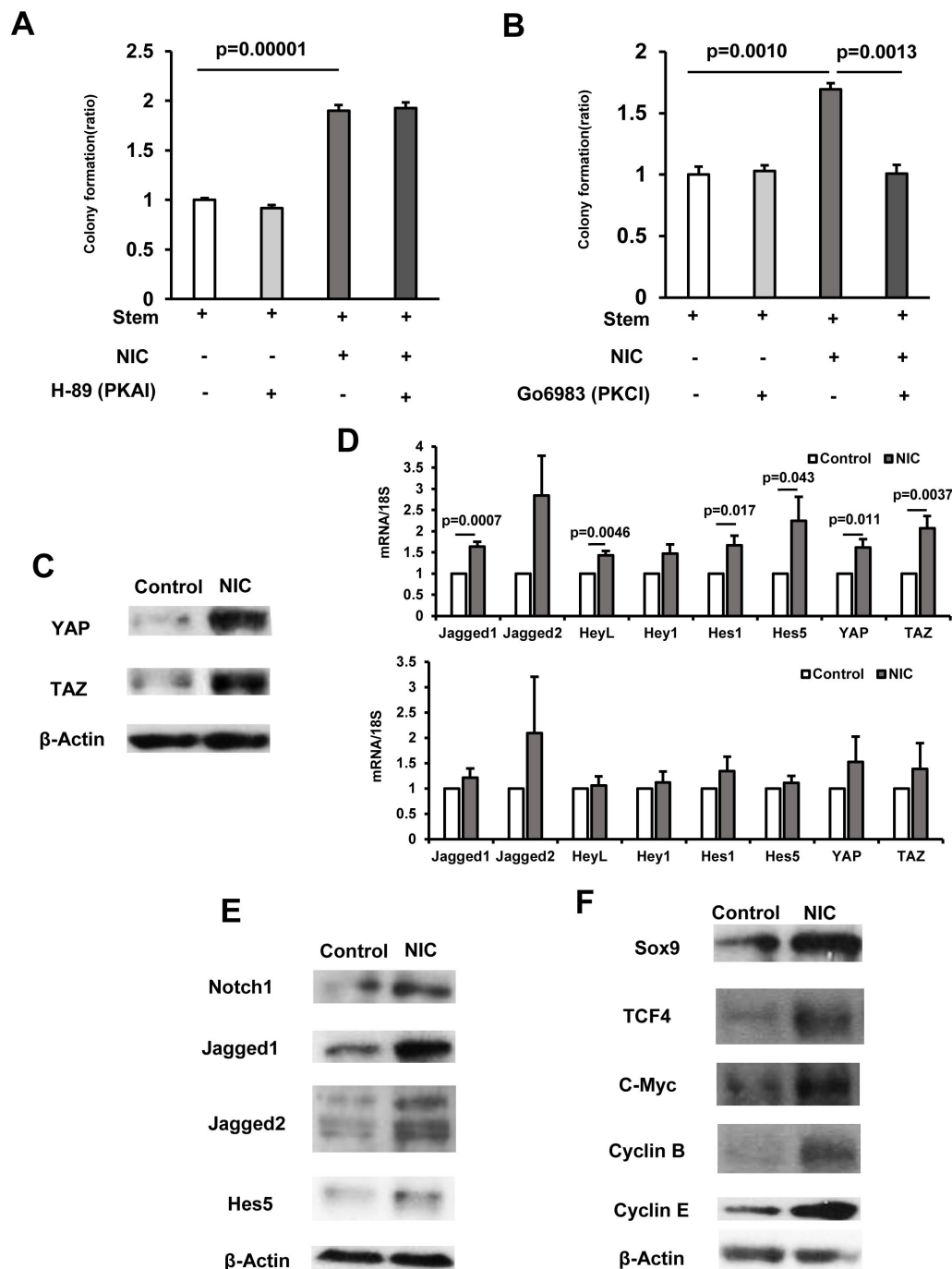


Figure 4.

NIC induces Hippo-YAP/TAZ and notch signaling in ISCs

(A) Isolated ISCs cultured using a medium supplemented with or without 1 μ M NIC combined with either (A) 1 μ M H89 (PKA inhibitor) or (B) 10 nM Go6983 (PKC inhibitor) (3 wells/group).. (C) Crypt lysates isolated from control and NIC-treated mice were immunoblotted using antibodies against YAP, TAZ, and β -actin. (D) In ISCs (n = 4-5 per group) or Paneth cells (n = 4 per group) isolated from control or NIC mice, mRNA levels of genes associated with Hippo-YAP/TAZ and Notch signaling were determined through quantitative real-time PCR. (E) Crypt lysates obtained from control and NIC-treated mice were immunoblotted using antibodies against Notch1, Jagged1, Jagged2, Hes5, and β -actin. (F) Crypt lysates obtained from control and NIC-treated mice were immunoblotted using antibodies against Sox9, TCF4, c-Myc, Cyclin B, Cyclin E, and β -actin. Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t-test). See also Figure S3.

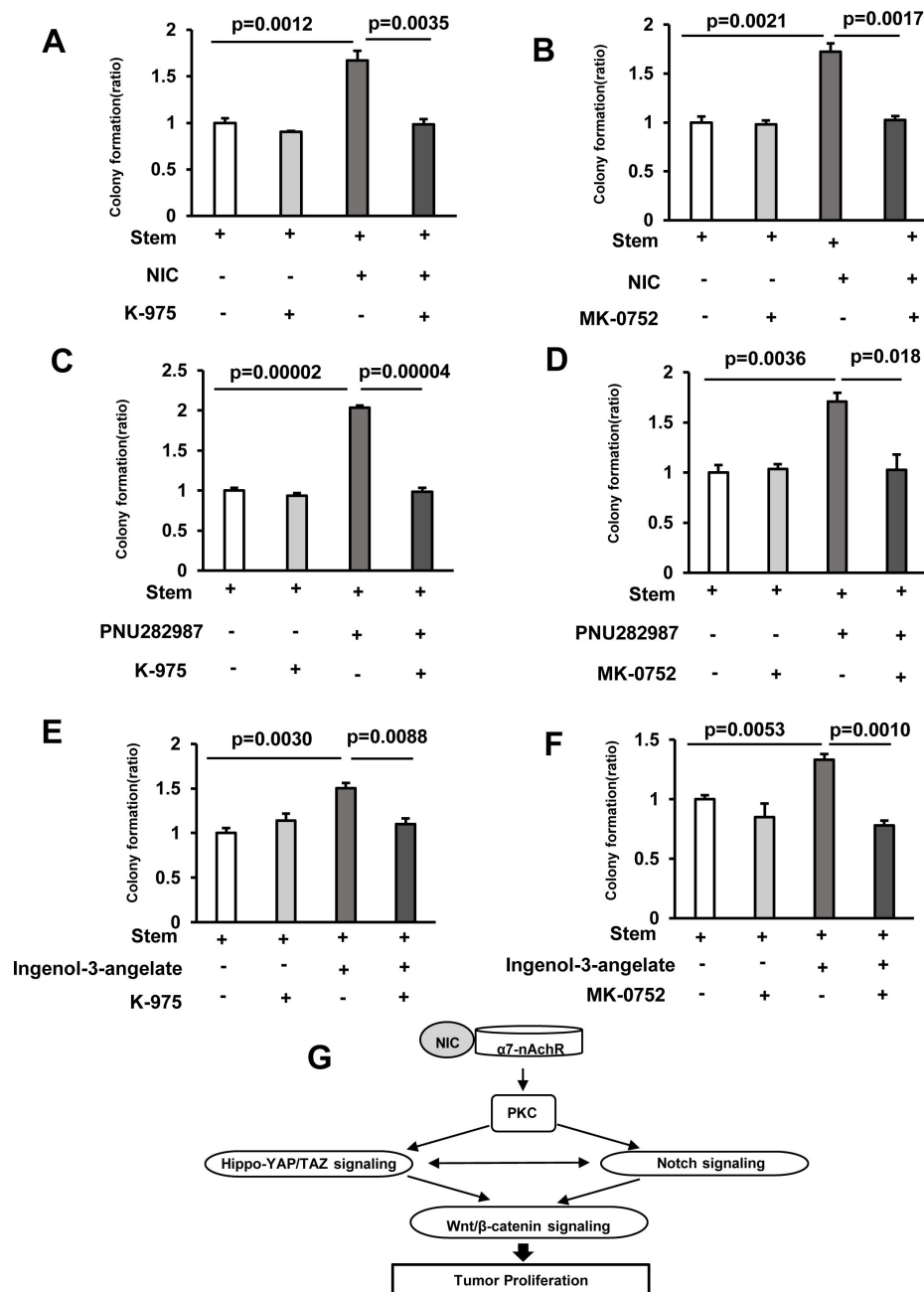


Figure 5.

Inactivation of Hippo-YAP/TAZ and Notch signaling suppresses NIC-induced Colony Formation in mice

(A) Isolated ISCs were cultured using a medium with or without 1 μ M Nicotine and 5 nM K-975 (3 wells/group). (B) Isolated ISCs were cultured using a medium with or without 1 μ M Nicotine and 1 μ M MK-0752 (3 wells/group). (C) Isolated ISCs were cultured using a medium with or without 10 μ M PNU282987 and 5 nM K-975 (3 wells/group). (D) Isolated ISCs were cultured using a medium with or without 10 μ M PNU282987 and 1 μ M MK-0752 (3 wells/group). (E) Isolated ISCs were cultured in a medium with or without 1 nM Ingenol-3-angelate and 5 nM K-975 (3 wells/group). (F) Isolated ISCs were cultured in a medium with or without 1 nM Ingenol-3-angelate and 1 μ M MK-0752 (3 wells/group). (G) Schematic model of NIC-associated signaling pathway in ISCs. The model traces a signaling cascade via $\alpha 7$ -nAChR, PKC, Hippo-YAP/TAZ and Notch signaling, and Wnt/ β -catenin signaling in ISCs. Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t-test).

Next, to investigate the possible downstream signaling of $\alpha 7$ -nAChR and PKC associated with NIC-induced renewal of ISCs, we explored PI3K/AKT signaling¹⁹, p38/ mitogen-activated protein kinase (MAPK) signaling²⁰, and mTORC1 signaling²¹, each of which plays a crucial role in the expansion of ISCs. Results indicate that NIC does not induce these cascades and these were not required for the effects of NIC on ISCs (Figures S3 A-D).

YAP/TAZ, the downstream effectors of the Hippo signaling pathway, and Notch receptor 1 (Notch1)/Delta-Like protein 1 (Dll1) are the main components of Notch signaling; previously, these factors are reported to be upregulated in NIC-treated organoids²². Both the Hippo-YAP/TAZ and Notch signaling pathways regulate intestinal homeostasis via the control of ISC function^{23,24} and Notch signaling is positively regulated by YAP/TAZ in the intestine²⁵. Hence, we examined Hippo-YAP/TAZ and Notch signaling. YAP1 and TAZ expression was significantly induced in the crypts of NIC-treated mice (**Figure 4C**). *YAP1* and *TAZ* also upregulated at mRNA level in ISCs from NIC mice (**Figure 4D**). The expression of genes, including *Jagged1*, *HeyL*, *Hes1*, *Hes5*, and *Dll1*, involved in Notch signaling, significantly increased in ISCs obtained from NIC-treated mice (**Figure 4D**). Notably, Hippo-YAP/TAZ and Notch signaling were not significantly activated in Paneth cells, indicating that NIC affects $\alpha 7$ -nAChR of ISCs rather than Paneth cells. Furthermore, activation of Notch signaling in crypts of NIC-treated mice was confirmed through immunoblotting assay (**Figure 4E**).

In the intestine, YAP activation enhances the expression of both β -catenin and transcriptional targets of Wnt signaling²⁶. Moreover, Notch signaling concomitantly regulates intestinal cell proliferation via Wnt signaling²⁷. Similarly, the expression of target proteins (Sox9, TCF4 and, C-myc) of the Wnt/ β -catenin pathway as well as cell-cycle regulatory proteins, such as cyclin B, and cyclin E, was up-regulated in crypts obtained from NIC-treated mice (**Figure 4F**).

Collectively, these results suggest that NIC induces a Hippo-YAP/TAZ and Notch signal pathway in ISCs via activation of $\alpha 7$ -nAChR and PKC, leading to the activation of Wnt signaling.

Inactivation of Hippo-YAP/TAZ and Notch signaling suppresses the NIC-induced colony formation

To further explore the role of the Hippo-YAP/TAZ and Notch signaling in NIC-induced ISC expansion, ISCs were cultured with NIC in the presence of either K-975, a specific inhibitor of transcriptional enhanced associate domain (TEAD), which binds to its transcriptional co-activators YAP or TAZ and forms a transcription complex²⁸, or γ -secretase inhibitor MK-0752 that inhibits the cleavage of Notch into its active signaling effector, Notch intracellular domain (NICD)²⁹. Treatment with K-975 and MK-0752 completely abolished the NIC-induced increased organoid formation (**Figures 5A** and **B**). Furthermore, K-975 or MK-0752 prevented the increase in the organoid formation in ISCs treated with PNU 298987 or Ingenol-3-angelate (**Figures 5C-F**), suggesting that YAP/Notch signaling acts downstream of $\alpha 7$ -nAChR or PKC leading to the response of ISC to NIC (**Figure 5G**).

DBZ treatment suppresses the expansion of ISCs by NIC in vivo

The significance of Notch signaling in the ISC expansion was validated in vivo. NIC-treated mice were subjected to daily IP injection of γ -secretase inhibitor DBZ (1 mg/kg body weight) for 2 weeks (**Figure 6A**). We confirmed that DBZ treatment significantly downregulated Hes5 protein expression in the crypts of NIC-treated mice (**Figure 6B**). Notably, DBZ suppressed the expression of YAP and TAZ in NIC-treated mice (**Figure 6B**). In the intestine, YAP/TAZ regulates Notch signaling²⁵ and Notch activation can activate YAP/TAZ³⁰. Consistent with previous reports, our results demonstrate that Notch inhibitor suppresses YAP/TAZ and Notch activities, indicating a positive feedback loop between Hippo-YAP/TAZ and Notch signaling in ISCs of NIC mice (**Figure 5G**).

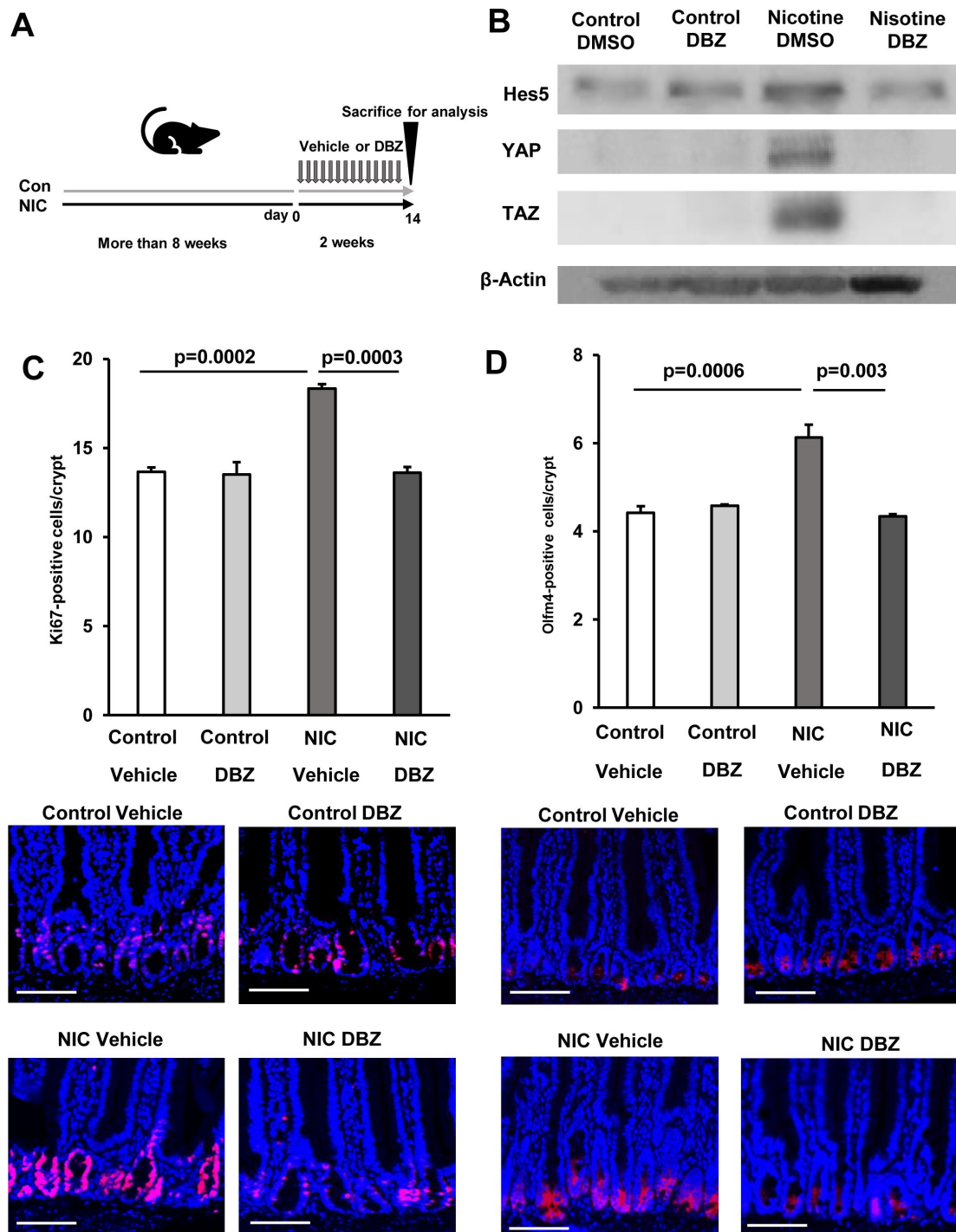


Figure 6.

Dibenzazepine (DBZ) treatment suppresses the NIC-induced expansion of ISCs in vivo

(A) Schematic representation of the treatment showing daily injection of DBZ (1 mg/kg body weight) for 2 weeks. (B) Immunoblotting analysis of crypt lysate isolated from DBZ- and vehicle-treated mice in control and NIC-treatment groups using Hes5, YAP, TAZ, and β -actin antibodies. (C and D) Immunostained Ki67-positive and (C) (Red, Ki67; Blue, DAPI) Olm4 positive cells (D) (Red, Olm4; blue, DAPI) and their quantification in the proximal jejunum of DBZ- or vehicle-treated mice (NIC-treated and untreated) ($n = 3$ per group). Original magnifications: 200 $\times$ (C and D). Scale bar: 100 μ m (C and D). Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t -test). See also Figure S4.

Ki67 labeling and immunostaining for the ISC marker *Olfm4* elucidated the effect of DBZ treatment on the frequency of ISCs in control and NIC-treated mice. DBZ treatment did not alter the population of ISCs in the control mice but significantly suppressed the expansion of Ki67+ and *Olfm4*+ cells in NIC-treated mice (**Figures 6C and D**). Moreover, DBZ suppressed the expansion of Ki67+ cells and CSCs in the colon of NIC-treated mice (Figures S4A and B). These outcomes demonstrate that the Hippo-YAP/TAZ and Notch signaling pathways are crucial for ISC expansion in NIC-treated mice analyzed in vivo.

DBZ inhibits intestinal tumor growth by NIC

As ISCs are the potential origin of tumors⁴, we hypothesized that NIC-induced ISC expansion can promote tumor formation in a tumor-initiating background, such as *Apc* loss. We crossed stem cell-specific *Lgr5-EGFP-IRES-creERT2* knock-in mice with *Apc^{flx/flx}* mice (*Lgr5Cre^{ER} Apc^{fl/fl}* mice); in the resulting mice, the transformation of *Lgr5*–GFP positive stem cells efficiently drives adenoma formation throughout the intestine after *Apc* loss induced by Cre activation using tamoxifen (**Figure 7A**).

To test whether NIC promotes tumor formation via ISC expansion, tumor formation was induced in NIC-treated *Lgr5Cre^{ER} Apc^{fl/fl}* (NIC-*Lgr5Cre^{ER} Apc^{fl/fl}*) mice, and entire intestines, isolated from them, were examined for polyps (**Figure 7A**). A marked increase in the abundance of polyps was detected throughout the intestine of NIC-treated *Lgr5Cre^{ER} Apc^{fl/fl}* mice; moreover, these polyps were significantly larger than that in the control mice (**Figure 7B**). Consistently, the area of β -catenin positive adenomatous lesions throughout the entire intestine significantly increased in NIC-*Lgr5Cre^{ER} Apc^{fl/fl}* mice (**Figure 7C**). These results indicated that NIC increased the overall polyp burden in the intestines of *Lgr5Cre^{ER} Apc^{fl/fl}* mice by increasing their size and number.

Finally, to validate whether DBZ can suppress NIC-induced intestinal adenomas, we treated NIC-*Lgr5Cre^{ER} Apc^{fl/fl}* mice with DBZ four weeks after the induction of *Apc* loss (**Figure 7D**). Notably, this treatment effectively reduced the abundance of polyps and β -catenin positive adenomatous lesions in NIC-*Lgr5Cre^{ER} Apc^{fl/fl}*, indicating the efficiency of DBZ for the prevention and treatment of NIC-induced intestinal tumors (**Figures 7E and F**).

Discussion

Our data propose a model in which NIC enhances the self-renewal of ISCs via activated Hippo-YAP/TAZ and Notch signaling (**Figure. 5G**). Our analyses revealed an increase in the number of ISCs in NIC-treated mice. In contrast to ISCs, Paneth cells showed no increase in cell numbers in NIC-treated mice. Similarly, we assessed the functional ability of ISCs and Paneth cells in terms of ex vivo organoid formation, which indicated a NIC-induced gain-of-function in ISCs but not in Paneth cells. Hence, we propose that the stem cells are not dependent on Paneth cells in functional assays. Furthermore, we traced the signaling pathway in ISCs and detected that ISCs respond to NIC via $\alpha 7$ -nAChR, PKC activation, and stimulation of Hippo-YAP/TAZ and Notch signaling with consequent Wnt/ β -catenin activation (**Figure. 5G**). Consistent with this model, DBZ treatment inhibited Hippo-YAP/TAZ and Notch signaling in mice and prevented NIC-induced ISC expansion and transformation through *Apc* loss.

Treatment of organoids with NIC has been reported to enhance cell growth and expression of marker genes of stem cells²². Moreover, mRNA analysis of NIC-treated organoids showed that the expression of *YAP1/TAZ* and *Notch1/Dll1* was upregulated after treatment with NIC³⁰. Although Hippo and Notch signaling pathways are putative targets for nAChR signaling, our model predicted that NIC activates the Hippo and Notch signaling pathway in Paneth cells rather than ISCs, because the $\alpha 2\beta 4$ -nAChR mainly expressed in Paneth cells. The mRNA analyses of sorted ISCs

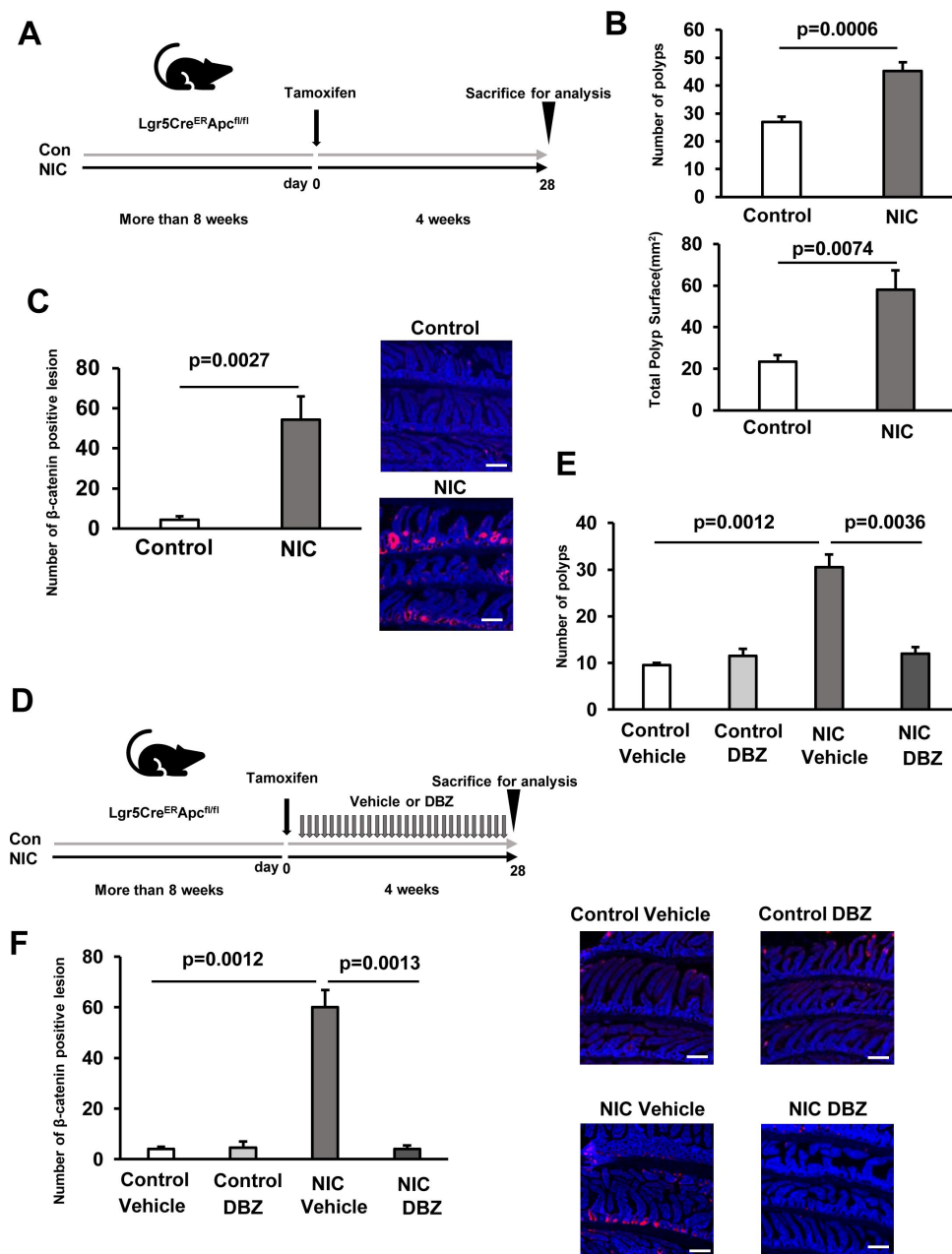


Figure 7.

DBZ inhibits intestinal tumor growth by NIC

(A) Schematic representation of *Apc^{fl/fl}*, *Lgr5-eGFP-IRES-CreERT2* (*Lgr5Cre^{ER}Apc^{fl/fl}*) tumor initiation. Mice were treated with control or NIC more than 8 weeks before a single Tamoxifen injection (30 mg/kg body weight), continued for 4 weeks before tissue collection. (B) Macroscopic quantification of the number and area of polyps in the entire intestine of control or NIC-treated *Lgr5Cre^{ER}Apc^{fl/fl}* mice. (C) Representative images (Red: β-catenin, Blue: DAPI) and the quantification of the number of β-catenin positive adenomatous lesions in the entire intestine of control or NIC-treated *Lgr5Cre^{ER}Apc^{fl/fl}* mice. (D) Schematic presentation of *Lgr5Cre^{ER}Apc^{fl/fl}* tumor initiation. Control or NIC-treated *Lgr5Cre^{ER}Apc^{fl/fl}* mice were subjected to a single Tamoxifen injection (30 mg/kg body weight), followed by daily DBZ or vehicle injections continued for 4 weeks before tissue collection. (E) Macroscopic quantification of the number of polyps in the entire intestine of DBZ or vehicle-treated *Lgr5Cre^{ER}Apc^{fl/fl}* mice (NIC-treated and untreated). (F) Representative images (Red: β-catenin, Blue: DAPI) and the quantification of the number of β-catenin positive adenomatous lesions in the entire intestine of DBZ or vehicle-treated *Lgr5Cre^{ER}Apc^{fl/fl}* mice (NIC-treated and untreated). Original magnifications: 200× (C, and F). Scale bar: 50 μm (C, and F). Values represent the mean ± SEM. Significant differences are denoted by p values (Student's t-test).

or Paneth cells and ex vivo functional assays were not reported previously³¹, our analysis validates that NIC affects ISC rather than Paneth cells via Hippo-YAP/TAZ and Notch signaling activated through nAChR7.

The crosstalk between Hippo, Notch, and Wnt signaling regulates mammalian intestinal homeostasis^{30,32,33}. Activated YAP/TAZ, which act downstream of Hippo signaling, translocate to the nucleus and induce the gene expression of Notch receptors and Notch ligands, and thus, Notch signaling and YAP1-induced ISC expansion are regulated in the intestine^{25,30}. Moreover, YAP/TAZ and Notch signaling congruently induces nuclear translocation of YAP/TAZ and NICD, regulating the expression of common target genes³⁰. YAP with TEADs enhances Jagged1-Notch1 signaling in breast cancer cells; Notch1 has been reported to promote YAP stability through inhibited β -TrCP-mediated degradation and formation of a YAP1-jagged-1/Notch1 positive feedback loop in breast cancer³⁴. Similarly, we propose a YAP/TAZ-Notch positive feedback loop in ISCs of NIC-treated mice. This model is consistent with DBZ-induced suppression of Hippo-YAP/TAZ and Notch signaling in ISCs obtained from NIC-treated mice. As NIC effectively expands the ISC population through the upregulated $\alpha 7$ -nAChR and the formation of the YAP/TAZ-Notch loop, we speculate these factors to be good therapeutic targets for treating NIC-induced colon cancer.

Our study demonstrated that NIC increased the expression of YAP/TAZ and Notch target genes, as well as the ISC population. Our ex vivo organoid assay revealed the role of Hippo-YAP/TAZ and Notch signaling in NIC-induced ISC expansion. However, the mechanism underlying NIC-activated Hippo-YAP/TAZ and Notch signaling remains unclear. NIC administration can induce the nuclear translocation and activation of YAP in Esophageal Squamous Cell Cancer³⁵. The nAChRs physically interact with YAP, leading to the upregulation and nuclear translocation of YAP1. This process is considered to be mediated by PKC activation because PKC-specific inhibitors block NIC-induced YAP activation³⁵. Moreover, PKC activity induces the translocation of ADAM-10, which is implicated in the cleavage of Notch receptors³⁶, to the cell membrane of glioblastoma³⁷. Hence, we propose the possibility of NIC-induced activation of YAP and ADAM via PKC, leading to Hippo-YAP/TAZ and Notch activation and ISC expansion.

The lifetime risk of various cancers is strongly correlated with frequency of stem cell divisions that maintain tissue homeostasis³⁸. However, the risk of cancer associated with stem cell divisions is heavily influenced by both extrinsic and intrinsic factors³⁹. Extrinsic factors, such as NIC, may increase the risk of cancer by promoting stem cell division. Our data indicated that NIC increased the abundance and proliferation of ISCs, which may partly explain the increased rate of intestinal tumors in smokers.

In conclusion, we demonstrated that NIC enhances the ISC population via $\alpha 7$ -nAChR as well as Hippo-YAP/TAZ and Notch signaling. These findings revealed the pivotal role of NIC as a stimulant of the cancer stem cell proliferation in intestinal tumors, and thus, explains colon cancer development in cigarette smokers. The development of drugs that can block the $\alpha 7$ -nAChR, Hippo-YAP/TAZ, and Notch signaling may provide a new therapeutic strategy for treating colon cancers.

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Author Contributions

R.I., M.I., and T.Y. designed the experiments. R.I., M.I., M.M., K.N., and S.K. performed the experiments. R.I., M.I., and T.Y. analyzed the data. R.I. and M.I. prepared the manuscript.

Declaration of interests

The authors declare no competing interests.

Material and Methods

Animals

Lgr5-EGFP-IRES-CreERT2 mice were purchased from Jackson Laboratories (Bar Harbor, ME). *Apc^{fllox}* mice were obtained from the National Cancer Institute. *Lgr5-EGFP-IRES-CreERT2* mice were crossed with *Apc^{fllox/fllox}* mice (*Lgr5Cre^{ER} Apc^{fl/fl}*). *Lgr5Cre^{ER} Apc^{fl/fl};tdTomato* mice were generated by crossing *Lgr5Cre^{ER} Apc^{fl/fl}* mice with *Rosa26-CAG-lsl-tdTomato* mice, provided by the National Cancer Institute (Bethesda, MD). All lines were maintained in the C57BL/6 background.

Mice were housed in a controlled environment maintaining 12 hr:12 hr light:dark cycle at 25 ± 1 °C. All animal procedures were performed following the guidelines of the Animal Care Committee of the University of Tokyo.

Nicotine treatment

Mice were administered with 200 µg/ml NIC (Nicotine hemisulfate salt, Sigma-Aldrich, Saint Louis, MO) through drinking water for more than 8 weeks. Water bottles were replaced every alternate day.

Tamoxifen treatment

Recombination by *Lgr5Cre^{ER}* in *Lgr5Cre^{ER} Apc^{fl/fl};tdTomato* mice was induced with a single dose of tamoxifen (30 mg kg⁻¹ body weight) suspended in corn oil, administered through the intraperitoneal injection. *Lgr5 Cre^{ER}*-induced mice were analyzed 4 weeks after induction.

DBZ treatment

The mice were intraperitoneally injected with DBZ (1 mg/kg body weight; Cayman Chemical, Ann Arbor, MI) or DMSO (in PBS) for 2 or 4 weeks.

Crypt Isolation and Culture

Crypts were isolated as described previously²⁰[\[20\]](#). For this purpose, the proximal half of the small intestine was isolated, opened longitudinally, and washed with cold PBS. After washing the intestine with cold PBS, it was cut into small (5 mm long) pieces with scissors and washed using cold PBS. Subsequently, the pieces were gently incubated in PBS supplemented with 5 mM EDTA for 40 minutes at 4°C and resuspended in ice-cold PBS without EDTA followed by vigorous shaking performed manually for crypt isolation. Isolated crypts were filtered using a 70 µm mesh (Corning), collected in crypt culture medium, quantified, and embedded in Matrigel (Corning, Inc. Corning, NY). In a 48-well plate, 300 isolated crypts were plated per well and cultured using crypt culture medium, Dulbecco's Modified Eagle Medium:Nutrient Mixture F-12 (DMEM/F12) (Thermo Fisher Scientific) supplemented with 1× N2 (Thermo Fisher Scientific), 1× B27 (Thermo Fisher Scientific), 1 mM N-acetyl-L-cysteine (Sigma-Aldrich), 50 ng/mL EGF (PeproTech, Inc., Cranbury, NJ), 100 ng/mL Noggin (PeproTech, Inc.), and R-spondin1 conditioned media (R&D Systems, Minneapolis, MN). The medium was changed in 2 days. Nicotine hemisulfate salt or cotinine ([-]-Cotinine, Sigma-Aldrich) was added to the crypt culture medium as required for the specific analyses.

Flow cytometry

ISC and Paneth cells were isolated from dissociated intestinal crypts using flow cytometry as described previously²⁰. The crypts were centrifuged for 5 min at $300 \times g$ at 4 °C and the pellets were gently resuspended in 800 μ l TrypLE Express (Thermo Fisher Scientific) supplemented with 200 μ l PBS followed by incubation in a water bath at 32 °C for 1.5 min; after incubation, the samples were placed on ice. Next, 12 mL of cold minimum essential medium (MEM; FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) was added, and the samples were gently triturated twice. After centrifugation for 5 min at $200 \times g$ at 4 °C, the pellets were resuspended and incubated for 15 min on ice in 0.5 ml MEM containing CD24-APC antibody (1:500, 101814, Biolegend, San Diego, CA). After centrifugation for 5 min at $200 \times g$ at 4 °C, the pellets were resuspended in MEM containing 1.5 μ M propidium iodide (PI) (Fujifilm Wako Pure Chemical Corporation). The samples were filtered through a 40 μ m mesh (Corning) and immediately sorted using a BD FACS Aria III Cell Sorter (BD Life Sciences, San Jose, CA). ISCs were isolated as Lgr5-EGFP^{hi}CD24^{low}PI⁻ and Paneth cells were isolated as CD24^{hi}SideScatter^{hi}Lgr5-EGFP⁻PI⁻.

Co-culture of Isolated ISCs and Paneth Cells

Isolated ISCs and Paneth cells were suspended separately in the medium containing $1 \times N2$, $1 \times B27$, and 10 μ M Y-27632 (FUJIFILM Wako Pure Chemical Corporation). ISCs (2,000 cells) and Paneth cells (2000 cells) were then seeded into 30 μ l Matrigel containing 1 μ M Jagged-1 (AnaSpec, San Jose, CA) and 10 μ M Y-27632. The matrigel drops with ISCs and Paneth cells were allowed to solidify on a 48-well plate for 15 minutes in a 37°C incubator. The culture medium containing $1 \times N2$, $1 \times B27$, 1 mM N-Acetyl-L-cysteine, 50 ng/ml EGF, 200 ng/ml Noggin, R-spondin1 conditioned media (R&D Systems, Minneapolis, MN), and CHIR99021 (FUJIFILM Wako Pure Chemical Corporation) was then added onto the drops of matrigel followed by incubation at 37°C incubator. Isolated ISCs and Paneth Cells were co-cultured without CHIR99021 (Figure S2).

Other supplements, including Nicotine hemisulfate salt, Mecamylamine (Cayman Chemical), Adiphenine hydrochloride (MedChemExpress), PNU282987 (MedChemExpress and Cayman Chemical), Bungarotoxin (MedChemExpress), H-89 (MedChemExpress), Go 6983 (MedChemExpress), K-975 (MedChemExpress), MK-0752 (MedChemExpress), Ingenol-3-angelate (Cayman Chemical), AKT Inhibitor VIII (MedChemExpress), SB203580 (Tokyo Chemical Industry CO., LTD, Tokyo, Japan), and Rapamycin (LKT Labs, Inc, St. Paul, MN), was added to the culture medium as needed in different experiments. The absolute values of the organoids are plotted on the y-axis in **Figure 2** and S2. The ratio to the control is presented on the y-axis in **Figure 3**, **4** and **5**. The number of colonies with lumens was quantitated on days 3 (Figure S2) and 5 (**Figure 2**, **3**, **4** and **5**) of the culture.

Colonic crypt isolation and culture

Colonic crypts were isolated from the large intestine as described previously with a few modifications²⁰. For this purpose, a 5–7 cm part of the proximal large intestine was isolated, opened longitudinally, and washed with cold PBS. After washing with cold PBS, the intestine was cut into small (5 mm long) pieces with scissors, placed in cold 5 mM EDTA-PBS, and gently rocked for 15 min at 4 °C. After removal of EDTA-PBS, pieces of the intestine were incubated in DMEM/F12 containing 500 U/ml Collagenase Type IV (Worthington Biochemical Corporation, Lakewood, NJ) for 30 min at 37 °C using a water bath. Subsequently, pieces of the intestine were pipetted up and down in cold PBS until most of the crypts were released. The crypt fraction was obtained by passing the suspension through a 70 μ m cell strainer followed by centrifuging at $250 \times g$ for 5 min. Isolated crypts were collected in a crypt culture medium, counted, and embedded in Matrigel. A total of 1,000 crypts were plated per well of a 48-well plate and cultured using a colonic crypt culture medium (DMEM/F12 supplemented by $1 \times N2$, $1 \times B27$, 1 mM N-Acetyl-L-cysteine, 50 ng/ml EGF, 100 ng/ml Noggin, 500 ng/ml R-spondin, 2 mM Valproic acid [FUJIFILM Wako Pure Chemical Corporation], and 10 μ M CHIR99021). The medium was replaced in 2 days.

Nicotine hemisulphate salt was added to the crypt culture medium as needed for experiments. The number of spherical organoids formed from the crypts was measured five days after plating them.

Investigation of intestinal polyps

The entire intestine of *Lgr5Cre^{ER} Apc^{fl/fl};tdTomato* mice, in which adenomatous polyps were labeled with tdTomato using tamoxifen injection, was promptly excised and cut with the mucosal side up, washed with ice-cold PBS, pinned open on a dissection tray, and fixed using 10% neutral buffered formalin (FUJIFILM Wako Pure Chemical Corporation). The fixed intestine was then photographed, polyps were counted, their diameters were measured using a caliper, and the surface of the polyps was estimated. For the histopathological assay, the entire intestine was fixed on a dry board and gently rolled to form a Swiss roll, which was further used in the immunohistological test.

Immunohistochemistry

Pieces of the proximal jejunum (1–4 cm from the pylorus), proximal colon (1–2 cm from the cecum), and the entire rolled intestine were fixed overnight using 10% neutral-buffered formalin, embedded in paraffin, and sections were prepared. The sections were deparaffinized and subjected to heat-induced antigen retrieval using 10 mM sodium citrate buffer (pH 6.0) in a microwave. Slides were then incubated overnight with the following primary antibodies at 4°C: rabbit anti-Ki67 (1/200; 12202; Cell Signaling Technology, Danvers, MA), rabbit anti-Olfm4 (1/400; 39141, Cell Signaling Technology), mouse anti-GFP (1/50; sc-9996, Santa Cruz Biotechnology, Dallas, TX), rabbit anti-Lysozyme (1/50; PA5-16668; Thermo Fisher Scientific), mouse anti-chromogranin A (ChgA; 1/50; sc-393941, Santa Cruz Biotechnology), and rabbit anti- β -catenin (1/200; 9562; Cell Signaling). For samples incubated with mouse primary antibodies, Alexa Fluor-conjugated secondary antibody (1/200; ab150113; Abcam, Cambridge, UK) were used, whereas, a TSA Plus Cyanine 3 System (Akoya Biosciences, Marlborough, MA,) was used for rabbit primary antibody treated sets following instructions provided by the manufacturer. Finally, the slides were mounted using VECTASHIELD Mounting Medium containing DAPI (Abcam, Cambridge, MA). Images were recorded using an all-in-one fluorescence Microscope BZ-X710 (KEYENCE, Osaka, Japan).

Quantification

The lengths of the crypt (from the bottom of the crypt to the crypt-villus junction) and villus (from the crypt-villus junction to the tip of the villus) were measured using ImageJ software. The quantification was repeated for > 30 crypt/villus units per mouse. Immunostained cells were quantified using randomly selected 50 intact, well-oriented crypts per mouse.

Immunoblotting

The following antibodies, obtained from different sources, were used for immunoblotting: mouse anti- β -actin (sc-47778; Santa Cruz), mouse anti-YAP (Santa Cruz sc-101199), mouse anti-TAZ (Santa Cruz sc-293183), mouse anti- α 7-AchR (Santa Cruz sc-58607), mouse anti-Notch1 (Santa Cruz sc-376403), mouse anti-Jagged1 (Santa Cruz sc-390177), mouse anti-Jagged2 (Santa Cruz sc-515725), mouse anti-Hes5 (Santa Cruz sc-293445), mouse anti-Sox9 (Santa Cruz sc-166505), mouse anti-ITF2(TCF4) (Santa Cruz sc-393407), mouse anti-c-Myc (Santa Cruz sc-40), mouse anti-Cyclin B (Santa Cruz sc-245), mouse anti-Cyclin E (Santa Cruz sc-247), mouse anti-p38 (Santa Cruz sc-81621), mouse anti-phospho-p38 (Santa Cruz sc-166182), rabbit anti-S6 (Cell Signaling 2217), and rabbit anti-phospho-S6 Ser235/236 (Cell Signaling 4858). Crypts or sorted cells were lysed using RIPA buffer supplemented with protease and phosphatase inhibitors (Santa Cruz Biotechnology). Subsequently, the protein extracts were denatured by adding SDS loading buffer, boiled, and resolved using SDS-PAGE; immunoblotting was performed using primary antibodies listed above. Mouse IgG (NA931; Cytiva, Tokyo, Japan) and rabbit IgG (NA934; Cytiva) antibodies were used as

HRP-conjugated secondary antibodies. The band signals were enhanced using Can Get Signal® Immunoreaction Enhancer Solution (TOYOBO CO., LTD., OSAKA, Japan) following the instructions provided by the manufacturer.

RNA Analysis by Real-Time qPCR

RNA was extracted from crypts or sorted cells using the RNeasy Plus Mini Kit (QIAGEN, Hilden, Germany). Reverse transcription was performed using ReverTra Ace® qPCR RT Master Mix (TOYOBO CO., LTD.). qRT-PCR was performed on a QuantStudio 5 Real-Time PCR System (Applied Biosystems, Waltham, MA) using KAPA SYBR FAST qPCR Master Mix (Kapa Biosystems, Inc., Wilmington, MA). Sequences of the primers used for the Real-

Time qPCR are listed below. 18S rRNA was considered an endogenous reference gene.

α 7-AchR-F: GGTCATTTGCCCACTCTG;

α 7-AchR-R: GACAGCCTATCGGGTGAG;

Jagged1-F: CCTCGGGTCAGTTTGAGCTG;

Jagged1-R: CCTTGAGGCACACTTTGAAGTA;

Jagged2-F: ACGAGGAGGATGAAGAGCTGA;

Jagged2-R: GGGGTCTTTGGTGAACCTGTG;

HeyL-F: GTCTTGCAGATGACCGTGGA;

HeyL-R: CTCGGGCATCAAAGAACCCT;

Hey1-F: CACCTGAAAATGCTGCACAC;

Hey1-R: ATGCTCAGATAACGGGCAAC;

Hes1-F: ACACCGGACAAACCAAAGAC;

Hes1-R: AATGCCGGGAGCTATCTTTC;

Hes5-F: GCAGCATAGAGCAGCTGAAG;

Hes5-R: AGGCTTTGCTGTGTTTCAGG;

YAP-F: CGCTCTTCAATGCCGTCATG;

YAP-R: AGTCATGGCTTGCTCCCATC;

TAZ-F: TCTGTCATGAACCCCAAGCC;

TAZ-R: GGTGGTTCTGTGGAAGTACAGG;

18S-F: GTAACCCGTTGAACCCATT;

18S-R: CCATCCAATCGGTAGTAGCG.

Statistical analysis

Quantitative results are presented as mean $\pm$ standard error of the mean. Two groups were compared using unpaired two-tailed Student's t-test, assuming data normality. P was set at $p < 0.05$, significant.

Supplemental figure legends

Figure S1. NIC suppresses the differentiation of ISCs.

(A) Images of the H&E-stained crypt and villus and quantification of their length after or without NIC treatment (3-4 mice per group). (B) The quantification of the number of enterocytes per villus in NIC-treated and untreated samples (3 mice per group). (C) Chromogranin A staining image (Green: Chromogranin A, Blue: DAPI) and the quantification of Chromogranin A-positive cells per villus-crypt unit in NIC-treated and untreated samples (3 mice per group). Original magnifications: 100 $\times$ (A), 200 $\times$ (C). Scale bar: 100 μ m (A and C). Values represent the mean $\pm$ standard error of the mean (SEM). Significant differences are denoted by p values (Student's t-test). See also [Figure 1](#).

Figure S2. NIC induces the formation of intestinal organoids from ISCs

ISCs and Paneth cells were isolated from the small intestine of *Lgr5-EGFP^JIRES CreERT2* mice (NIC-treated and untreated); 2×10^3 cells were co-cultured using medium without 10 μ M CHIR99021. Representative images of the formed organoids and quantification of the organoid number on day 3 are shown (three wells per group). Values represent the mean $\pm$ SEM. Significant differences were denoted by p-values (Student's t-test). See also [Figure 2](#).

Figure S3. PI3K/AKT, mTORC1, and p38/ MAPK signaling cascades do not mediate the effect of NIC

(A) Immunoblotting analyses of p38, p-p38, p-S6, or S6 in ISCs isolated from mice treated with vehicle or NIC. (B) Isolated ISCs were cultured in a medium with or without 1 μ M NIC and 1 μ M AKT inhibitor VIII (3 wells/group). (C) Isolated ISCs were cultured in a medium with or without 1 μ M Nicotine and 5 μ M SB 203580 (3 wells/group). (D) Isolated ISCs were cultured in a medium with or without 1 μ M NIC and 1 μ M Rapamycin (3 wells/group). Significant differences are denoted by p values (Student's t-test). See also [Figure 4](#).

Figure S4. DBZ treatment suppresses the NIC-induced expansion of CSCs in vivo

(A and B) Immuno-stained Ki67-positive cells (A) (Red, Ki67; Blue, DAPI) and Lgr5-GFP positive cells (B) (Red, Olfm4; blue, DAPI) and quantification of their abundance in the colon of DBZ or vehicle-treated *Lgr5-EGFP-IRES-CreERT2* mice (NIC-treated and untreated) ($n = 3$ per group). Original magnifications: 200 $\times$. Scale bar: 100 μ m. Values represent the mean $\pm$ SEM. Significant differences are denoted by p values (Student's t-test). See also [Figure 6](#).

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Editors

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Reviewer #1 (Public Review):

Summary:

In their manuscript, "Nicotine enhances the stemness and tumorigenicity in intestinal stem cells via Hippo-YAP/TAZ and Notch signal pathway", authors Isotani et al claimed that this study identifies a NIC-triggered pathway regulating the stemness and tumorigenicity of ISCs and suggest the use of DBZ as a potential therapeutic strategy for treating intestinal tumors. However, the presented data do not support the primary claims.

Weaknesses:

My main reservation is that the quality of the results presented in the manuscript may not fully substantiate their conclusions. For instance, in Figure 2 A and B, it is challenging to discern a healthy organoid. This is significant, as the entirety of Figure 2 and several panels in Figures 3 - 5 are based on these organoid assays. Additionally, there seems to be a discrepancy in the quality of results from the western blot, as the lanes of actin do not align with other proteins (Figure 6B).

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Reviewer #2 (Public Review):

Summary:

The manuscript by Isotani et al characterizes the hyperproliferation of intestinal stem cells (ISCs) induced by nicotine treatment in vivo. Employing a range of small molecule inhibitors, the authors systematically investigated potential receptors and downstream pathways associated with nicotine-induced phenotypes through in vitro organoid experiments. Notably, the study specifically highlights a signaling cascade involving $\alpha 7$ -nAChR/PKC/YAP/TAZ/Notch as a key driver of nicotine-induced stem cell hyperproliferation. Utilizing a Lgr5CreER Apcfl/fl mouse model, the authors extend their findings to propose a potential role of nicotine in stem cell tumorigenesis. The study posits that Notch signaling is essential during this process.

Strengths and Weaknesses:

One noteworthy research highlight in this study is the indication, as shown in Figure 2 and S2, that the trophic effect of nicotine on ISC expansion is independent of Paneth cells. In the Discussion section, the authors propose that this independence may be attributed to distinct expression patterns of nAChRs in different cell types. To further substantiate these findings, it is suggested that the authors perform tissue staining of various nAChRs in the small intestine and colon. This additional analysis would provide more conclusive evidence regarding how stem cells uniquely respond to nicotine. It is also recommended to present the staining of $\alpha 7$ -nAChR from different intestinal regions. This will provide insights into the primary target sites of nicotine in the gut tract. Additionally, it is recommended that the authors consider rephrasing the conclusion in this section (lines 123-124). The current statement implies that nicotine does not affect Paneth cells, which may be inaccurate based on the suggestion in line 275 that nicotine might influence Paneth cells through $\alpha 2\beta 4$ -nAChR. Providing a more nuanced conclusion would better reflect the complexity of nicotine's potential impact on Paneth cells.

As shown in the same result section, the effect of nicotine on ISC organoid formation appears to be independent of CHIR99021, a Wnt activator. Despite this, the authors suggest a potential involvement of Wnt/ β -catenin activation downstream of nicotine in Figure 4F. In the Lgr5CreER Apcfl/fl mouse model, it is known that APC loss results in a constitutive stabilization of β -catenin, thus the hyperproliferation of ISCs by nicotine treatment in this mouse model is likely beyond Wnt activation. Therefore, it is recommended that the authors reconsider the inclusion of Wnt/ β -catenin as a crucial signaling pathway downstream of nicotine, given the experimental evidence provided in this study.

In Figure 4, the authors investigate ISC organoid formation with a pan-PKC inhibitor, revealing that PKC inhibition blocks nicotine-induced ISC expansion. It's noteworthy that PKC inhibitors have historically been used successfully to isolate and maintain stem cells by promoting self-renewal. Therefore, it is surprising to observe no effect or reversal effect on ISCs in this context. A previous study demonstrated that the loss of PKC ζ leads to increased ISC activity both in vivo and in vitro (DOI: 10.1016/j.celrep.2015.01.007). Additionally, to

strengthen this aspect of the study, it would be beneficial for the authors to present more evidence, possibly using different PKC inhibitors, to reproduce the observed results with Gö 6983. This could help address potential concerns or discrepancies and contribute to a more comprehensive understanding of the role of PKC in nicotine-induced ISC expansion.

An additional avenue that could enhance the clinical relevance of the study is the exploration of human datasets. Specifically, leveraging scRNA-seq datasets of the human intestinal epithelium (DOI: 10.1038/s41586-021-03852-1) could provide valuable insights. Analyzing the expression patterns of nAChRs across diverse regions and cell types in the human intestine may offer a potential clinical implication.

In summary, the results generally support the authors' conclusions that nicotine directly influences ISC growth, potentially contributing to tumorigenesis. The identification of the $\alpha 7$ -nAChR/PKC/YAP/TAZ/Notch pathway adds significant mechanistic insight. However, certain aspects of the experimental evidence, such as the receptor expression pattern, PKC inhibition response, and the involvement of Wnt/ β -catenin activation, may require further clarification and exploration, especially considering previous literature suggesting potential discrepancies.

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