研究成果の刊行に関する一覧表　平成２５年度

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Yugawa T, Nishino K, Ohno S, Nakahara T, Fujita M, Goshima N, Umezawa A, Kiyono T.	Noncanonical NOTCH signaling limits self-renewal of human epithelial and induced pluripotent stem cells through ROCK activation.	Mol Cell Biol	33	4434-47	2013
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IV　研究成果の刊行物・別冊

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Noncanonical NOTCH Signaling Limits Self-Renewal of Human Epithelial and Induced Pluripotent Stem Cells through ROCK Activation

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NOTCH plays essential roles in cell fate specification during embryonic development and in adult tissue maintenance. In keratinocytes, it is a key inducer of differentiation. ROCK, an effector of the small GTPase Rho, is also implicated in keratinocyte differentiation, and its inhibition efficiently potentiates immortalization of human keratinocytes and greatly improves survival of dissociated human pluripotent stem cells. However, the molecular basis for ROCK activation is not fully established in these contexts. Here we provide evidence that intracellular forms of NOTCH1 trigger the immediate activation of ROCK1 independent of its transcriptional activity, promoting differentiation and resulting in decreased clonogenicity of normal human keratinocytes. Knockdown of NOTCH1 abrogated ROCK1 activation and conferred sustained clonogenicity upon differentiation stimuli. Treatment with a ROCK inhibitor, Y-27632, or ROCK1 silencing substantially rescued the growth defect induced by activated NOTCH1. Furthermore, we revealed that impaired self-renewal of human induced pluripotent stem cells upon dissociation is, at least in part, attributable to NOTCH-dependent ROCK activation. Thus, the present study unveils a novel NOTCH-ROCK pathway critical for cellular differentiation and loss of self-renewal capacity in a subset of immature cells.

Notch is an evolutionarily conserved cell surface receptor that plays essential roles in cell fate decisions as well as maintenance of self-renewing tissue organization (1–3). Notch proteins are expressed in most adult tissues, and the biological consequence of Notch activation is critically dependent on the cell type and the cellular context (4–7). In keratinocytes, Notch1 has been shown to be a key inducer of differentiation (8–11). Keratinocyte-specific conditional deletion of the *Notch1* gene results in epidermal hyperproliferation and tumor formation in mice, thus indicating a tumor-suppressive role of Notch1 in mammalian postnatal epidermis (12). The Notch receptor is generally activated by interaction with its ligands displayed on the neighboring cell surface. Cell-cell contact is a strong inducer of keratinocyte differentiation in culture, where Notch1 acts as a critical determinant in the transition from proliferation to differentiation (13, 14). Due to *cis* inhibition of Notch by its ligand when these are expressed on the same cell surface (15, 16), the relative increase in expression levels of the Notch receptor over its ligand is also shown to be a pivotal cue to activate Notch signaling and generate distinct cell fates among neighboring cells (17). We previously demonstrated that p53 and TAp63 transactivate *Notch1* gene expression and induce keratinocyte differentiation, while ΔNp63 is a transcriptional repressor of the *Notch1* gene and inhibits keratinocyte differentiation (14, 18). p63, especially ΔNp63α, is a master regulator of development and maintenance of stratified epithelia (19, 20). ΔNp63α expresses predominantly in the basal proliferating compartment, where Notch1 signaling is suppressed (21). In suprabasal layers, downregulation of ΔNp63α by miR-203 or another factor(s) (22–24) evokes activation of Notch1 signaling, which in turn further downmodulates ΔNp63α expression so as to induce differentiation (9, 21). The Notch1 precursor (~300 kDa) is processed by furin protease in the Golgi apparatus and transported to the cell surface as a mature heterodimeric complex (~120/~180 kDa) that is held by Ca^{2+}-dependent noncovalent interaction (25). Ligand binding dissociates the Notch1 extracellular domain (~180 kDa) by *trans* endocytosis. The residual transmembrane domain (~120 kDa) is sequentially cleaved by tumor necrosis factor alpha-converting enzyme/metalloprotease (TACE) and γ-secretase, resulting in release of the Notch1 intracellular domain (~110 kDa) into the cytosol (3). EDTA is reported to activate Notch signaling through disruption of the heterodimeric complex of Notch1 (25) and thus used as a tool to study Notch1 signaling (26–28). In canonical Notch1 signaling, the liberated Notch1 intracellular domain (~110 kDa) translocates into the nucleus to activate Notch-responsive genes, such as Hes1, by making a complex with CSL family members {CBF1 and RBP-Jκ in mammals, Suppressor of hairless [Su(H)] in *Drosophila*, and Lag1 in *Caenorhabditis elegans*} and its transcriptional coactivator Mastermind (MAM). Besides this canonical pathway, accumulating evidence suggests noncanonical cytoplasmic Notch functions (29–31).

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Rho-associated coiled-coil protein kinases (ROCKs) (also known as Rho kinases [ROKs]) are effectors of the small GTPase Rho and belong to a family of protein serine/threonine kinases (32–34). Activated ROCK proteins regulate actomyosin cytoskeletal dynamics and contractility through phosphorylation of multiple downstream targets, such as myosin phosphatase (MYPT1), to drive cell motility. In keratinocytes, ROCK proteins play a role in differentiation (35, 36), and their selective inhibitor, Y-27632, completely inhibits differentiation as well as stratification of keratinocytes in organotypic raft culture (37). Y-27632 also enables efficient immortalization of not only human primary keratinocytes but also several other primary human epithelial cells in the presence of fibroblast feeders (37, 38), although molecular details supporting immortalization remain elusive.

In addition, Y-27632 has been shown to increase the survival rate and cloning efficiency of human embryonic stem cells (hESCs) dissociated with EDTA (39) through blocking the Rho-ROCK-myosin light chain signaling cascade (40, 41). However, the precise mechanisms by which EDTA activates ROCK have not been elucidated (41, 42).

These results let us hypothesize a possible link between NOTCH1 and ROCK activation. Here we show a novel function of NOTCH1 as a critical upstream regulator of ROCK1 and its relevance to loss of self-renewal capacity in human keratinocytes as well as human induced pluripotent stem (hiPS) cells.

MATERIALS AND METHODS

Cell culture. Normal human cervical keratinocytes (HCKs) were obtained with written consent from a patient who underwent abdominal surgery for a gynecological disease other than cervical cancer and were retrovirally transduced with the catalytic subunit of human telomerase reverse transcriptase (hTERT) for immortalization (HCK1Ts) (14). HCK1Ts were cultured in serum-free keratinocyte-SF medium supplemented with 5 ng/ml epidermal growth factor (EGF) and 50 μg/ml of bovine pituitary extract (Invitrogen, Life Technologies, Saint Aubin, France). Primary human dermal keratinocytes (HDKs) were purchased from Cell Applications Inc. (San Diego, CA). Primary human foreskin keratinocytes (HFKs) were obtained from Denise A. Galloway (Fred Hutchinson Cancer Research Center, Seattle, WA). HDKs and HFKs were cultured in serum-free keratinocyte-SF medium supplemented with 5 ng/ml EGF and 50 μg/ml of bovine pituitary extract (Invitrogen, Life Technologies). Human endometrium cells were collected by scraping tissues from surgical specimens, with signed informed consent and with ethical approval of the Institutional Review Board of the National Institute for Child Health and Development, Japan. All experiments involving human cells and tissues were performed in line with Tenets of the Declaration of Helsinki. Human iPS cell lines, MRC-hiPSCs and UtE-hiPSCs, were established from MRC-5 fetal lung fibroblasts (43) and UtE1104 endometrium-derived cells (44), respectively, via procedures described by Takahashi et al. (45) with slight modification (46, 47). Human iPS cells were maintained in iPSellon medium (Cardio Incorporated, Osaka, Japan) supplemented with 10 ng/ml recombinant human basic fibroblast growth factor (bFGF) (Wako Pure Chemical Industries, Ltd., Osaka, Japan) in the presence of irradiated mouse embryonic fibroblast (MEF) feeders.

Retroviral vector construction and transduction. Retroviral vector plasmids were constructed using the Gateway system according to the manufacturer's instructions (Invitrogen). Segments of the intracellular domain of human NOTCH1 (ICN1), a truncated form of MAML1 corresponding to amino acids 13 to 74 fused to N-terminal hemagglutinin (HA) tag (MAML61-3HA), and c-MYC were cloned and recombined into retroviral expression vectors to generate pCLXSN-ICN1 (14), pCLXSN-MAML61-3HA (48, 49), and pCMSCVpuro-c-MYC (50). Human ROCK1, ROCK1ΔC241, ROCK1-D1113A, ROCK1-K105A, ICN1-ERT, ICN2-ERT2, RhoA, and enhanced green fluorescent protein (EGFP) were cloned into a lentiviral vector, CSII-TRE-Tight-RfA, in which the elongation factor promoter in CSII-EF-RfA (a gift from Hiroyuki Miyoshi, RIKEN, BioResource Center) was replaced with the tetracycline-responsive promoter from pTRE-Tight (Clontech, Mountain View, CA). The Notch1 short hairpin RNA (shRNA) vectors were described previously (14, 18). To generate ROCK1- or ROCK2-specific shRNA expression vectors pCL-SI-MSCVpuro-ROCK1Ri-1,-2,-3 and pCL-SI-MSCVpuro-ROCK2Ri-1,-2,-3, the following sequences were chosen as the targeted sites: 5′-GTACTTGTATGAAGATGA-3′ (51), 5′-GGTATATGCTATGAAGCTT-3′, and 5′-GCGAAATGGTGTAGAAGAA-3′ for ROCK1 and 5′-GAAACTAATAGGACACTAAC-3′ (52), 5′-GGTTTATGCTATGAAGCTT-3′, and 5′-GGATAAACATGGACATCTA-3′ for ROCK2. The retroviral vector and packaging constructs pCL-GagPol and pEF6/env (10A1) or the lentiviral vector and packaging constructs pCAG-HIVgp and pCMV-VSV-G-RSV-Rev were cotransfected into 293FT cells (Invitrogen) using TransIT-293 (Mirus Co., Madison, WI) according to the manufacturer's instructions, and the culture fluid was harvested at 60 to 72 h posttransfection. Titers of the recombinant viruses were determined by drug resistance with HeLa cells or a real-time PCR method (TaKaRa, Otsu, Japan) to detect the viral RNA genome, yielding titers equivalent to greater than 1×10^6 CFU/ml. Following addition of the recombinant viral fluid to cells in the presence of 4 μg/ml Polybrene, infected cells were selected in the presence of 0.5 μg/ml puromycin or 50 μg/ml G418, and promptly after drug selection, pooled cell populations were used for most subsequent experiments.

Tet-On keratinocytes. HCK1T cells were stably transduced with Tet-On ADV and tTS expression vectors, encoding the rtTA-Advanced transactivator and transcriptional silencer, respectively (Clontech). The resultant HCK1T Tet-On cells were then introduced with CSII-TRE-Tight-ROCK1, ROCK1ΔC241, ROCK1-D1113A, ROCK1-K105A, ICN1-ERT, ICN2-ERT2, RhoA (constitutive active and dominant negative forms), and EGFP by retroviral gene transfer. Induction of these transgenes was routinely achieved by treatment with 1 μg/ml doxycycline (DOX) for 72 h.

Inhibitors. The following pharmacological inhibitors were used: cycloheximide (CHX) (239764; Calbiochem, Darmstadt, Germany), z-VAD-fmk (caspase inhibitor IV) (219007; Calbiochem), γ-secretase inhibitor IX (DAPT) (565784; Calbiochem), Y-27632 (08945-84; Nacalai Tesque, Kyoto, Japan), C3 ADP-ribosyltransferase (Rho inhibitor) (CT04; Cytoskeleton, Inc., Denver, CO), and blebbistatin (sc-203532; Santa Cruz Biotechnology, Santa Cruz, CA). Cells were pretreated with inhibitors for 2.5 h. For DAPT, in addition to pretreatment, cells were incubated with this inhibitor during and after exposure to EDTA or differentiation stimuli for up to 48 h.

Induction of keratinocyte differentiation. At 48 h after plating, HCK1T cells were treated with 2.5 mM EDTA in phosphate-buffered saline without Ca^{2+} and Mg^{2+} [PBS(−)] for 10 min or exposed to 0.7% and 5% bovine serum albumin (BSA) or 10% serum-containing medium in the presence of 10 μg/ml of bovine pituitary extract. To induce ligand-dependent NOTCH activation, HCK1T cells were harvested in subconfluent and 7-day-postconfluent states. HCK1T cells were also introduced with ICN1 by retroviral gene transfer to induce differentiation.

Dissociation of human iPS cells. First, hiPSC colonies were treated with collagenase IV solution at 37°C for 10 min. The detached hiPSC clumps were recovered, incubated with 0.005% trypsin–2.5 mM EDTA solution at 37°C for 5 min, and dissociated into single cells by pipetting. The dissociated cells were counted with Vi-CELL (Beckman Coulter, Brea, CA) and seeded onto MEF feeders.

Immunoblotting. Whole-cell protein extracts were used for analysis, and immunoblotting was conducted as described previously (14). Primary antibodies against Notch1 (sc-6014; Santa Cruz Biotechnology), activated Notch1 (cleaved Notch1 Val1744 2421; Cell Signaling Technology, Danvers, MA), Notch2 (clone C651.6DbHN; Developmental Studies Hybridoma Bank, University of Iowa), Hes1 (Toray Industries, Inc., To-

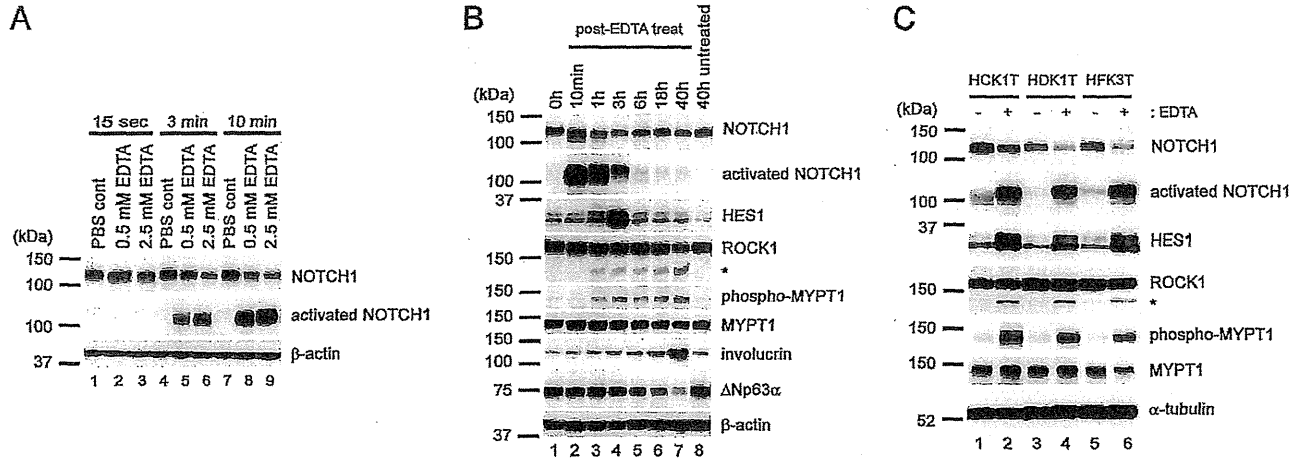

FIG 1 Immediate activation of ROCK1 following release of the NOTCH1 intracellular fragment in normal human keratinocytes. (A) HCK1T cells were either left untreated (PBS cont) or treated with 0.5 or 2.5 mM EDTA in PBS(−) for indicated time points. Cell lysates were prepared and analyzed by immunoblotting with the indicated antibodies. (B) HCK1T cells were either left untreated or treated with 2.5 mM EDTA in PBS(−) for 10 min at 37°C. After washing twice with PBS(−), cells were incubated with keratinocyte-SF medium. Cell lysates were prepared at the indicated time points after EDTA treatment. Extracts were analyzed by immunoblotting with the indicated antibodies. The band corresponding to the furin-processed transmembrane domain of NOTCH1 with a molecular mass of 120 kDa is shown as NOTCH1 here. An asterisk indicates a smaller fragment of ROCK1 protein with a molecular mass of ~130 kDa. (C) Keratinocytes from cervix (HCK1T), dermis (HDK1T), and foreskin (HFK1T) were either left untreated or treated with 2.5 mM EDTA for 10 min. After washing twice with PBS(−), cells were incubated with keratinocyte-SF medium for 3 h. Extracts were analyzed by immunoblotting with the indicated antibodies.

kyo, Japan), Hey1 (sc-16424; Santa Cruz Biotechnology), involucrin (clone SY5; Sigma, Saint-Quentin Fallavier, France), loricrin (AF 62; Covance, Princeton, NJ), Rock1 (sc-5560; Santa Cruz Biotechnology), phospho-MYPT1 (07-251; Merck-Millipore, Billerica, MA), MYPT1 (07-672; Merck-Millipore), Rock2 (sc-5561; Santa Cruz Biotechnology), p63 (clone 4A4; Santa Cruz Biotechnology), caspase-3 (9662; Cell Signaling Technology), poly(ADP-ribose) polymerase (PARP) (9542; Cell Signaling Technology), OCT3/4 (sc-5279; Santa Cruz Biotechnology), HA tag

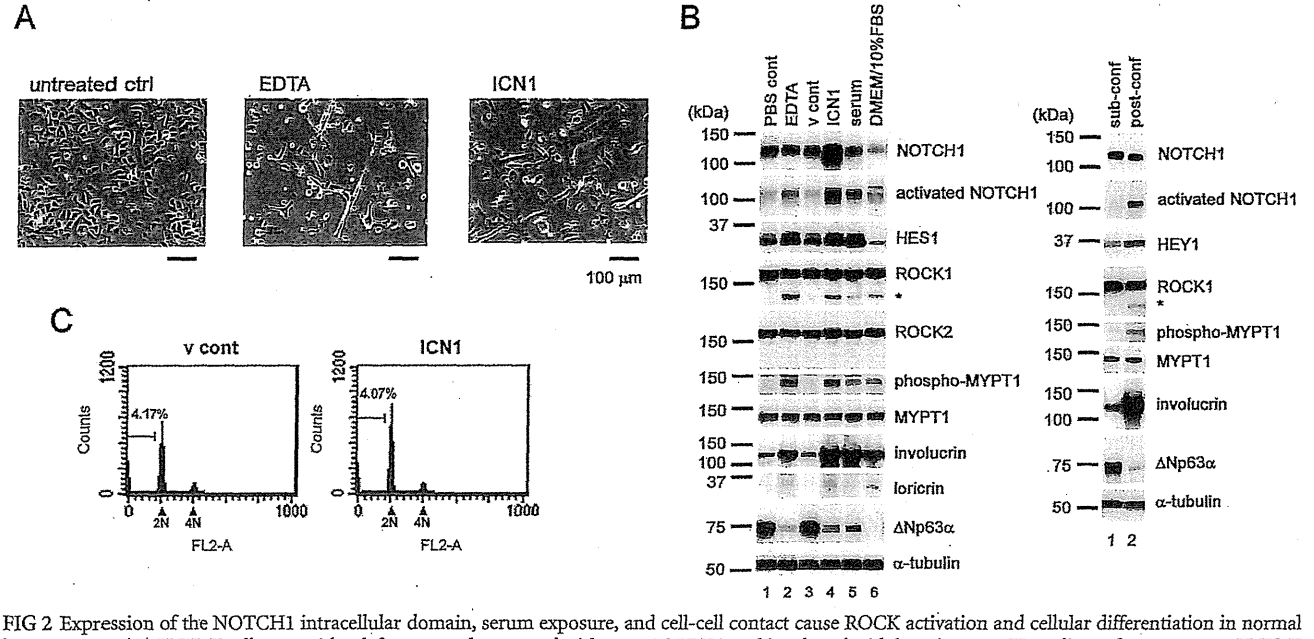

FIG 2 Expression of the NOTCH1 intracellular domain, serum exposure, and cell-cell contact cause ROCK activation and cellular differentiation in normal keratinocytes. (A) HCK1T cells were either left untreated or treated with 2.5 mM EDTA and incubated with keratinocyte-SF medium after treatment. HCK1T cells were transduced with the constitutively active form of NOTCH1 (ICN1). Typical areas were photographed at 3 days posttreatment or posttransduction. Scale bars represent 100 μm. (B) HCK1T cells were either left untreated or treated with 2.5 mM EDTA and incubated with keratinocyte-SF medium after treatment. HCK1T cells were transduced with the constitutively active form of NOTCH1 (ICN1) or control (v cont). HCK1T cells were exposed to serum-containing keratinocyte-SF medium (serum) or Dulbecco modified Eagle medium with 10% fetal bovine serum (DMEM–10% FBS). Cell lysates were harvested at 3 days posttreatment or posttransduction. HCK1T cells were also harvested in subconfluent and 7-day-postconfluent states. Extracts were analyzed by immunoblotting with the indicated antibodies. (C) HCK1T cells were transduced with the constitutively active form of NOTCH1 (ICN1) or control (v cont). At 3 days posttransduction, cells were collected and DNA content was analyzed by flow cytometry. The percentage of apoptotic cells displaying a sub-G_1 DNA content is shown between markers.

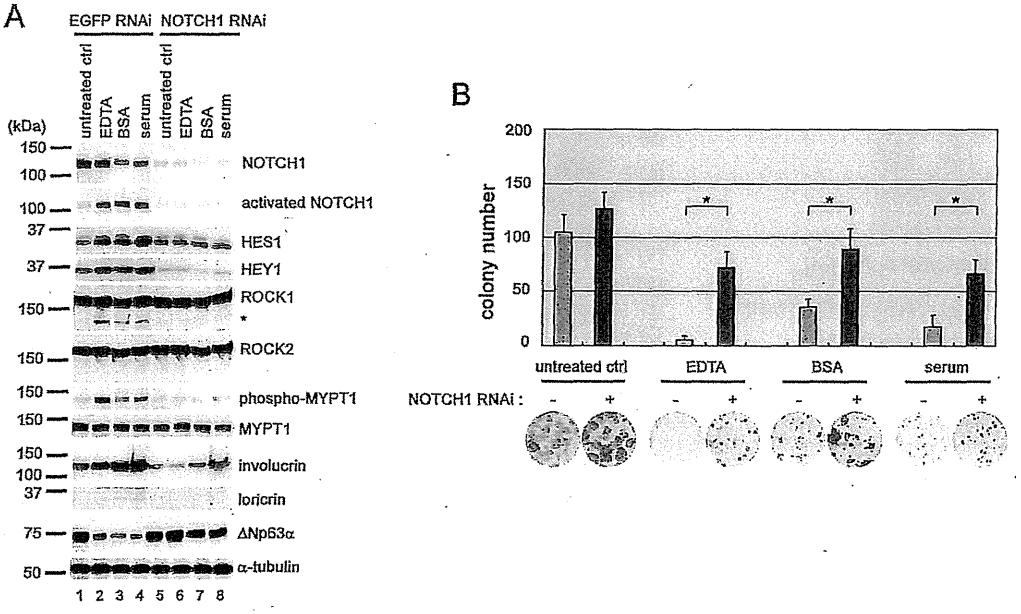

FIG 3 Knockdown of NOTCH1 abrogates the production of the smaller ROCK1 and MYPT1 phosphorylation with restoration of clonogenic growth potential in normal keratinocytes exposed to EDTA, BSA, or serum. (A) HCK1T cells stably expressing NOTCH1 shRNA (NOTCH1 RNAi) or control shRNA (EGFP RNAi) were treated with 2.5 mM EDTA, 5% bovine serum albumin, or 10% serum or left untreated. Cells were harvested at 3 days posttreatment, and cell extracts were subjected to immunoblotting analysis with the indicated antibodies. (B) Aliquots of 500 HCK1T cells stably expressing NOTCH1 shRNA (NOTCH1 RNAi) or control shRNA (EGFP RNAi) were seeded on 35-mm dishes under sparse conditions. Then cells were treated similarly to those for panel A. After being cultivated for 2 weeks, the cells were stained with Giemsa's dye, and colonies were counted. The photographs are of representative dishes, and the graph represents means ± SDs. *, $P < 0.05$ according to Student's *t* tests.

(ab72479; Abcam, Paris, France), β-actin (sc-1616; Santa Cruz Biotechnology), α-tubulin (2144; Cell Signaling Technology), and GAPDH (glyceraldehyde-3-phosphate dehydrogenase) (AM4300; Ambion, Inc., Austin, TX) were used as probes. Horseradish peroxidase-conjugated anti-mouse and anti-rabbit (Jackson ImmunoResearch Laboratories, West Grove, PA) and anti-goat (sc-2033; Santa Cruz Biotechnology) immunoglobulins were used as the secondary antibodies. The LAS3000 charge-coupled device (CCD) imaging system (Fujifilm Co. Ltd., Tokyo, Japan) was employed for detection of proteins visualized by Lumi-light Plus Western blotting substrate (Roche, Basel, Switzerland). The exposure time was adjusted to keep the signals within a linear and nonsaturated range, and the band signal intensities were quantified by densitometry using imaging software (Fujifilm Multi-Gauge) after normalization to that of internal controls, such as β-actin, α-tubulin, or GAPDH.

Fluorescence-activated cell sorting analysis. Cells were treated with a CycleTEST Plus DNA reagent kit (Becton Dickinson, Franklin Lakes, NJ) for propidium iodide staining and then analyzed with a Becton Dickinson FACSCalibur instrument.

Clonogenic assay. Aliquots of 500 cells were seeded on 35-mm dishes under sparse conditions. After cultivation for 2 weeks, the cells were stained with Giemsa's dye, and the colonies were counted.

Statistical analysis. Statistical analysis was carried out using Microsoft Excel software. Unless stated otherwise, all data are presented as means ± standard deviations (SD) from at least three independent experiments; error bars represent SD in all figures. Intergroup comparisons were performed by the two-tailed Student's *t* test. A *P* value of <0.05 was considered to be statistically significant.

RESULTS

Immediate activation of ROCK following expression of the NOTCH intracellular form. Previous work has shown stabilization of the noncovalent interaction between a ligand-binding extracellular domain and a transmembrane signaling subunit of NOTCH by millimolar Ca^{2+} and transient activation of this heterodimeric NOTCH receptor by EDTA-mediated shedding of its extracellular domain, independent of cell-cell contact or binding of a ligand displayed on the surface of a neighboring cell (25). In line with this notion, somatic activating mutations of NOTCH1 within the heterodimerization domain are frequently found in human T cell acute lymphoblastic leukemia and are thought to increase the production of the intracellular form of NOTCH1 (53). To ascertain whether calcium depletion could induce activation of NOTCH1, normal human keratinocytes, which were maintained with serum-free, low-calcium medium, were subjected to EDTA treatment. We found that this chelator treatment elicited immediate and robust expression of the cleaved intracellular form of NOTCH1 in a time- and dose-dependent manner (**Fig. 1A**). Time course experiments revealed that this intracellular NOTCH1 arose transiently and that thereafter activation of the NOTCH target gene was induced, as well as upregulation of a differentiation marker and downregulation of a keratinocyte stemness marker, ΔNp63α, in agreement with its proposed role in keratinocyte differentiation (**Fig. 1B**) (8, 9, 11). We also noted that the EDTA-treated cells underwent a drastic morphological change (**Fig. 2A**) with increased motility (see Movie S1 in the supplemental material), which was also seen in cells transduced with the NOTCH1 intracellular domain (ICN1) in much the same fashion (**Fig. 2A**). We have previously shown that these morphologically altered cells are differentiating cells strongly expressing K10 and involucrin (14).

ROCK inhibition with Y-27632 has been reported to inhibit differentiation and increase the proliferative capacity of primary human keratinocytes in culture, pointing to a role for ROCK

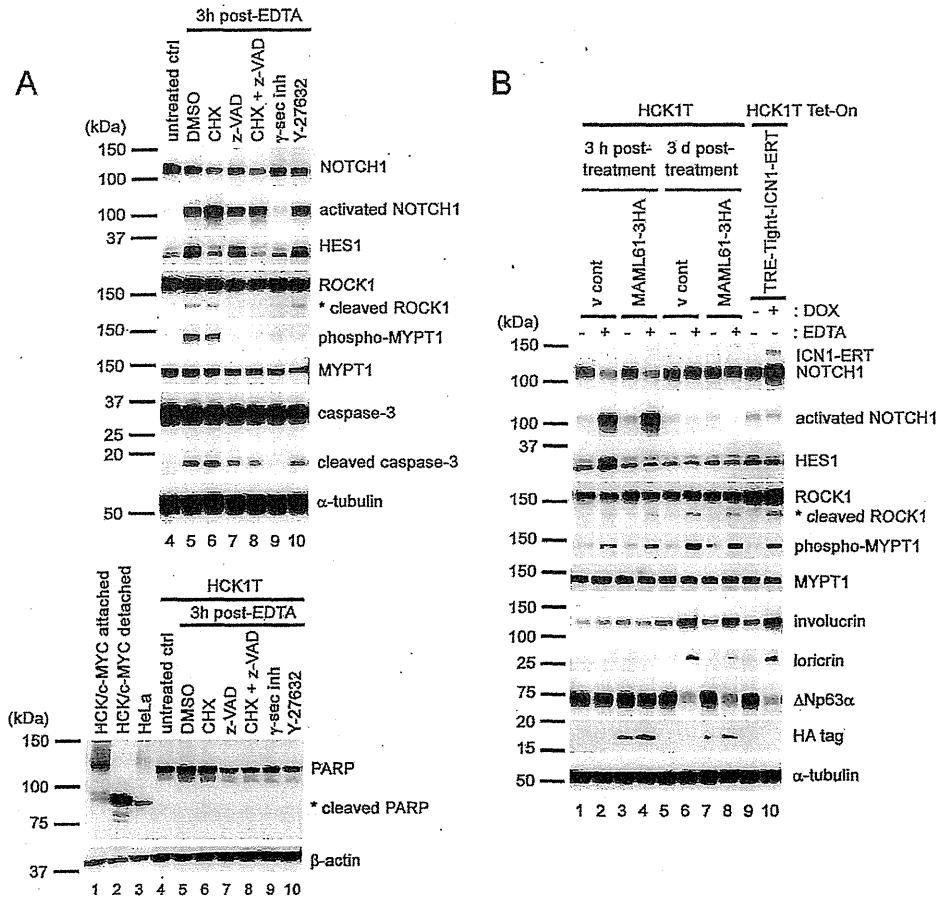

FIG 4 ROCK1 activation is independent of NOTCH1 transcriptional activity. (A) HCK1T cells, pretreated where indicated with 10 μg/ml cycloheximide (CHX) for 2.5 h, 20 μM z-VAD-fmk for 2.5 h, 10 μM γ-secretase inhibitor (DAPT) for 2.5 h, or 10 μM Y-27632 for 2.5 h, were either left untreated or treated with 2.5 mM EDTA for 10 min and incubated with keratinocyte-SF medium for 3 h. Whole-cell extracts were subjected to immunoblotting analysis with the indicated antibodies. As a positive control for PARP cleavage, cell extracts from detached HCKs after c-MYC transduction were used. (B) HCK1T cells were stably transduced with dominant negative MAML1 (MAML61-3HA) or vector control (v cont). Cells were exposed to 2.5 mM EDTA (+) or left untreated (−), and cell lysates were prepared at 3 h and 72 h posttreatment. HCK1T Tet-On cells were then introduced with the TRE-Tight-ICN1-ERT tetracycline-inducible gene cassette. HCK1T Tet-On-ICN1-ERT cells were either left untreated (−) or treated (+) with 1 μg/ml doxycycline (DOX) for 72 h.

in keratinocyte differentiation (35, 37). These observations prompted us to determine whether NOTCH activation by EDTA treatment during passage could induce differentiation or a decrease in proliferative potential, possibly through ROCK activation. As shown in Fig. 1B, immediately after production of the NOTCH1 intracellular form, additional ROCK1 polypeptides of smaller size emerged. The ROCK1 fragment with a relative molecular weight of ~130,000 was reminiscent of that observed in cells undergoing apoptosis, which has been identified as a caspase-3-cleaved, constitutively activated form (54, 55). Indeed, MYPT1, a downstream molecule of ROCK, was phosphorylated concomitantly with the appearance of the smaller ROCK1 proteins, indicating increased ROCK1 activity in cells with active NOTCH1 signaling.

In keratinocytes, NOTCH1 has been shown to be activated in response to differentiation stimuli such as suspension in methylcellulose, confluence-triggered cell-cell contact, and serum exposure, as well as with genotoxic stress (13, 14, 18, 49, 56). Therefore, we examined whether differentiation stimuli or expression of ICN1 could cause ROCK activation. The additional smaller proteins of ROCK1, but not ROCK2, and phosphorylation of MYPT1 were observed in response to serum exposure (Fig. 2B, left panel). Since albumin is the major protein in serum, to which approximately half of extracellular calcium is bound, we further tested the possibility that albumin exerts a differentiation-inducing effect through a mechanism similar to that for EDTA. As expected, albumin exposure also induced activation of NOTCH1, production of the smaller ROCK1, and upregulation of the differentiation markers (Fig. 3A, lane 3). Similarly, retroviral transduction of keratinocytes with ICN1 gave rise to the smaller ROCK1 in association with MYPT1 phosphorylation (Fig. 2B, left panel). Of importance, confluence-triggered cell-cell contact also induced smaller ROCK1 and MYPT1 phosphorylation, indicating that the ligand-mediated NOTCH activation is responsible for these events (Fig. 2B, right panel). Assuming that activated NOTCH1 evokes some apoptotic cascade, ROCK activation may occur in parallel in cells undergoing apoptosis. However, we failed to detect any indication of apoptotic cell death after ICN1 transduction (Fig. 2C). To further corroborate involvement of NOTCH1 in ROCK1 activation, we knocked down NOTCH1 expression. In contrast to the control case, NOTCH1 silencing abrogated the production of the smaller

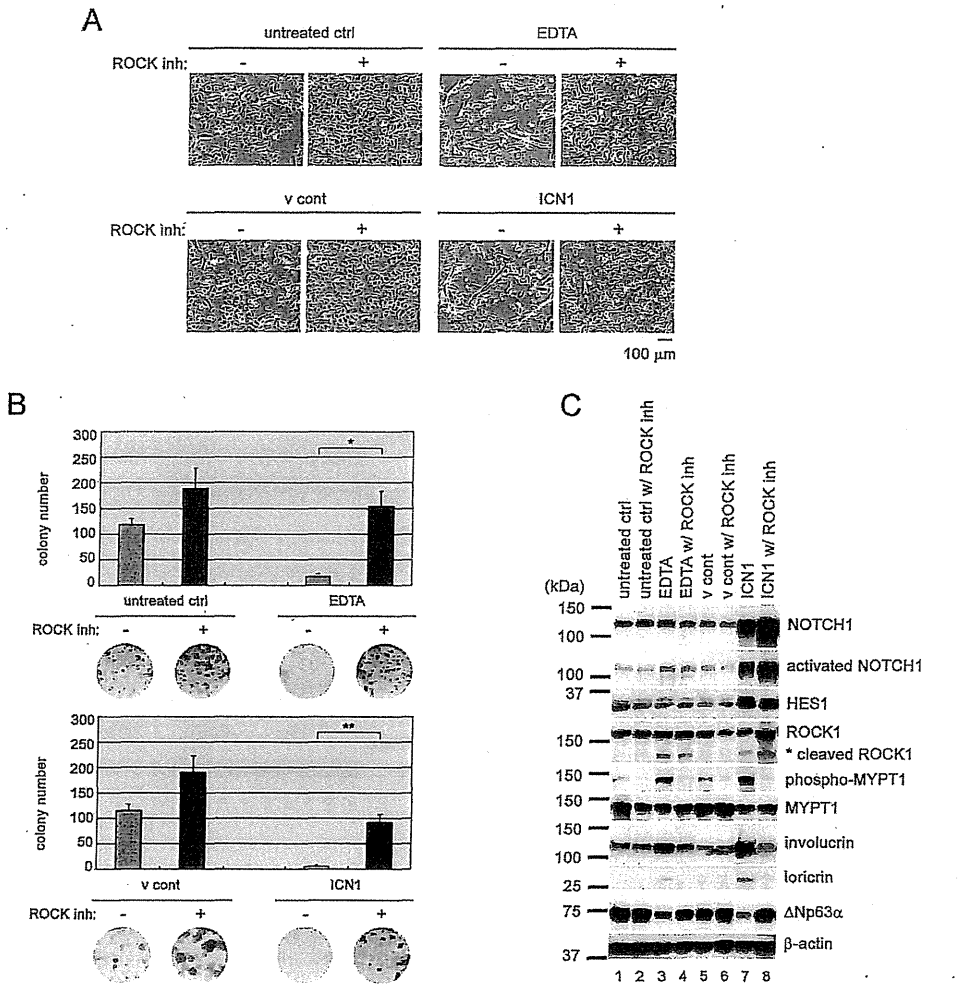

FIG 5 ROCK inhibition alleviates the growth-suppressive and differentiation-inducing effects of NOTCH1. (A) HCK1T cells pretreated with or without Y-27632 were either left untreated, treated with 2.5 mM EDTA, or transduced with ICN1 or vector control (v cont). Thereafter, cells were incubated in the presence or absence of Y-27632. Typical areas were photographed at 72 h after EDTA treatment. (B) Aliquots of 500 HCK1T cells were seeded on 35-mm dishes under sparse conditions. Cells pretreated with or without Y-27632 were then either left untreated, treated with 2.5 mM EDTA for 10 min, or transduced with ICN1 or vector control (v cont). After being cultivated for 2 weeks, the cells were stained with Giemsa's dye, and colonies were counted. The photographs are of representative dishes, and the graph represents means ± SDs. *, $P < 0.05$; **, $P < 0.01$ (according to Student's *t* tests). (C) Cells were treated similarly to those for panel A and incubated for 72 h. Cell extracts were subjected to immunoblotting analysis with the indicated antibodies.

ROCK1 and MYPT1 phosphorylation after differentiation stimuli (**Fig. 3A**) with restoration of clonogenic growth potential (**Fig. 3B**). Treatment with a γ-secretase inhibitor had the same effects as NOTCH1 knockdown (**Fig. 4A** and unpublished observations). These results suggest that the observed ROCK activation is not an outcome of apoptosis but is positively regulated by NOTCH1 signaling in differentiating cells.

The intracellular form of NOTCH is responsible for ROCK activation independently of its transcriptional activity. Given the immediate appearance of the smaller ROCK1 after expression of the intracellular NOTCH1, it can be hypothesized that NOTCH1 activation of ROCK1 does not occur through *de novo* protein expression. In an effort to clarify this, we treated cells with cycloheximide (CHX), an inhibitor of translation. While CHX treatment completely inhibited induction of the NOTCH1 transcriptional target, HES1, it did not affect the generation of the smaller ROCK1 and MYPT1 phosphorylation (**Fig. 4A**, upper panel, compare lanes 5 and 6). Since NOTCH1 requires the transcriptional coactivator, MAML1, in its transactivation complex, we also assessed the effect of dominant negative MAML1, MAML61-3HA. While exogenous expression of MAML61-3HA blocked the induction of HES1, it exerted no effect on the smaller ROCK1 production, MYPT1 phosphorylation, and expression of a differentiation marker, involucrin (**Fig. 4B**). It is still possible that the canonical NOTCH1 signaling plays a role in differentiation at a later stage, as the level of a terminal differentiation marker, loricrin, appeared to be attenuated to some extent in MAML61-3HA-expressing cells. To further explore the transcription-independent function of NOTCH1 in ROCK1 activation, we established tetracycline-inducible ICN1-ERT keratinocytes, expressing a chimeric protein consisting of the intracellular domain of NOTCH1 fused at the amino terminus to a mutated ligand-binding domain of the estrogen receptor (ERT) (57). In the presence of doxycycline (DOX) for 3 days and without addition of the

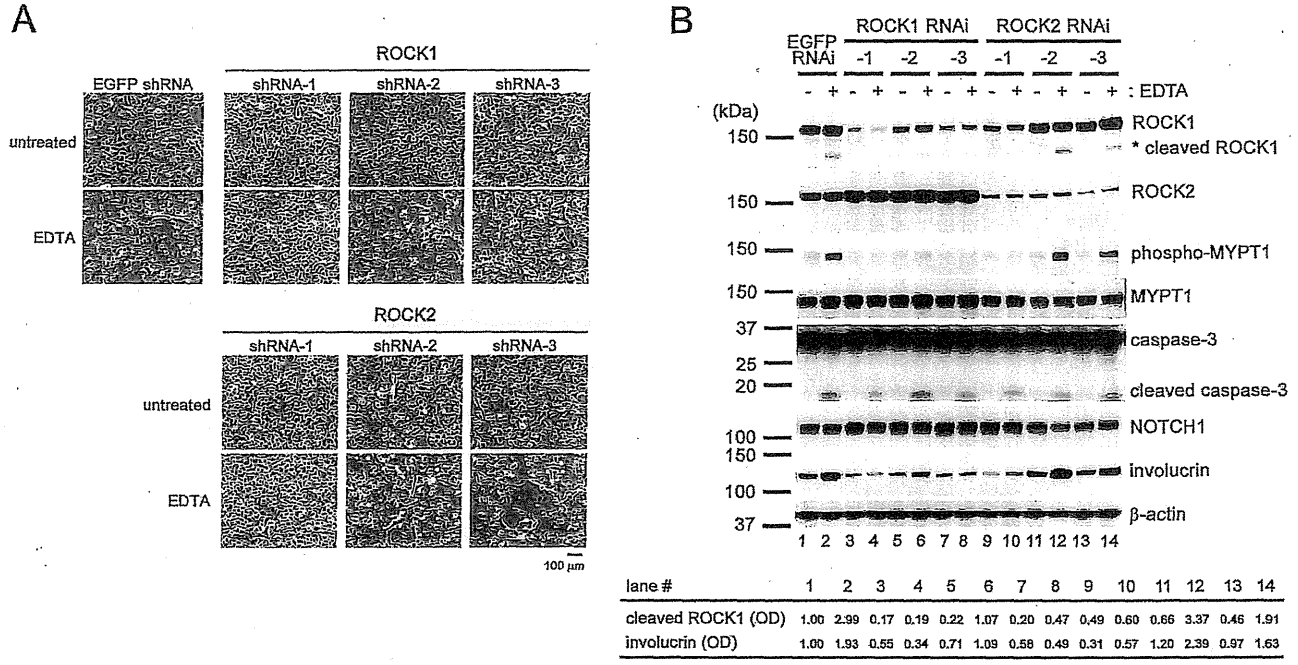

FIG 6 Knockdown of ROCK1 inhibits keratinocyte differentiation after EDTA treatment. (A) HCK1T cells stably transduced with shRNAs for ROCK1 and -2 were either left untreated or treated with 2.5 mM EDTA and then incubated with keratinocyte-SF medium. Typical areas were photographed at 3 days after EDTA treatment. Note that ROCK2 shRNA-2 knocked down ROCK1 expression as well. (B) HCK1T cells were transduced with three different shRNAs for ROCK1 and -2 or with control shRNA for EGFP. Cells were then either left untreated (−) or treated (+) with 2.5 mM EDTA for 10 min. After cultivation for 72 h, cells were harvested and analyzed by immunoblotting. The band optical densities (OD) for the cleaved ROCK1 and involucrin were quantified densitometrically, normalized to that of β-actin with the value for untreated control defined as 1.

estrogen homolog, ICN1-ERT did not transactivate the target gene but triggered the smaller ROCK1 production and MYPT1 phosphorylation (Fig. 4B, compare lanes 9 and 10). These results indicate a transcription-independent or cytoplasmic function of NOTCH1 in control of ROCK1 activity and its roles in cellular differentiation.

To elucidate whether the additional smaller fragment of ROCK1 is a constitutively active form generated by caspase-3-mediated cleavage (54, 55), cells were treated with the caspase inhibitor z-VAD prior to EDTA exposure. In the presence of active forms of NOTCH1, z-VAD markedly blocked generation of the smaller ROCK1 as well as MYPT1 phosphorylation (Fig. 4A, upper panel, compare lanes 5 and 7), indicating that the NOTCH intracellular form could induce immediate and constitutive activation of ROCK1 through caspase. This activation of caspase is much weaker than that observed in apoptotic cells, since cleavage of the well-known caspase substrate PARP was marginally detected only when pretreated with CHX (Fig. 4A lower panel), suggesting a nonapoptotic function of caspase activation in keratinocyte differentiation.

ROCK inhibition rescues the phenotype induced by NOTCH activation. Next, to address whether ROCK activation is the critical downstream event in NOTCH signaling, we tested whether the NOTCH gain-of-function phenotype could be reversed by ROCK inhibition. To this end, we assessed the differentiation status and clonogenic growth potential after EDTA treatment or ICN1 transduction in the presence of a ROCK inhibitor. ROCK inhibition significantly restored the morphology and clonogenicity of keratinocytes upon EDTA treatment or ICN1 transduction (Fig. 5A and B), and suppressed both induction of differentiation markers and reduction of ΔNp63α (Fig. 5C). Silencing of ROCK1 but not ROCK2 also blocked differentiation after EDTA treatment (Fig. 6A and B). Intriguingly, continuous ROCK inhibition rendered cells permissive to constitutive ICN1 expression as well as HES1 induction without indication of differentiation and maintained growth potential during at least three passages, while only cells expressing a small amount of ICN1 survived without the ROCK inhibitor (Fig. 7A). ROCK inhibition may allow increased NOTCH1 levels, possibly due to counterbalancing its biological effects. ROCK inhibitor withdrawal resulted in a prompt resumption of differentiation following MYPT1 phosphorylation in ICN1-expressing cells (Fig. 7B). These results suggest that ROCK is the critical downstream effector of NOTCH signaling in loss of stemness and differentiation of keratinocytes.

Ectopic expression of constitutively active ROCK1 induces keratinocyte differentiation. We next asked whether activated ROCK1 itself could initiate differentiation of normal human keratinocytes. For this purpose, we established several lines of keratinocytes expressing various exogenous ROCK1 mutants in a doxycycline-dependent manner. Upon induced expression of ROCK1ΔC241, a truncated mutant corresponding to a caspase-cleaved constitutively active form, downregulation of ΔNp63α and upregulation of a differentiation marker were evident to a level comparable to that observed in ICN1-ERT cells (Fig. 8A, compare lanes 2 and 8). Expression of wild-type ROCK1 exhibited only marginal effects (Fig. 8A, lane 6), while caspase-cleavage resistant ROCK1-D1113A and kinase-inactive ROCK1-K105A mutants failed to induce differentiation (Fig. 8A, lanes 10 and 12).

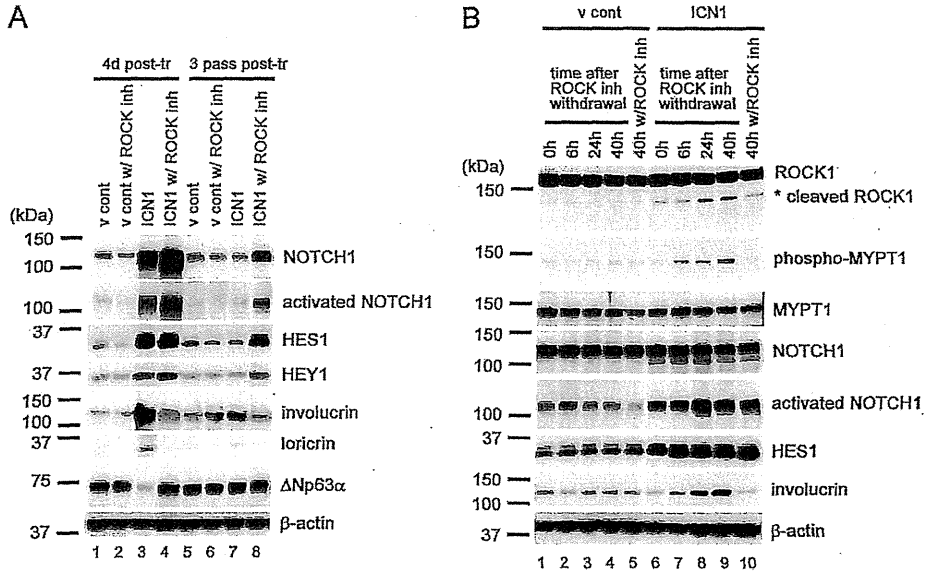

FIG 7 ROCK inhibition allows propagation of keratinocytes in the presence of constitutively active NOTCH1. (A) HCK1T cells pretreated with or without Y-27632 were transduced with the constitutively active form of NOTCH1 (ICN1) or vector control (v cont). Cells were cultivated until 22 days posttransduction (three passages) in the presence or absence of Y-27632. Cell extracts were prepared at 4 and 22 days posttransduction and subjected to immunoblotting analysis with the indicated antibodies. Note that the ROCK inhibitor inhibits differentiation and permits proliferation of ICN1-expressing cells. In contrast, control cells which have escaped after ICN1 transduction showed decreased levels of activated NOTCH1. (B) Cells were treated as for panel A. Cell lysates were prepared at the indicated time points after withdrawal of Y-27632 and subjected to immunoblotting analysis with the indicated antibodies.

It has been shown that the Rho inhibitor C3 as well as Y-27632 inhibited differentiation induced by single-cell suspension, although RhoA activity is unvaried during differentiation (35). In our monolayer culture model, conditional overexpression of a constitutively active form of RhoA was able to promote differentiation to some extent (**Fig. 8B**, lane 2). We then examined C3's effect on the process of keratinocyte differentiation. C3 only partially inhibited overall ROCK activation, judging from the phosphorylation levels of MYPT1 (**Fig. 8C**, compare lanes 2 and 7). Furthermore, this inhibition seemed to be closely associated with unexpected inhibition of the NOTCH1-caspase-ROCK1 axis through unknown mechanisms. Therefore, unlike keratinocyte differentiation induced by single-cell suspension assays, ROCK1 activation in monolayer culture essentially depends on its cleavage by caspase but not much on Rho activation, though we have not confirmed Rho activity during keratinocyte differentiation. These data support the conclusion that the NOTCH1-caspase-ROCK1 axis plays a major role in keratinocyte differentiation at least in monolayer culture. It is noteworthy that ROCK1 acts downstream of NOTCH1 but not NOTCH2, as ICN2 (a NOTCH2 intracellular form) did not induce ROCK1 cleavage and keratinocyte differentiation (**Fig. 8A**, compare lanes 2 and 4).

Proliferative defects upon dissociation in hiPSCs are partly attributable to NOTCH activity. It is well-known that human pluripotent stem cells such as hESCs undergo massive apoptosis when dissociated and that ROCK inhibitor treatment efficiently ameliorates such vulnerability to permit survival in clonal culture (**39, 58**). It is tempting to speculate that the NOTCH-ROCK pathway may also be activated in human pluripotent stem cells during the dissociation step with EDTA treatment and that this could be one mechanism underlying dissociation-induced loss of clonal growth potential. In an attempt to assess this possibility, we employed two lines of human induced pluripotent stem cells (hiPSCs). As shown in **Fig. 9A** and **B**, virtually no hiPSC colonies were formed from cells dissociated by trypsin-EDTA treatment, whereas NOTCH inhibition by a γ-secretase inhibitor partially restored the efficiency of colony formation to a degree comparable to that with Rho inhibitor C3-treated cells. Combination inhibition of γ-secretase and Rho had an additive effect on the clonogenic growth capacity to the same extent as ROCK inhibition, suggesting that the NOTCH-ROCK and the Rho-ROCK axis act in parallel in this cellular context.

In line with a previous study showing ROCK-dependent myosin activation as the direct cause of dissociation-induced cell death in hESCs (**41**), we also found that treatment with the myosin inhibitor blebbistatin showed equal efficacy as ROCK inhibition (**Fig. 9C** and **D**).

To substantiate further the link between NOTCH and ROCK in hiPSCs, we next assessed the status of NOTCH and ROCK in adherent small clumps of cells treated with EDTA. In accordance with the data with keratinocytes, EDTA treatment triggered immediate NOTCH1 activation accompanied by ROCK1 cleavage and MYPT1 phosphorylation (**Fig. 10A**, lanes 2 and 6). Importantly, treatment with a γ-secretase inhibitor resulted in abrogation of ROCK1 activation (**Fig. 10A**, lanes 4 and 8), suggesting that regulation of ROCK1 activity by NOTCH1 is also conserved in hiPSCs. Because EDTA treatment instigated drastic morphological change which was blocked by NOTCH or ROCK inhibition (**Fig. 10B**), we speculated that this stimulus may have an impact on the cell fate. Indeed, 3 days after EDTA treatment, expression of the stemness marker OCT3/4 was substantially downregulated in still-attached control cells (**Fig. 10C**, compare lanes 7 and 8). In-

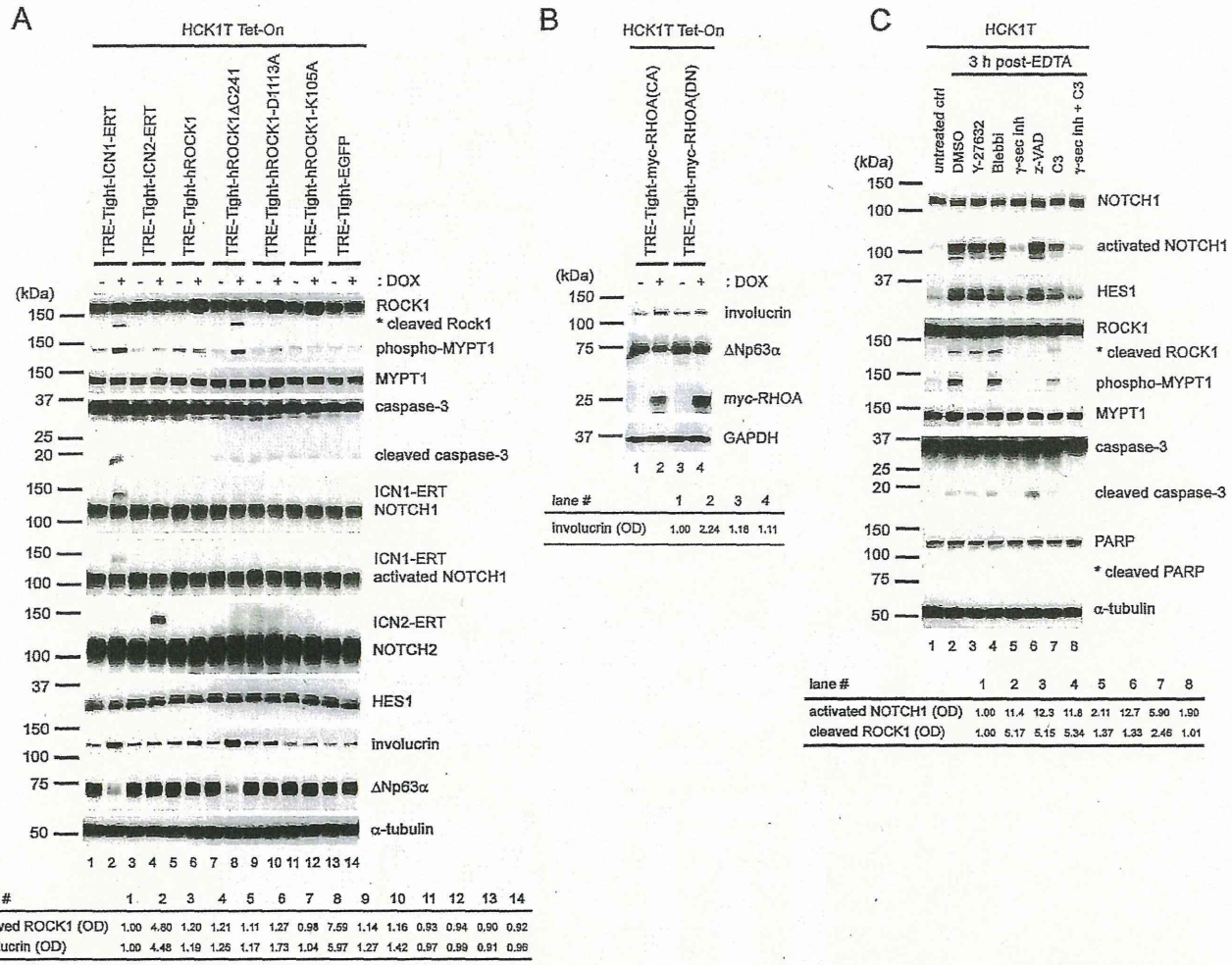

FIG 8 Ectopic expression of active ROCK1 induces keratinocyte differentiation. (A and B) HCK1T Tet-On cells were stably transduced with the indicated tetracycline-inducible gene constructs by retroviral gene transfer. Cells were either left untreated (−) or treated (+) with 1 μg/ml doxycycline (DOX) for 72 h. Cell extracts were analyzed by immunoblotting with the indicated antibodies. A long-exposed image for activated NOTCH1 is shown. Quantification of relative optical densities (OD) for the cleaved ROCK1 and involucrin bands, normalized to the value for the α-tubulin or GAPDH control, are indicated. (C) HCK1T cells, pretreated where indicated with 10 μM Y-27632, 10 μM blebbistatin, 10 μM γ-secretase inhibitor (DAPT), 20 μM z-VAD-fmk, or 1.0 μg/ml C3 for 3 h, were either left untreated or treated with 2.5 mM EDTA for 10 min and incubated with keratinocyte-SF medium for 3 h. Cell extracts were subjected to immunoblotting analysis with the indicated antibodies. Quantification of relative optical densities (OD) for the activated NOTCH1 and cleaved ROCK1 bands, normalized to the value for α-tubulin with the untreated control defined as 1, are indicated.

hibition of either NOTCH or Rho significantly prevented this transition (Fig. 10C). Of note, the inhibitor-treated colonies showed normal morphology in a mass, whereas the EDTA-treated controls exhibited heterogeneous and differentiated traits at this time point. These observations indicate that EDTA treatment induces acute ROCK1 activation and consequent loss of stemness at least partly in a NOTCH-dependent manner in hiPSCs.

DISCUSSION

Identification of NOTCH1 as a novel upstream regulator for ROCK1. The best-known upstream regulator for ROCK activity is Rho GTPase (32). In the normal cellular context, ROCK becomes an active kinase by conformational change through interaction with the GTP-bound form of Rho, which is thought to release the kinase domain from the carboxy-terminal autoinhibitory domain. In apoptotic cells, removal of the autoinhibitory domain of ROCK1 by caspase-3-mediated cleavage renders this protein constitutively active (54, 55, 59). In the present study, we first found that the cleaved ROCK1 is also generated immediately after emergence of the NOTCH1 intracellular form in the context of keratinocyte differentiation and revealed that activated NOTCH1 causes constitutive activation of ROCK1 through caspase cleavage upon EDTA treatment or exposure to differentiation-inducing stimuli such as serum as well as cell-cell contact (Fig. 11). We further demonstrated that this type of ROCK1 activation is mediated by a transcription-independent function of NOTCH1. Thus, we conclude that noncanonical NOTCH1 signaling triggers differentiation and a consequential decrease in clonogenicity mostly if not completely through ROCK1 activation in keratinocytes. To our knowledge, this is the first demonstration of NOTCH1 function as a novel and critical upstream regulator for ROCK1 activity. The Rho inhibitor C3 inhibited MYPT1 phosphorylation to some extent in concert with reduction of activated NOTCH1 and

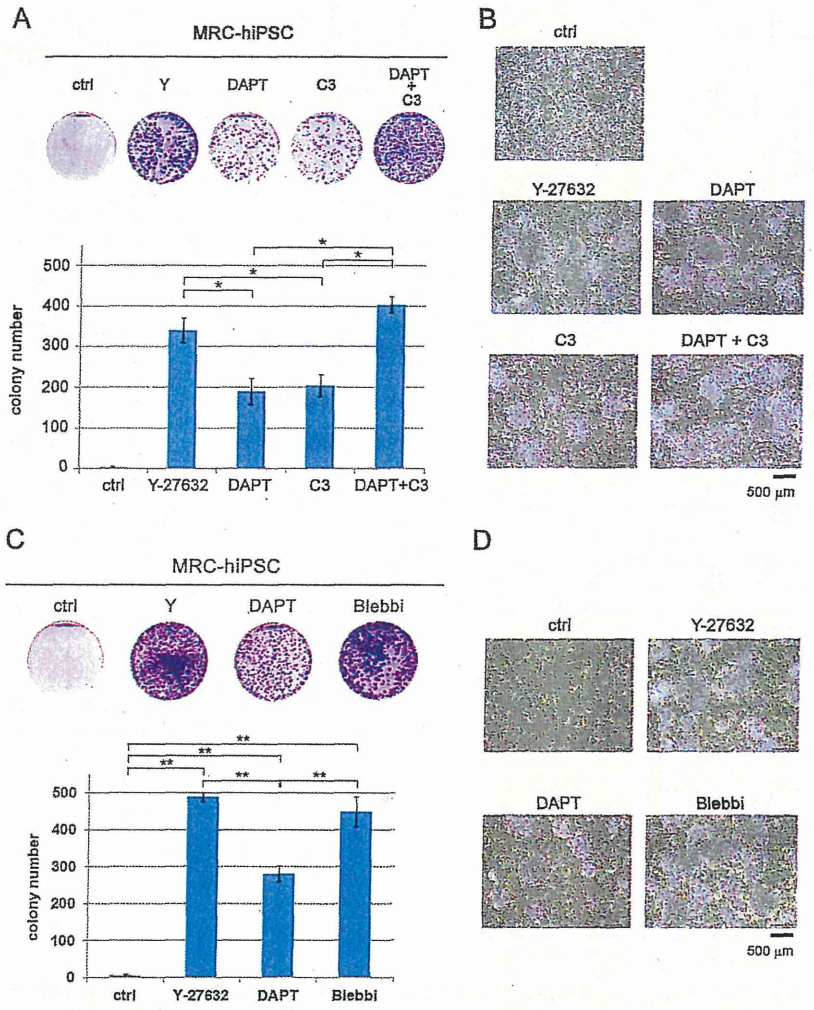

FIG 9 Activation of NOTCH and ROCK upon dissociation instigates loss of clonogenic growth capacity in hiPSCs. (A) MRC-hiPSCs, pretreated where indicated with 10 μM Y-27632 (Y) for 3 h, 10 μM DAPT for 3 h, 2.0 μg/ml C3 for 3 h, and 10 μM DAPT and 2.0 μg/ml C3 for 3 h, were completely dissociated by trypsin-EDTA treatment and pipetting. The dissociated cells were counted with Vi-CELL to confirm that the viabilities of each samples were greater than 90%, and aliquots of 2,000 cells were seeded on 60-mm dishes in the presence of MEF feeders. After 10 days of cultivation, the cells were stained with Giemsa's dye, and colonies were counted. The photographs are of representative dishes, and the graph illustrates means ± SDs. Treatment with any of these inhibitors significantly restored the clonal growth potential after dissociation. *, $P < 0.05$ according to Student's *t* tests. (B) Typical areas were photographed at 6 days postreplating. (C) MRC-hiPSCs, pretreated where indicated with 10 μM Y-27632 for 3 h, 10 μM DAPT for 3 h, and 10 μM blebbistatin for 3 h, were completely dissociated. The dissociated cells were seeded as for panel A, and colonies were counted. The photographs are of representative dishes, and the graph represents means ± SDs. **, $P < 0.01$ according to Student's *t* tests. (D) Typical areas were photographed at 6 days postreplating.

caspase-3 (Fig. 8C), implying a novel mechanism of ROCK inhibition by C3 independent of Rho inhibition. However, the mechanism underlying the inhibitory effect of C3 on NOTCH1 activation is currently unknown and awaits further investigation.

A recent report on the NOTCH1 nuclear interactome reveals ROCK1 as one of its interacting partners, raising the possibility of cross talk between these proteins (60). However, we have no evidence for interaction of the intracellular NOTCH1 proteins with caspase-3 and ROCK1 at present. Certainly, identification of a signaling mediator between NOTCH1 and ROCK1 warrants more research to provide a better understanding of this novel signaling pathway in cell biology. Interestingly, we failed to detect the intracellular form of NOTCH2 after differentiation induction, and ectopic expression of the NOTCH2 intracellular forms had a limited effect, if any, on ROCK1 cleavage and differentiation (Fig. 8A, lane 4), suggesting different regulatory mechanisms for activation and downstream signaling among NOTCH family members.

Functional diversity of caspases in cellular processes other than apoptosis has been described (61). In embryonic mouse keratinocytes, caspase-3 has been shown to be a transcriptional target of Notch1 and to have a role in high commitment to terminal differentiation (62). It is likely that ROCK1 activity is fostered by canonical NOTCH1 signaling through upregulation of caspase-3 gene expression. Because there is also a report showing that caspase-8 functions in epidermal homeostasis and regeneration through regulation of proliferation and inflammatory responses (63), we tested the possible involvement of caspase-8 in ROCK1 cleavage in differentiated keratinocytes. However, caspase-8 inhibition demonstrated little influence on activation of the

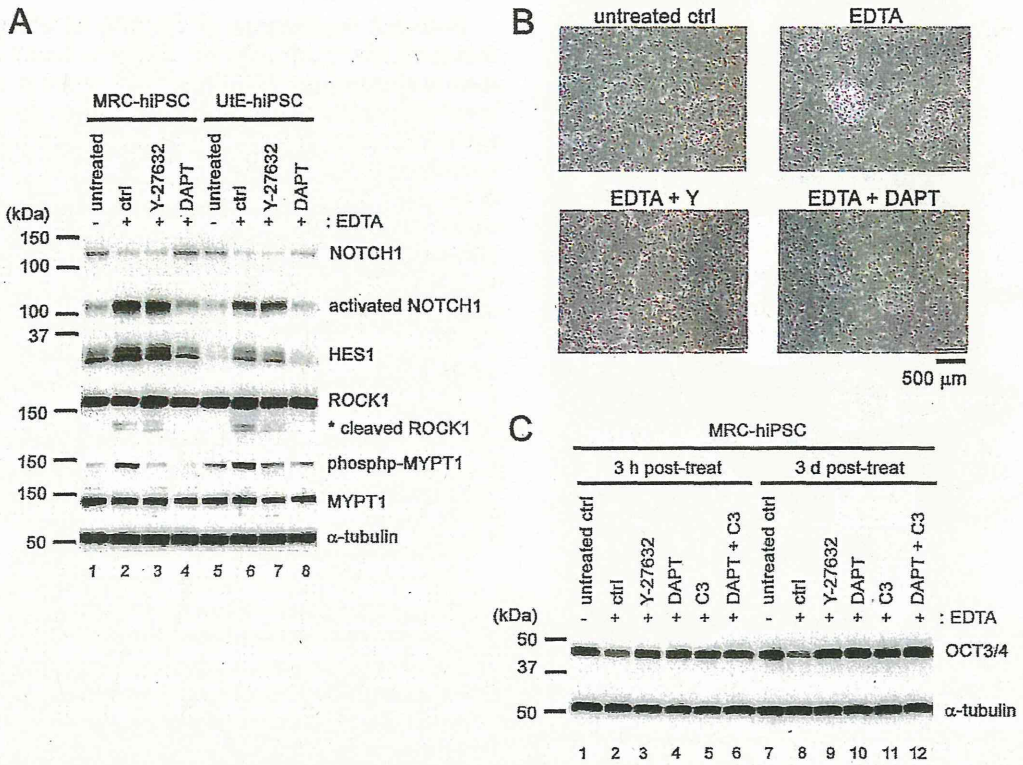

FIG 10 The defect in clonogenic growth upon dissociation in hiPSCs is partly attributable to NOTCH-dependent ROCK activation. (A) Adherent small clumps of MRC-hiPSCs and UtE-hiPSCs were pretreated with 10 μM Y-27632 for 3 h or 10 μM DAPT for 3 h and then either left untreated or treated with 2.5 mM EDTA in Hanks balanced salt solution without Ca^{2+} and Mg^{2+} [HBSS(−)] for 10 min at 37°C. After 3 h of incubation, hiPS cell extracts were prepared and subjected to immunoblotting analysis with the indicated antibodies. (B) Typical MRC-hiPSC colonies were photographed at 3 days after EDTA treatment. (C) Adherent small clumps of MRC-hiPSCs, pretreated where indicated with 10 μM Y-27632 for 3 h, 10 μM DAPT for 3 h, 2.0 μg/ml C3 for 3 h, and 10 μM DAPT and 2.0 μg/ml C3 for 3 h, were then either left untreated or treated with 2.5 mM EDTA. After 3 h and 3 days of cultivation, hiPS cell extracts were prepared and subjected to immunoblotting analysis.

NOTCH1-ROCK1 pathway and keratinocyte differentiation (unpublished observations), suggesting that activation of caspase-3 is unlikely to be mediated by caspase-8 downstream of NOTCH1.

Biological relevance of the NOTCH-ROCK pathway. In stratified epithelia such as the epidermis, cells in the basal layer constitute a proliferating population including stem cells and transit-amplifying cells. In the upper layer, differentiation-committed daughter cells are thought to arise by asymmetric cell division and then move toward the surface to undergo terminal differentiation (64). During the transition from the basal to the suprabasal layer, downregulation of p63, particularly its predominant isoform ΔNp63α, results in detachment from the basement membrane, at least partly via decreased expression of cell adhesion molecules (65). Downregulation of ΔNp63α also leads to upregulation of NOTCH1 gene expression and activity (9, 18). Having established that activated NOTCH1 triggers constitutive activation of ROCK1, we speculate that activated NOTCH1 may drive active movement of daughter cells toward the surface. This idea is supported by experiments showing that active ROCK1 induces formation of thick stress fibers and a cell contraction force which pushes cells upwards (54) and by the fact that Y-27632 inhibits differentiation as well as stratification in organotypic raft culture (37). Indeed, we observed that keratinocytes treated with EDTA exhibited increased cell motility and clambering movement, which were inhibited by Y-27632 (see Movies S1 and S2 in the supplemental material). We previously reported that ΔNp63α represses both p53-dependent and -independent expression of the Notch1 gene to support the proliferative capacity of normal human keratinocytes as well as a subset of cervical cancer cell lines (18). Thus, we propose that the p63-NOTCH1-ROCK1 axis plays an essential role in establishment of stratified epithelia through actomyosin-driven cell movement, though we cannot exclude the possible involvement of the Rho-ROCK pathway in this process. In terms of cancer biology, loss of p63 function is paradoxically associated with metastatic progression (66), implying another face of p63 as a tumor suppressor through the NOTCH1-ROCK1 pathway.

Two isoforms of ROCK, ROCK1 (ROKβ, p160ROCK) and ROCK2 (ROKα), have been identified in mammals; they share 65% overall identity and 92% identity in their kinase domains, and a number of lines of investigation have suggested nonoverlapping functions for these two isoforms (67–69). In this regard, ROCK1, but not ROCK2, has been shown to be constitutively activated by caspase-3 and to play roles in membrane blebbing during apoptosis (54, 55). We observed that knockdown of ROCK1 but not ROCK2 resulted in a reduced propensity for differentiation (Fig. 6B) and that a constitutively active form of ROCK1 induced differentiation (Fig. 8A). In parallel with our data, previous work has shown that the conditional expression of the activated form of ROCK2 also results in induction of differen-

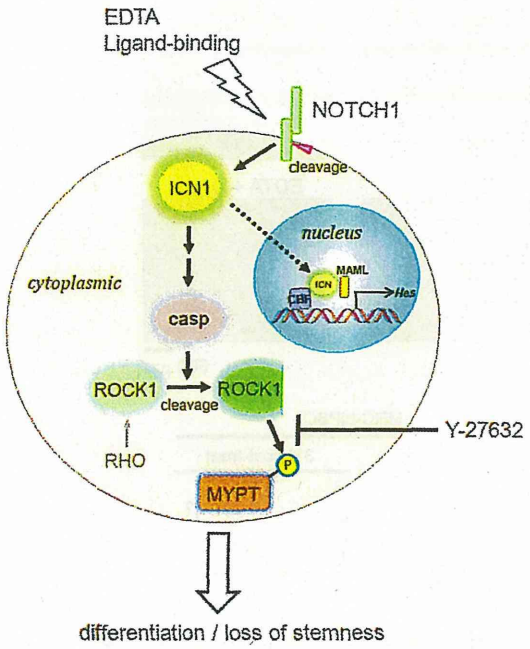

FIG 11 Proposed model for the NOTCH-ROCK pathway and its biological significance. NOTCH1 can be activated by dissociation of cells with EDTA as well as physiological ligand binding. The cytoplasmic form of NOTCH1, independent of its transcriptional activity, triggers caspase-mediated cleavage (activation) of ROCK1 by an as-yet-unknown mechanism. ROCK1 activation drives actomyocin reorganization through MYPT phosphorylation which results in cell differentiation or loss of stemness. The ROCK inhibitor Y-27632 blocks this pathway so as to inhibit differentiation of keratinocytes and maintain stemness of hiPSCs, as shown in this study.

tiation markers in keratinocytes (35). In contrast, it was reported that a ROCK inhibitor accelerated calcium- or suspension-induced keratinocyte differentiation (70). More recently, Notch1 was reported to be a p53 target gene involved in human keratinocyte tumor suppression through negative regulation of ROCK1,2 and MRCKalpha kinases (56). Furthermore, an oncogenic aspect of ROCK2 has also been reported (52, 71, 72). Apparent anomalies between these studies and our results imply complexity of the signals downstream of ROCK1 and ROCK2. However, our results clearly demonstrate that prompt activation of ROCK1 by noncanonical NOTCH1 signaling promotes keratinocyte differentiation and limits clonogenic cell growth. Part of the discrepancies may be explained by the use of different experimental systems. Our experimental system focused on early stages of keratinocyte differentiation in monolayer culture. However, our results are consistent with a more recent report that ROCK inhibition blocks differentiation as well as stratification in organotypic raft culture (37). It is possible that the canonical NOTCH1 signal and transcriptional repression of ROCK1,2 plays different roles in later stages of differentiation or tumor formation.

In spite of these important functions of ROCK1,2 in keratinocyte differentiation, no abnormalities in the epidermis of either Rock1- or Rock2-null mice have been described (67, 68, 73, 74). This suggests functional redundancy and compensatory mechanisms for these two proteins, though they show apparently quite different functions in culture. Synthetic effects in mice with compound heterozygous and/or homozygous disruptions in the Rock1 and Rock2 genes need to be delineated in detail.

Technical implications of NOTCH-ROCK dysregulation during cell passage. Our data show that keratinocytes of different tissue origins as well as hiPSCs exhibiting epiblast-like cell states have a conserved NOTCH1-ROCK1 pathway and that NOTCH activation is at least partly responsible for impaired clonogenicity upon dissociation with EDTA (Fig. 1C, 9, and 10). ROCK inhibition could robustly restore the proliferation capacity and contribute to the maintenance of stemness through blockade of cellular differentiation and/or apoptosis, unscheduled biological outcomes imposed by the EDTA treatment in cell culture. A recent groundbreaking report provided evidence that the combination of a ROCK inhibitor and fibroblast feeders indefinitely extends the life spans of many different types of human epithelial cells (38). Thus, it is highly likely that dissociation of cells with EDTA activates the NOTCH1-ROCK1 pathway and adversely affects the proliferative capacity of a broad spectrum of normal epithelial cells. Furthermore, most cell lines established through such procedures may represent a selected population resistant to the activation of the NOTCH-ROCK pathway.

In conclusion, our present study unveiled a link between noncanonical NOTCH signaling and ROCK activation and revealed a previously unrecognized function of NOTCH1 as a critical regulator of ROCK1 in dictating the cell fate. Our findings also imply a possible pitfall in cell culture and delineate a molecular rationale for the beneficial effects of the ROCK inhibitor Y-27632 in cultivating various cell types.

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T.Y. conceived the project, designed, performed, and analyzed experiments, and wrote the manuscript. K.N. performed the hiPSC clonogenic assay. N.G. and S.-I.O. provided cDNA clones and performed plasmid construction, respectively. M.F., A.U., and T.N. discussed and gave important advice on some experiments. T.K. participated in the experimental design and performed experiments.

We declare no conflict of interest related to this work.

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