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Nicotinamide Promotes Cell Survival and Differentiation as Kinase Inhibitor in Human Pluripotent Stem Cells

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SUMMARY

Nicotinamide, the amide form of vitamin B3, is widely used in disease treatments and stem cell applications. However, nicotinamide's impact often cannot be attributed to its nutritional functions. In a vitamin screen, we find that nicotinamide promotes cell survival and differentiation in human pluripotent stem cells. Nicotinamide inhibits the phosphorylation of myosin light chain, suppresses actomyosin contraction, and leads to improved cell survival after individualization. Further analysis demonstrates that nicotinamide is an inhibitor of multiple kinases, including ROCK and casein kinase 1. We demonstrate that nicotinamide affects human embryonic stem cell pluripotency and differentiation as a selective kinase inhibitor. The findings in this report may help researchers design better strategies to develop nicotinamide-related stem cell applications and disease treatments.

INTRODUCTION

Balanced cellular metabolism and signaling regulation are both essential for mammalian cells to survive, proliferate, and function. Nutrients are conventionally thought to act only as enzyme cofactors or energy sources. However, recent advances demonstrate that specific nutrients could also be involved in functions beyond nutritional support, such as epigenetic regulations and kinase cascades (Blaschke et al., 2013; Chen et al., 2013; Gao et al., 2016; Liu et al., 2017; Lu and Thompson, 2012; Sciacovelli et al., 2016; Tzatsos and Kandror, 2006; Yuan et al., 2013). In this report, we explored nicotinamide's role in stem cell regulation, and showed its regulatory roles as a kinase inhibitor.

Nicotinamide is the amide form of niacin, and both of them belong to the vitamin B3 family. They are the precursors of nicotinamide adenine dinucleotide (NAD), which acts as coenzyme in multiple cellular processes, including energy metabolism and DNA repair. Nicotinamide can be converted into nicotinamide mononucleotide (NMN) by nicotinamide phosphoribosyltransferase (NAMPT), which is then turned into NAD^+ by nicotinamide mononucleotide adenylyltransferase (NMNAT) (Maiese et al., 2009). The normal plasma concentration of nicotinamide and niacin is around 5 μM (Odum and Wakwe, 2012). Deficiencies in nicotinamide and niacin could lead to decreased NAD^+ production and cause pellagra, which affects the skin, digestive system, and CNS (Prakash et al., 2008). Nicotinamide, but not niacin, is also an inhibitor of sirtuin and poly(ADP-ribose) polymerase (PARP), which regulate protein deacetylation and DNA repair (Avalos et al., 2005; Jackson et al., 2003; Kuchmerovska et al., 2004; Saldeen and Welsh, 1998).

Nicotinamide has been widely used to treat diseases such as diabetes, schizophrenia, Alzheimer's disease, psoriasis, obesity, and cancer (Aisen et al., 2008; Bagcchi, 2015; Chase et al., 1992; Chen et al., 2015; Gale, 2004; Knip et al., 2000; Siadat et al., 2013; Smythies, 1973). High dosage of nicotinamide is often required in clinical treatment, and the concentration in serum could reach the millimolar range (Dragovic et al., 1995). At the same time, nicotinamide is also used in various cell culture practices. High dosage (more than 10 mM) of nicotinamide promotes cell survival in different cell types, including neural, liver, and heart cells (Ieraci and Herrera, 2006; Lin et al., 2000; Shen et al., 2004; Shi et al., 2012; Tong et al., 2012). Nicotinamide is extensively used in the *in vitro* culture of organoids, including cell types from colon, liver, pancreas, and fallopian tube (Huch et al., 2013b, 2015; Kessler et al., 2015; Sachs et al., 2018; Sato and Clevers, 2015; Sato et al., 2011; Yin et al., 2016). Nicotinamide also enhances expansion of adult stem cells from pancreas, colon, bone marrow, and umbilical cord (Horwitz et al., 2014; Huch et al., 2013a; Jung et al., 2011; Peled et al., 2012; Sugiyama et al., 2013). In pluripotent stem cells, nicotinamide promotes reprogramming, improves maintenance (Son et al., 2013), and facilitates cell differentiation

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to various lineages, including neural, pancreatic, and cardiac lineages (Buchholz et al., 2013; Griffin et al., 2017; Idelson et al., 2009; Nostro et al., 2015; Parsons et al., 2011; Vaca et al., 2008). Despite its numerous applications, the molecular mechanisms of nicotinamide are still unclear in many circumstances.

In this study, we set to explore the roles of common vitamins in human pluripotent stem cells (hPSCs), and identified nicotinamide as a regulator of hPSC pluripotency, survival, and differentiation. Nicotinamide promoted hPSC cell survival and differentiation. Further analysis showed that nicotinamide promoted cell survival as a Rho-associated protein kinase (ROCK) inhibitor, while it also inhibited other kinases including casein kinase 1 (CK1) and a few others. Finally, we demonstrated that nicotinamide also initiated differentiation as a kinase inhibitor. Our study revealed the mechanisms underlying nicotinamide's key functions, and expanded our understanding of its application in cell culture practices.

RESULTS

Nicotinamide Promotes hPSC Survival after Individualization through the Regulation of ROCK Pathway

hPSCs are vulnerable to cell death after individualization (Chen et al., 2010; Ohgushi et al., 2010). To identify the function of vitamins in stem cell regulation, we tested a set of 12 vitamins at three doses (based on their concentration in DMEM/F12) on cell survival after dissociation in H1 human embryonic stem cells (hESCs) (Figure S1A). Nicotinamide was the only vitamin that promoted hESCs survival after individualization, while high concentrations of retinol and cholecalciferol inhibited cell survival (Figure S1A). The effect of nicotinamide was dose dependent. Nicotinamide promoted survival of individualized cells at 5 and 10 mM, but at 25 mM showed significant toxicity to hESCs (Figure 1A). We then examined cell apoptosis during passage, and found that 10 mM nicotinamide significantly reduced the Annexin V-positive and propidium iodide-negative cells (Figures S1B and S1C). It suggested that nicotinamide suppressed apoptosis, and the observation was consistent with the improved cell survival by nicotinamide. Microscopy images showed that nicotinamide also suppressed the cell blebbing phenotype after dissociation in a dose-dependent manner (Figures 1B and 1C). The beneficial effect was also observed in other pluripotent stem cells (Figures S1D–S1F) as well as on different coating surfaces (Figures S1G and S1H).

To understand nicotinamide's role in cell survival, we tested modulators of a few known nicotinamide targets, including sirtuin inhibitors (EX527 and SirReal2) and PARP inhibitor (ABT888). However, neither single inhibitor nor their combination demonstrated the ability to improve cell survival (Figure S1I). It indicates that nicotinamide could function through some other pathways to promote cell survival. It is well known that individualized hESCs were killed through ROCK/actomyosin activation (Chen et al., 2010; Ohgushi et al., 2010). We compared the impact of nicotinamide on cell survival with ROCK inhibitor Y27632. After cell individualization and passaging, nicotinamide improved cell survival with similar efficiency as ROCK inhibitor. However, no additive beneficial effect was observed when they were applied together (Figure 1D), which suggested that nicotinamide and ROCK inhibitor possibly functioned through the same pathway. We then analyzed the impact of nicotinamide on the ROCK pathway. ROCK directly phosphorylates myosin phosphatase-targeting protein (MYPT) at Thr696, and also regulates the phosphorylation of myosin light chain (MLC) directly or indirectly through MYPT (Totsukawa et al., 2000). After dissociation, the phosphorylation of MLC and MYPT increased, and Y27632 and nicotinamide suppressed the phosphorylation of both MLC and MYPT significantly (Figure 1E). This impact of nicotinamide was dose dependent (Figure 1F). Immunostaining results showed that both nicotinamide and Y27632 decreased the colocalization between p-MLC (Ser19) and actin filament after hESC dissociation (Figure 1G). These data indicated that nicotinamide was a modulator of the ROCK pathway.

Nicotinamide Is a Direct ROCK Inhibitor Independent of NAD Pathway

Nicotinamide is the precursor of NAD^+ and NADH, so we tested whether nicotinamide improved cell survival through NAD metabolites. Niacin, NMN, NAD^+, and NADH were added to individualized cells, but none of them had significant effect on cell survival (Figure 2A), and these molecules did not block the cell blebbing after individualization (Figure S2A). NAMPT converts nicotinamide into NMN, but NAMPT inhibitors did not alter nicotinamide impact on cell survival (Figures 2B and S2B). Niacin also had no impact on the phosphorylation of MLC and MYPT (Figure 2C). These results suggested that the effects of nicotinamide on cell survival and ROCK pathway regulation were possibly independent of the NAD pathway, and nicotinamide itself might be the direct effector.

To study how nicotinamide inhibited ROCK, we tested the protein level of ROCK1 and ROCK2 during dissociation, and found that nicotinamide had no impact (Figure S2C). Then we evaluated the activity of ROCK1 and ROCK2 *in vitro* with different doses of nicotinamide

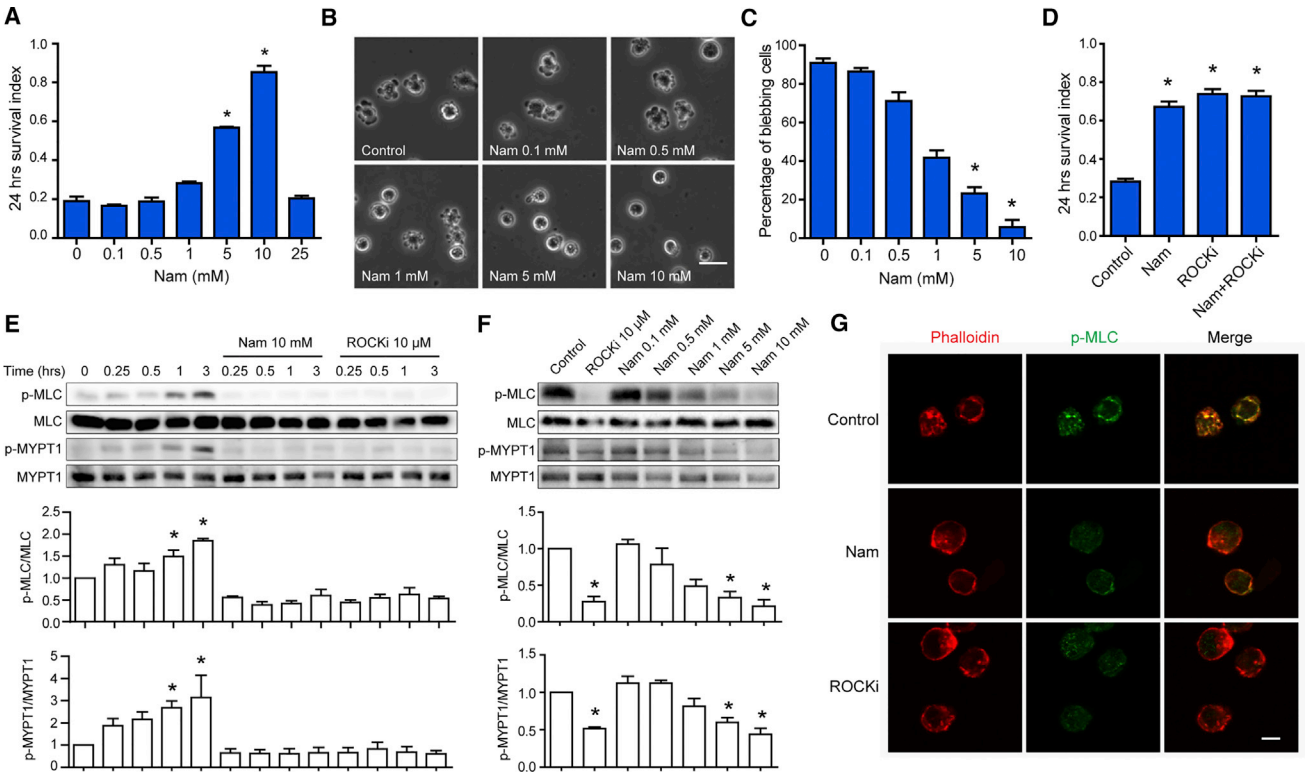

Figure 1. Nicotinamide Promotes hESC Survival through the Inhibition of the ROCK-Actomyosin Axis

(A) Dose-dependent effect of nicotinamide on cell survival after dissociation. hESCs (H1 cells unless otherwise stated) were counted 24 hr after individualization. The cell survival index represents the number of surviving cells divided by the input cell number (n = 3). Nam, Nicotinamide.

(B) Phase contrast images after individualization. hESCs were dissociated by TrypLE, neutralized by 0.5% BSA, and then treated with the indicated concentration of nicotinamide for 30 min. Scale bar, 20 μm.

(C) The percentage of blebbing cells under nicotinamide treatments at different concentrations. The percentage of blebbing cells was normalized by the total cell number (n ≥ 5 images).

(D) The comparison of nicotinamide and ROCK inhibitor Y27632 on cell survival after individualization (n = 3). Nam, nicotinamide 10 mM; ROCKi, Y27632 10 μM.

(E) The phosphorylation of MYPT1 (Thr 696) and MLC (Ser 19) in individualized hESCs under nicotinamide treatment. 10 μM ROCK inhibitor (Y27632) was used as positive control. Top, western blot image. Bottom, quantification of the western blot results (n = 3).

(F) Dose-dependent effect of nicotinamide on the phosphorylation of MYPT1 (Thr 696) and MLC (Ser 19). Individualized hESCs were treated with nicotinamide at indicated concentrations for 1 hr. Top, western blot image. Bottom, quantification of the western blot results (n = 3).

(G) Confocal images of individualized hESCs treated with 10 mM nicotinamide (Nam) or 10 μM ROCK inhibitor Y27632 (ROCKi). Red, phalloidin 594; green, p-MLC (Ser19). Scale bar, 10 μm.

Data are shown as means ± SEM. *p < 0.05 compared with control.

and niacin (Figures 2D and 2E). Surprisingly, the addition of nicotinamide significantly suppressed ROCK1 and ROCK2 activity in a dose-dependent manner, but niacin had almost no effect (Figures 2D and 2E). Computational simulation demonstrated that nicotinamide could potentially interact with key amino acid functional groups in the active site of ROCK2 (Figure S2D). The binding constant assay also confirmed the inhibition of ROCK1 and ROCK2 by nicotinamide (Figures 2F and 2G).

Nicotinamide Regulates More Than the ROCK Pathway

ROCK inhibitor Y27632 increases the cloning efficiency of hPSCs (Chen et al., 2010), so we examined the impact of nicotinamide on cloning efficiency. Compared with Y27632, nicotinamide-treated cells showed much smaller improvement in cloning efficiency (Figure 3A), even though both reagents had similar impact on 24-hr cell survival (Figure 1D). High concentrations of nicotinamide decreased the cell growth rate of hESCs (Figure 3B) and

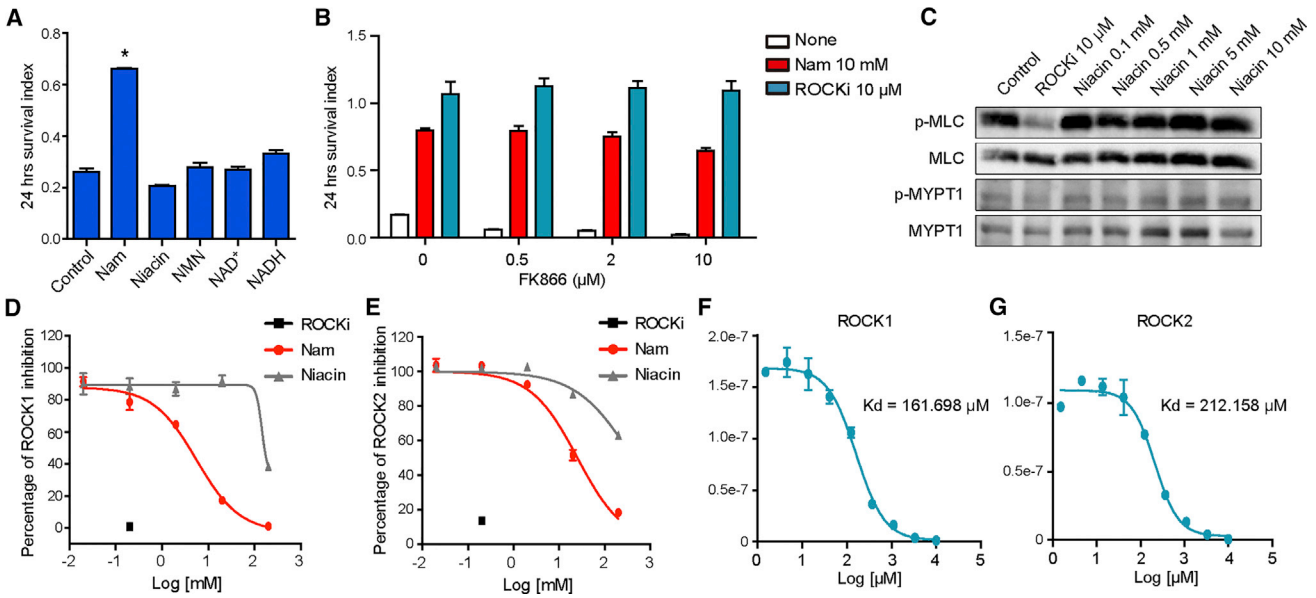

Figure 2. Nicotinamide Is a ROCK Inhibitor that Is Independent of the NAD Pathway

(A) The comparison of nicotinamide, niacin, NMN, NAD^+, and NADH on cell survival after individualization (n = 3). Nam, nicotinamide 10 mM; niacin, 5 mM; NMN, 5 mM; NAD^+, 5 mM; NADH, 1 mM.

(B) Nicotinamide phosphoribosyltransferase (NAMPT) inhibitor FK866 did not block the effect of nicotinamide on cell survival (n = 3). White, FK866 alone; red, FK866 together with 10 mM nicotinamide; blue, FK866 together with 10 μM Y27632.

(C) Niacin had no effect on the phosphorylation of MLC and MYPT. Individualized hESCs were treated with niacin at the indicated concentrations for 1 hr (n = 3).

(D and E) The impact of nicotinamide on ROCK activity *in vitro*. ROCK1 (D) and ROCK2 (E) activity was determined by ELISA under nicotinamide (Nam, red curve) or niacin (gray curve) treatment (n = 3 technical replicates). The results were repeated twice. 0.2 mM Y27632 (ROCKi) was used as positive control (black square).

(F and G) Binding constant measurements for the interactions of nicotinamide with ROCK1 (F) and ROCK2 (G). The x axis indicates the nicotinamide concentration (μM) in log10 scale (n = 2 technical replicates).

Data are shown as means ± SEM. *p < 0.05 compared with control.

reduced the mRNA level of *NANOG* and *POU5F1* (Figures 3C and 3D), which indicated that nicotinamide possibly induced hESC differentiation. Among the set of 12 vitamins examined in the differentiation of hESCs, nicotinamide was the only one that affected the pluripotency of hESCs (Figures S3A and S3B). Taken together, this evidence suggests that nicotinamide may have additional functions on pluripotency other than regulating the ROCK pathway.

To study the other functions of nicotinamide in hESCs beyond ROCK inhibition, we analyzed the global gene expression profile after 24 hr of nicotinamide and ROCK inhibitor treatment (Table S1). Hierarchical clustering analysis showed that nicotinamide treatment was not clustered with the ROCK inhibitor group (Figure 3E). Compared with control, nicotinamide increased the expression of 371 genes, and decreased the expression of 640 genes after a 24-hr treatment. However, only a small portion of these genes were shared by the cells treated with ROCK inhibitor (Figure S3C). The KEGG analysis showed that the genes downregulated by nicotinamide were enriched in pathways associated with pluripotency of stem cells, phosphatidylinositol 3-kinase, metabolism, transcription, and cancer (Figure 3F), and the gene expression patterns were different compared with the genes downregulated by the ROCK inhibitor (Figure S3D). The genes upregulated by nicotinamide were also enriched in different pathways from those upregulated by the ROCK inhibitor (Figures S3E and S3F). These data indicated that nicotinamide had multiple functions in hESC regulation.

Nicotinamide Affects hESC Differentiation in Multifaceted Manner

Because nicotinamide was a direct ROCK inhibitor at high concentration, we hypothesized that nicotinamide might be able to inhibit other kinases. Considering that most nicotinamide effects appeared at 10 mM in cell culture, we measured cellular nicotinamide amounts when 10 mM of nicotinamide was added in the medium. Liquid chromatography-mass spectrometry (LC-MS) results demonstrated that cellular nicotinamide concentration was around

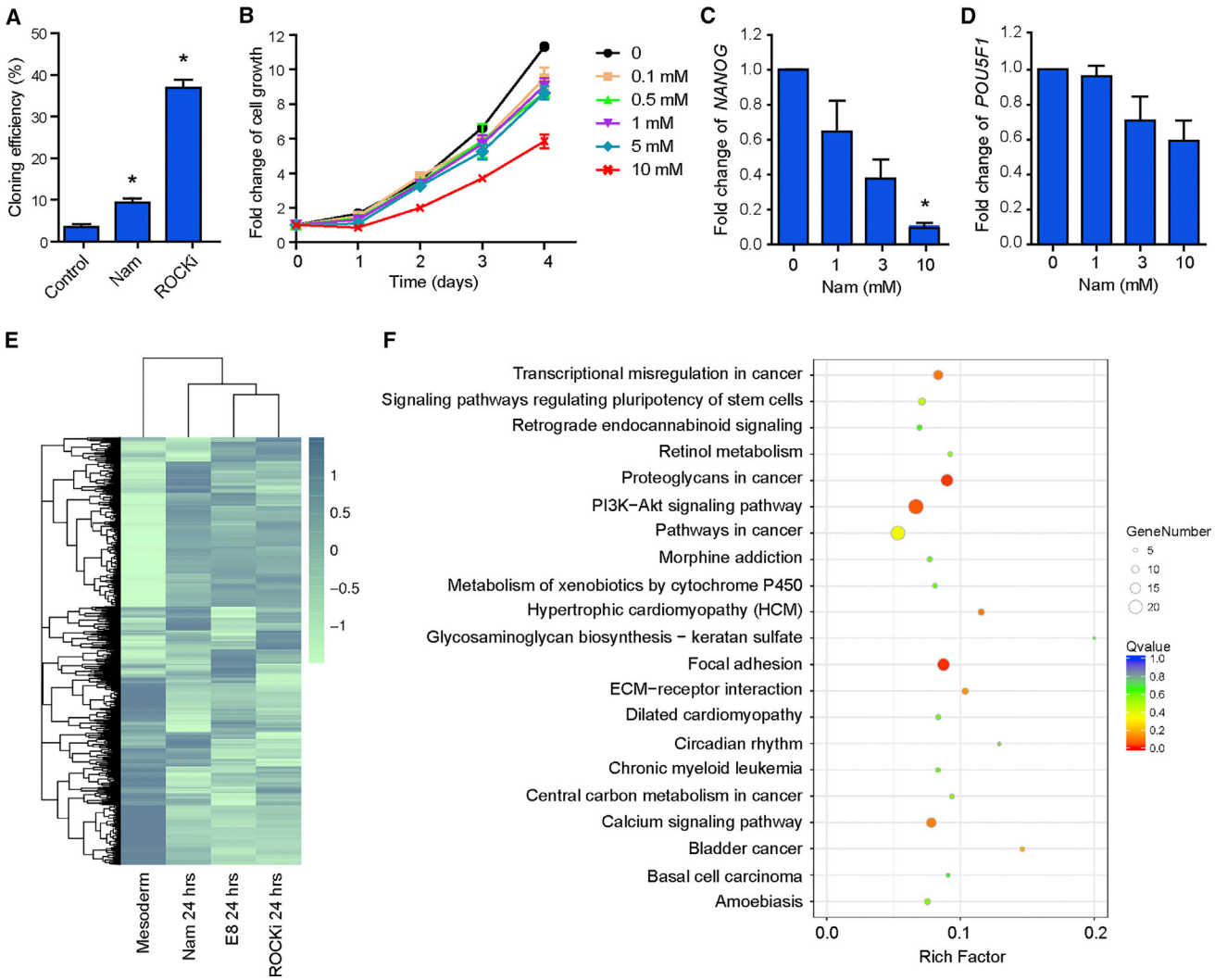

Figure 3. Nicotinamide Has More Functions Than the ROCK Inhibitor

(A) Comparison of ROCK inhibitor Y27632 (ROCKi) and nicotinamide (Nam) on cloning efficiency (n = 3).

(B) Dose-dependent effect of nicotinamide on cell growth. hESCs were treated with different doses of nicotinamide, and cell number was counted every day. The fold change was calculated by dividing the cell number by day 0 cell count (n = 3 technical replicates). The results were repeated three times.

(C and D) Dose-dependent effect of nicotinamide on pluripotency. *NANOG* (C) and *POU5F1* (D) expression (normalized to control without treatment) were analyzed by qPCR after 3 days of differentiation (n = 3).

(E) Hierarchical clustering of samples with indicated treatments in microarray analysis. The phylogenetic relationships of genes are shown on the left, and the cluster relationship of samples is indicated on the top. hESC samples were collected after 24 hr of treatment and compared with untreated control and differentiated mesoderm cells. ROCKi, Y27632 (10 μM for 24 hr). Nam, nicotinamide (10 mM for 24 hr). Mesoderm, hESC-derived mesoderm cells.

(F) Bubble plot of enriched KEGG pathways from nicotinamide downregulated genes.

Data are shown as means ± SEM. *p < 0.05 compared with control.

1.5 mM after 1 hr of incubation (Figure 4A). Based on the above information, the KINOMEscan assay in a competition-binding method was used to screen the interaction between nicotinamide and the active sites of 97 kinases (Davis et al., 2011; Egan et al., 2015; Fabian et al., 2005; Somoza et al., 2015), and the screening was performed at 1 and 3 mM. We found that multiple kinases were significantly inhibited by nicotinamide (Figure 4B; Table S2). Nicotinamide inhibited 96.7% of kinase-ligand interaction of ROCK2 at 3 mM, which is consistent with the *in vitro* kinase assay (Figure 2D). It also inhibited 92.3% of kinase-ligand interaction of CK1δ (Figure 4B; Table S2). The kinase

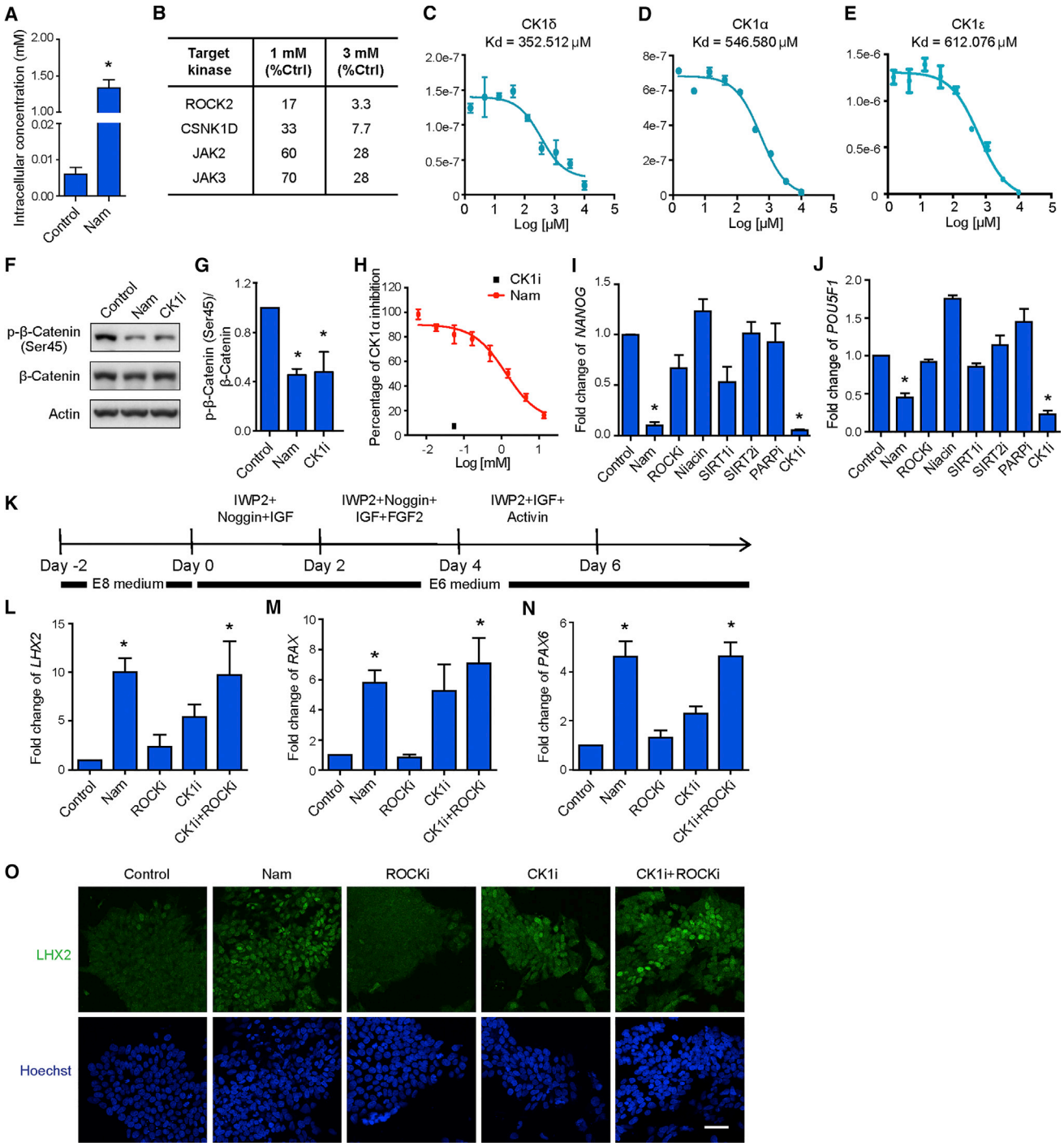

Figure 4. Nicotinamide Inhibits CK1 and Promotes hESC Differentiation

(A) The cellular concentration of nicotinamide determined by LC-MS after 1 hr of treatment. hESCs were cultured in normal E8 medium without additional nicotinamide (Control), or E8 medium with additional 10 mM nicotinamide (Nam) (n = 3).

(B) The kinase screening profile for nicotinamide, obtained using the DiscoverRx KINOMEscan service. Nicotinamide was screened at 1 and 3 mM for its ability to inhibit the binding of 97 kinases to substrates in the assay. % Ctrl represents the results of primary screen on binding interactions, and lower numbers indicate stronger hits (see also Table S2).

(C–E) Binding constant measurements for the interactions of nicotinamide with CK1δ, (C) CK1α (D), and CK1ε (E). The x axis indicates the nicotinamide concentration (μM) in log10 scale (n = 2 technical replicates).

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binding constants of nicotinamide with CK1δ, CK1α, and CK1ε were 352.512, 546.580, and 612.076 μM, respectively (Figures 4C–4E). β-Catenin is the substrate of CK1α, and is specifically phosphorylated at Ser45 (Amit et al., 2002; Liu et al., 2002). We examined β-catenin phosphorylation (Ser45) in hESC, and found that nicotinamide and CK1 inhibitor significantly suppressed Ser45 phosphorylation (Figures 4F and 4G). We also evaluated the impact of nicotinamide on the CK1α activity *in vitro* using the bioluminescent kinase assay, and the result showed that nicotinamide inhibited CK1α in a dose-dependent manner (Figure 4H).

Based on the findings in the kinase screen, we examined whether any of the nicotinamide-inhibited kinases or other targets could affect differentiation in hESCs. hESCs were treated with a set of small molecules that modulated the activities of nicotinamide targets, and allowed to spontaneously differentiate for 3 days. Similar to nicotinamide, CK1 inhibitor D4476 significantly reduced the mRNA level of pluripotency markers (*NANOG* and *POU5F1*); in contrast, other inhibitors in ROCK, PARP, and sirtuin pathways did not have a significant impact (Figures 4I and 4J). In embryoid body differentiation, nicotinamide inhibited the expression of meso-endoderm marker genes (*MIXL1*, *TBXT*, *EOMES*, and *SOX17*), and induced the expression of ectoderm marker genes (*PAX6* and *NEUROD1*). CK1 inhibitor D4476 demonstrated a similar effect (Figure S3G). We also confirmed that both nicotinamide and CK1 inhibitor D4476 blocked meso-endoderm differentiation in BMP4-induced differentiation (Figures S3H–S3J). These results suggest that nicotinamide could lead to hPSC differentiation through the inhibition of CK1.

Nicotinamide was reported as an inducer of retinal pigment epithelium (RPE) differentiation (Buchholz et al., 2013), so we explored whether nicotinamide affects RPE differentiation through CK1 inhibition (Figure 4K). Consistent with previous reports, nicotinamide increased the expression of early eye field markers *LHX2*, *PAX6*, and *RAX* on day 6 of RPE differentiation. ROCK inhibitor, SIRT2 inhibitor, PARP inhibitor, and niacin alone had little effect, while joint treatment with ROCK inhibitor and SIRT1 inhibitor improved the mRNA level of *LHX2*, *PAX6*, and *RAX*, even though the level was much lower than with nicotinamide (Figures S4A–S4C). At the same time, CK1 inhibitor D4476 significantly induced the expression of early eye field markers *LHX2*, *PAX6*, and *RAX* (Figures 4L–4N). The positive impact of nicotinamide, CK1 inhibitor, and CK1/ROCK dual inhibition on RPE differentiation was further confirmed by LHX2 immunostaining (Figure 4O) and flow cytometry analysis (Figure S4D). Similar results were obtained with H9 (Figures S4E–4G) and human induced pluripotent stem cell lines NL1 (Figures S4H–S4J) and NL4 (Figures S4K–S4M). These results indicate that the effect of nicotinamide on RPE differentiation potentially relies on its inhibition on ROCK and CK1 pathways.

DISCUSSION

Nicotinamide is widely used in disease treatments and stem cell applications, but many of its effects cannot be explained by its role in nutritional regulation. We demonstrated that nicotinamide regulates stem cell survival and differentiation through the inhibition of specific kinases. Besides its complicated role in metabolism, DNA repair, and epigenetic modification, nicotinamide can modulate various cellular functions through kinase cascades. This is consistent with the diverse applications related to nicotinamide.

Nicotinamide has long been used in stem cell culture to improve stem cell performance. Nicotinamide enhanced cell survival and reprogramming, but its function was attributed to its role in the sirtuin pathway and nutritional regulation (Avalos et al., 2005; Son et al., 2013). Our study showed that nicotinamide was a ROCK inhibitor. ROCK inhibitors are known to suppress actomyosin contraction, improve cell survival, and enhance reprogramming

(F) The phosphorylation of β-catenin was decreased by 10 mM nicotinamide or 5 μM CK1 inhibitor D4476 treatment for 6 hr (n = 3) as shown by western blot.
(G) Quantification of the western blot results by densitometry (n = 3).
(H) The impact of nicotinamide on CK1α activity *in vitro*. CK1α activity was determined using the bioluminescent kinase assay under nicotinamide (Nam, red curve) treatment (n = 3 technical replicates). The results were repeated three times. 50 μM D4476 (CK1i) was used as positive control (black square).
(I and J) Analysis of *NANOG* (I) and *POU5F1* (J) mRNA expression by qPCR after 3 days of spontaneous differentiation. Data are normalized to control (n = 3). Nam, nicotinamide 10 mM; ROCKi, Y27632 10 μM; Niacin, 5 mM; SIRT1i, Ex527 10 μM; SIRT2i, SirReal2 500 nM; PARPi, ABT888 50 nM; CK1i, D4476 5 μM.
(K) A schematic diagram showing the protocol to differentiate hESCs toward early eye field.
(L–N) Nicotinamide and CK1 inhibition promoted the expression of early eye field markers. Expression of *LHX2* (L), *RAX* (M), and *PAX6* (N) were analyzed by qPCR (n = 3). Nam, nicotinamide 10 mM; ROCKi, Y27632 10 μM; CK1i, D4476 5 μM.
(O) Immunostaining of LHX2 (green) on day 12 of RPE differentiation. ROCKi, Y27632 10 μM; Nam, nicotinamide 10 mM; CK1i, D4476 5 μM. Scale bar, 50 μm. Images are representative of three independent experiments.
Data are shown as means ± SEM. *p < 0.05 compared with control.

efficiency (Chen et al., 2010; Ohgushi et al., 2010; Watanabe et al., 2007). It is possible that nicotinamide benefits the stem cell culture through its role as a ROCK inhibitor. It is noteworthy that nicotinamide is used in many organoid culture systems, which are also benefited by ROCK inhibition in organoid formation (Miyoshi and Stappenbeck, 2013). The positive effect of nicotinamide on organoid culture may also be related to its role as a ROCK inhibitor.

Nicotinamide is used in many different stem cell differentiation platforms, and our data show that this function is likely not based on its inhibition of ROCK. The kinase screen data in this report showed that nicotinamide also inhibited CK1 and other kinases that are associated with pluripotency. In the limited tests, we showed that some of nicotinamide's impacts on differentiation could potentially be explained by its ability to inhibit CK1 pathways. In RPE differentiation, combination of ROCK and CK1 inhibitors achieved similar effects as nicotinamide alone, which supports our argument that nicotinamide might drive differentiation through CK1 modulation.

Unlike nicotinamide, niacin does not inhibit either ROCK or CK1, even though both belong to the vitamin B3 family. It is important to consider their differential impact on cellular functions when people plan to use vitamin B3 for specific treatments. The kinase pathways affected by nicotinamide could provide valuable references for relevant clinical applications.

We noticed that nicotinamide was effective in kinase inhibition only at high concentrations, and there is an obvious dose-dependent effect. The high concentration of nicotinamide is often used in disease treatment and cell culture. However, the level of nicotinamide in the serum is much lower. This suggests a dual role of nicotinamide controlled by its cellular concentration. Low-level nicotinamide is sufficient to meet cellular needs as a nutrient, but high concentrations lead to kinase inhibition and subsequently affect survival and differentiation. This partially explains why nicotinamide's effect on kinase activity was not previously revealed.

In summary, this report revealed nicotinamide as a kinase inhibitor regulating stem cell survival and differentiation. These results have practical implications for nicotinamide-related treatments, and provide another angle to further improve its applications.

EXPERIMENTAL PROCEDURES

Experimental procedures are also provided in Supplemental Information.

hPSC Culture and Survival Assays

The use of hESCs and hiPSCs was approved by the Institutional Review Board at the University of Macau. hESC culture and survival assays were carried out as described previously (Chen et al., 2010). See Supplemental Information for more details.

hESC Differentiation to Early RPE Lineage

hPSCs were passaged 1:6 on Matrigel (Corning Life Sciences) in E8 medium with 10 μM Y27632 and changed to fresh E8 after cell attachment for 24 hr. Then the differentiation was induced following the methods reported previously with slight modifications (Buchholz et al., 2013). The detailed method is in Supplemental Information.

Statistical Analysis

Data are shown as means ± SEM of at least three independent experiments unless otherwise specified, and Student's t test was used for statistical analysis. p values < 0.05 were considered significant.

ACCESSION NUMBERS

The accession number for the microarray data reported in this paper is GEO: GSE121230.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, four figures, and two tables and can be found with this article online at https://doi.org/10.1016/j.stemcr.2018.10.023.

AUTHOR CONTRIBUTIONS

G.C., Y.M., and J.A.T. conceived and designed the study. Y.M., W.L., and G.C. performed the cell survival assays and ROCK-related experiments. F.X. measured intracellular nicotinamide concentration by LC-tandem MS. Y.M. and X.Z. performed hPSC differentiation experiments. Z.R., C.S., and Y.M. prepared samples for microarray and analyzed the data. V.Y.-F.W. contributed to the structure modeling. L.L and Y.M. performed the Annexin V and propidium iodide staining. Y.M., W. L., and G.C. wrote the paper. Most authors contributed to the editing and proofreading of the manuscript.

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