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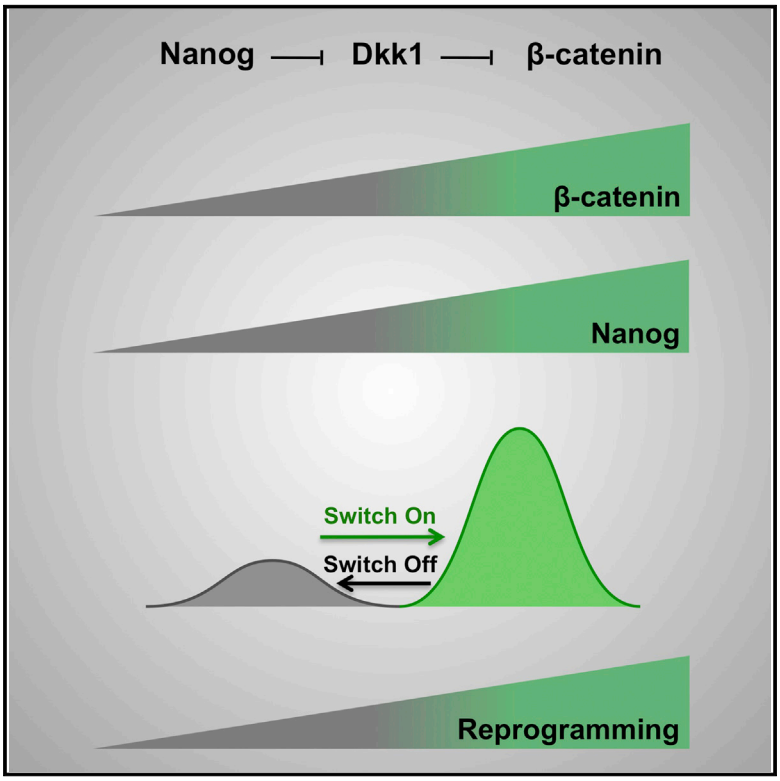
β-Catenin Fluctuates in Mouse ESCs and Is Essential for Nanog-Mediated Reprogramming of Somatic Cells to Pluripotency

Graphical Abstract



Highlights

Nanog activates the Wnt pathway by repressing Dkk1

Nanog enhances reprogramming by activating the Wnt pathway

β-Catenin fluctuates in ESCs following Nanog dynamics in serum+LIF medium

β-Catenin is metastable in ESCs cultured in serum+LIF and in 2i+LIF media

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In Brief

Embryonic stem cell (ESC) pluripotency is controlled by a network of transcription factors, which includes Nanog, and by the Wnt /β-catenin pathway. In this study, Marucci et al. show that repression of Dkk1 by Nanog is essential for Nanog-mediated reprogramming of somatic cells. β-Catenin and Nanog exhibit correlated heterogeneity, fluctuating synchronously in ESCs cultured in serum plus leukemia inhibitory factor (LIF). Instead, β-catenin fluctuations are independent of Nanog in 2i+LIF, a medium that favors pluripotency and loss of mosaic expression of stem genes.

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β-Catenin Fluctuates in Mouse ESCs and Is Essential for Nanog-Mediated Reprogramming of Somatic Cells to Pluripotency

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SUMMARY

The Wnt/β-catenin pathway and Nanog are key regulators of embryonic stem cell (ESC) pluripotency and the reprogramming of somatic cells. Here, we demonstrate that the repression of Dkk1 by Nanog, which leads indirectly to β-catenin activation, is essential for reprogramming after fusion of ESCs overexpressing Nanog. In addition, β-catenin is necessary in Nanog-dependent conversion of preinduced pluripotent stem cells (pre-iPSCs) into iPSCs. The activation of β-catenin by Nanog causes fluctuations of β-catenin in ESCs cultured in serum plus leukemia inhibitory factor (serum+LIF) medium, in which protein levels of key pluripotency factors are heterogeneous. In 2i+LIF medium, which favors propagation of ESCs in a ground state of pluripotency with many pluripotency genes losing mosaic expression, we show Nanog-independent β-catenin fluctuations. Overall, we demonstrate Nanog and β-catenin cooperation in establishing naive pluripotency during the reprogramming process and their correlated heterogeneity in ESCs primed toward differentiation.

INTRODUCTION

The activation of the Wnt signaling pathway enhances embryonic stem cell (ESC) self-renewal and reprogramming of somatic cells to pluripotency (Kühl and Kühl, 2013; Lluis et al., 2008; Marson et al., 2008; Sato et al., 2004; Sokol, 2011). β-Catenin is the key effector of this pathway, and its stability is modulated by the destruction complex, which is formed by Gsk3, Axin, APC, and CK1 (Stamos and Weis, 2013). Dickkopf-related protein 1 (Dkk1) is one of the β-catenin targets, and it binds the LRP-5/6 Wnt coreceptor to prevent the binding of its ligand (Kawano and Kypta, 2003).

Mouse ESCs are transcriptionally heterogeneous. In serum plus leukemia inhibitory factor (serum+LIF) medium, Esrrb (van den Berg et al., 2008), Stella (Hayashi et al., 2008), Nanog, zinc-finger protein 42, T box 3, and Klf4 show metastable protein expression levels (Cahan and Daley, 2013). In contrast, in ESCs cultured in 2i+LIF medium, which include Mek and GSK3 inhibitors (Ying et al., 2008), the expression profile is homogeneous (Marks et al., 2012; Wray et al., 2010).

Nanog is a key factor in the ESC core pluripotency network and is necessary for maintenance of the naive pluripotent state of ESCs (Chambers et al., 2003; Loh et al., 2006; Mitsui et al., 2003). Overexpression of Nanog enhances cell-fusion-mediated reprogramming (Silva et al., 2006) and is essential for conversion of preinduced pluripotent stem cells (pre-iPSCs) to fully reprogrammed iPSCs (Silva et al., 2009).

Here, we demonstrate that Nanog controls β-catenin through direct inhibition of Dkk1, which results in β-catenin accumulation in ESCs overexpressing Nanog. β-Catenin is essential for reprogramming of somatic cells after their fusion with Nanog-overexpressing ESCs and for the conversion of pre-iPSCs into iPSCs, when Nanog establishes naive pluripotency during the reprogramming process.

Furthermore, we show that β-catenin fluctuates synchronously with Nanog in mouse ESCs cultured in serum+LIF, while its fluctuations in 2i+LIF are independent of Nanog. We derived a differential equation-based model that captures Nanog and β-catenin fluctuations with bistable dynamics.

RESULTS

Nanog Regulates the Wnt/β-Catenin Pathway by Repressing Dkk1

ESC pluripotency is regulated by a network of signaling pathways and transcription factors. We examined the functional correlation between Nanog and β-catenin activities in ESCs.

First, we investigated Wnt pathway activity in ESCs that overexpress Nanog (EF4 cells) (Silva et al., 2006) and in ESC mutants lacking one Nanog allele (Nanog βgeo/+ cells) (Mitsui et al., 2003). EF4 cells accumulated high levels of β-catenin,

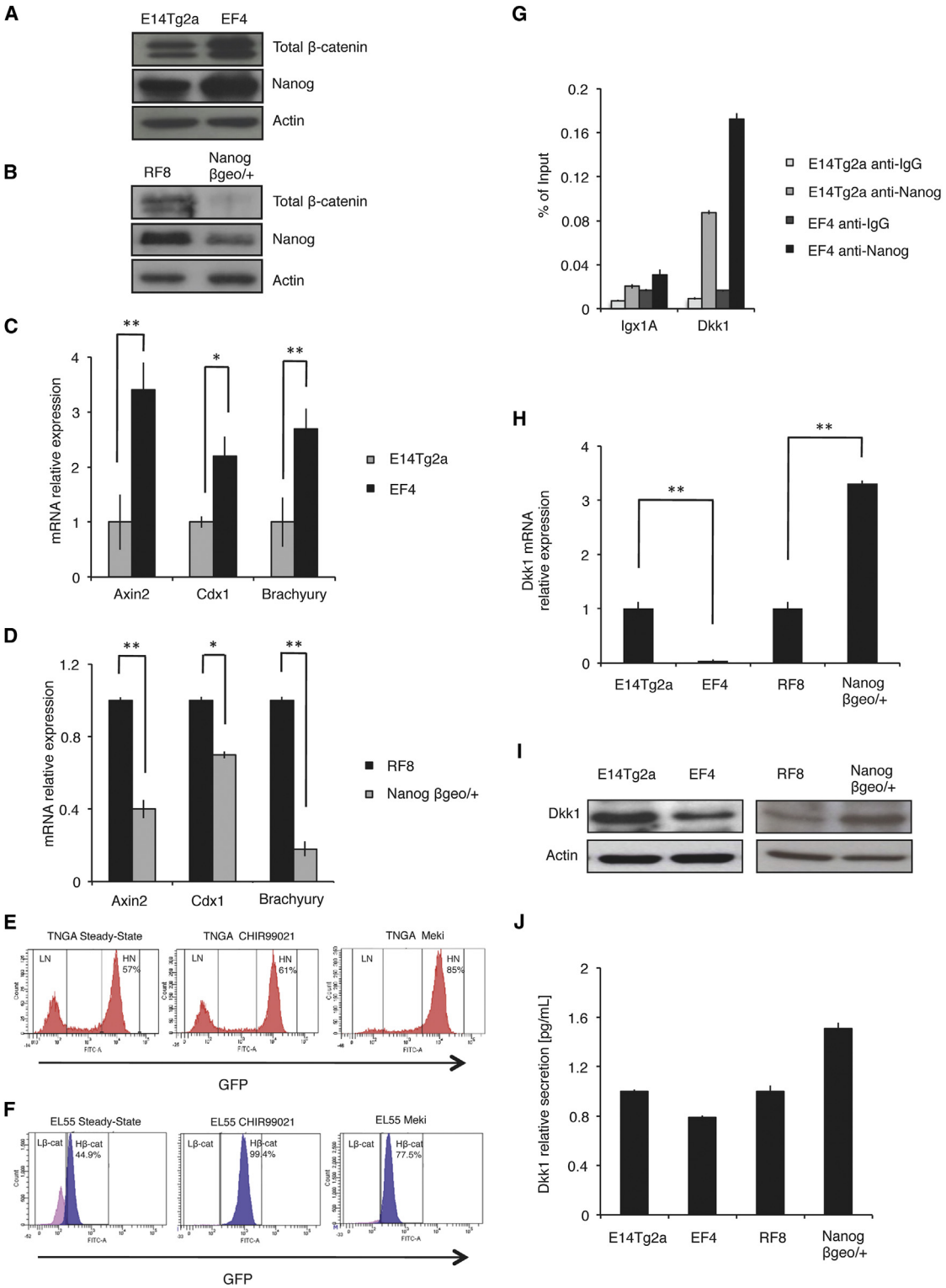

Figure 1. Nanog Stabilizes β-Catenin Levels by Inhibiting Dkk1

(A and B) Western blot of total β-catenin and Nanog in E14Tg2a, EF4 (A), RF8, and Nanog βgeo/+ cells (B).

(C and D) Quantitative PCR (qPCR) of Wnt pathway targets in E14Tg2a, EF4 (C), RF8, and Nanog βgeo/+ cells (D).

(E and F) FACS analysis of GFP distribution of TNGA and EL55 cells treated with Chiron (3 μM) for 1 day and the Mek inhibitor PD184352 (3 μM) for 7 days.

(G) Chromatin immunoprecipitation (ChIP) of Nanog on Dkk1 and Igx1A promoters in E14Tg2a and EF4 cells.

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while Nanog βgeo/+ cells showed reduced levels, as compared to controls (E14Tg2a and RF8 cells, respectively) (Figures 1A, 1B, and S1A). The Wnt/β-catenin target genes Axin2, Cdx1, and Brachyury were expressed at higher levels in EF4 cells (Figure 1C), and at lower levels in Nanog βgeo/+ cells (Figure 1D), compared to controls. These data suggest that Nanog promotes β-catenin accumulation in ESCs. Of note, levels of Nanog were not altered in EF4 cells treated with the Wnt pathway inhibitors Dkk1 or IWP2, while β-catenin levels and activity were reduced (Figures S1B–S1D).

We next asked whether β-catenin is Nanog dependent in TNGA cells, an ESC line expressing GFP from Nanog allele (Chambers et al., 2007), and in EL55 cells, an ESC line expressing endogenous β-catenin fused with GFP (Figures S1E–S1I). GFP-tagged β-catenin colocalized and had correlated expression levels with endogenous β-catenin and did not show abnormal endosomal accumulation (Figures S1J and S1K; $r = 0.98$). Untagged and GFP-tagged forms of β-catenin in EL55 cells were increased upon activation of the Wnt pathway using the GSK3 inhibitor Chiron (CHIR99021) (Figure S1L), and β-catenin target genes were turned on by Chiron treatment (Figure S1M).

To investigate whether β-catenin is Nanog dependent, we used a Mek inhibitor (Meki) (Ying et al., 2008), which upregulates Nanog (Silva et al., 2009), and Chiron. Upon Chiron treatment, the GFP distribution in TNGA cells was unaltered, while EL55 cells became almost all GFP+ (Figures 1E and 1F, Hβ-cat). In contrast, upon Nanog induction using the Meki, both TNGA and EL55 cells became GFP+ (Figures 1E and 1F, Hβ-cat, HN), which suggested that Nanog controls β-catenin stabilization. Moreover there was no β-catenin accumulation in Nanog null cells (Nanog βgeo/Hygro) (Mitsui et al., 2003) upon Meki treatment (Figure S1N).

Dkk1 is a secreted factor (Niehrs, 2006) expressed by ESCs (Kotini et al., 2011) that prevents binding of the Wnts (Kawano and Kypta, 2003). Having observed activation of Wnt targets in EF4 cells and induction of β-catenin accumulation by Nanog, we investigated whether Nanog is a repressor of Dkk1. We show Nanog binding to the Dkk1 promoter in ESCs and increased binding in EF4 cells (Figure 1G), which suggests direct regulation of Dkk1 transcription by Nanog. Accordingly, Dkk1 mRNA and protein levels were lower in EF4 cells and higher in Nanog βgeo/+ cells compared to controls (Figures 1H and 1I). Dkk1 levels were comparable in the different cell media (Figure 1J), indicating the prevalence of its autocrine regulation of the Wnt pathway.

Overall, these data show that Nanog represses Dkk1 transcription and thereby induces indirect activation of the Wnt/β-catenin pathway by promoting β-catenin accumulation.

Nanog Enhances Cell-Fusion-Mediated Reprogramming by Increasing β-Catenin Accumulation upon Dkk1 Repression

β-Catenin accumulation and Nanog overexpression in ESCs enhance reprogramming after fusion (Lluis and Cosma, 2009; Lluis et al., 2008, 2010; Silva et al., 2006). As Nanog overexpression stabilizes β-catenin in EF4 cells through Dkk1 repression, we investigated whether reprogramming of somatic cells after EF4-cell fusion was due to Nanog in cooperation with the Wnt/β-catenin pathway. Thus, we fused NPCs-Oct4-Puro-GFP (neural precursor cells carrying the Oct4-Puro-GFP transgene) with wild-type ESCs, with EF4, and with Dkk1-treated EF4 cells (Figures 2A and S1C). GFP-positive reprogrammed clones were stained for alkaline phosphatase (AP) and counted. As expected, overexpression of Nanog in EF4 cells increased reprogramming. In contrast, AP+ and GFP+ colonies were strongly reduced by Dkk1 pretreatment of EF4 cells (Figures 2B, 2C, and S2A). Of note, cell-fusion efficiency was not modulated by Nanog overexpression or Dkk1 treatment (Figure S2B). These data indicated that activation of the Wnt pathway is essential for enhancement of reprogramming by Nanog.

These results were confirmed by the silencing of Dkk1 in wild-type ESCs (E14Tg2a) with a small hairpin (ShRNA) (Figures S2C–S2E), which induced stabilization of β-catenin (Figure S2D), increased levels of Axin2, and no changes in Nanog expression (Figure S2E); AP+ and GFP+ colonies were increased in ShRNA-Dkk1-E14Tg2a fused with NPCs-Oct4-Puro-GFP (Figures S2F–S2H).

Next, we generated ΔN4 and N1 clones after overexpressing Nanog in ESCs deleted for β-catenin (Δ/Δ) and in the parental wild-type cell line (fl/fl) (Lyashenko et al., 2011). These lines carried Nanog expression levels comparable to those in EF4 cells (Figure S2I), while Axin2, Cdx1, and Brachyury were overexpressed in N1, but not in ΔN4 cells (Figure S2J).

There was no increase in AP+ and GFP+ clones after fusion of ΔN4 cells with NPCs-Oct4-Puro-GFP, while there was increased reprogramming after fusion of N1 cells, with respect to controls (Figures 2D, 2E, and S2K). These data show that β-catenin is essential in the reprogramming process mediated by Nanog.

We ruled out reprogramming defects due to loss of stem features or cell-fusion capability of β-catenin null cells. Indeed, in serum+LIF medium, β-catenin null and the parental line had similar morphology (Figure S2L) and expressed normal levels of pluripotency genes (Figures S2M and S2N, fl/fl, Δ/Δ; Lyashenko et al., 2011). Furthermore, β-catenin null cells had no cell-adhesion defects, as shown by normal E-cadherin levels, which was probably due to upregulation of Plakoglobin and unchanged fusion efficiency (Figures S2N–S2P, fl/fl, Δ/Δ; Lyashenko et al., 2011). Similar features were also confirmed in another β-catenin null ESC line (Wray et al., 2011) (Figures S2N and S2O, fl/−, Δ/−; Wray et al., 2011).

Esrrb cooperates with Nanog in enhancement of reprogramming (Festuccia et al., 2012; Martello et al., 2012). We observed no changes in the expression of Esrrb, thereby excluding its role in reprogramming when Wnt/β-catenin activity was perturbed (Figure S2Q).

Finally, we also noted that Wnt3a levels were slightly higher in EF4 cells as compared to ΔN4 cells (Figure S2R); however,

(H) Dkk1 qPCR in EF4, wild-type ESCs (E14Tg2a, RF8), and Nanog βgeo/+.
(I) Western blot of Dkk1 in wild-type and mutant ESCs.
(J) Secreted Dkk1 concentration measured by ELISA assay.
Data are means ± SEM (n = 3). $p > 0.1$, *$p < 0.05$, **$p < 0.01$.

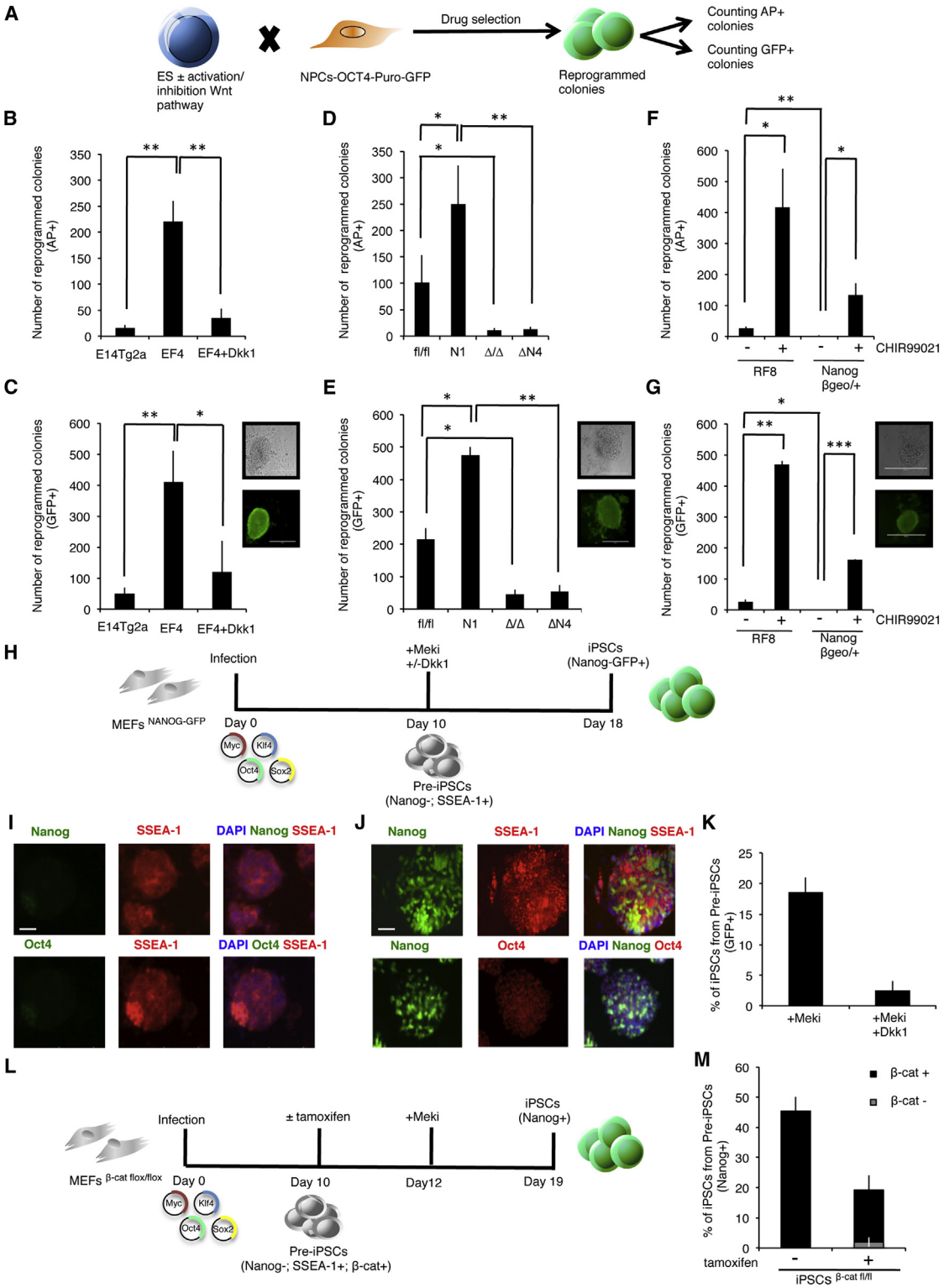

Figure 2. β-Catenin Is Essential for Nanog-Mediated Reprogramming of NPCs after Cell Fusion and for Conversion of Pre-iPSCs in iPSCs

(A) Scheme of spontaneous cell fusion between mESCs and NPCs.

(B and C) Reprogramming efficiency of E14Tg2a, EF4, and EF4 cells pretreated with Dkk1 (50 ng/ml, 24 hr), counting AP+ (B) and GFP+ (C) colonies. (C, inset) Representative GFP clone.

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Chiron treatment induced upregulation of Wnt3a to similar levels in wild-type and βgeo/+ ESCs over the controls (Figure S2S). These data therefore excluded that overexpression of Nanog induces an upregulation of Wnt3a, which is dependent on β-catenin instead.

To further investigate β-catenin and Nanog interplay in reprogramming, we asked whether ESCs deleted for Nanog in one allele (Nanog βgeo/+) might not reprogram somatic cells after fusion, due to low β-catenin accumulation. Thus, we treated Nanog βgeo/+ and RF8 cells with Chiron, to stabilize β-catenin and activate target genes, without altering the levels of Nanog (Figures S2T and S2U), and fused these cells with NPCs-Oct4-Puro-GFP. No reprogrammed clones were selected after fusion of Nanog βgeo/+ ESCs, while reprogramming was greatly increased after fusion of Nanog βgeo/+ ESCs pretreated with Chiron (Figures 2F, 2G, and S2V). These data demonstrate that β-catenin stabilization with Chiron can rescue the lack of reprogramming after fusion of Nanog βgeo/+ ESCs.

Of note, Nanog βgeo/+ cells do not show pluripotency defects (Mitsui et al., 2003). Furthermore, E-cadherin and Plakoglobin levels and fusion efficiency were comparable to the parental line (Figures S2W–S2Y). Finally, reprogramming efficiency was not rescued by Wnt3a pretreatment of Nanog βgeo/+ ESCs (Figures S2Z–S2B^{I}). The low Nanog levels and consequently high Dkk1 in this cell line (Figure 1I) likely impaired the binding of Wnt3a to its receptor, as shown also by the lack of Wnt pathway activity (Figure S2C^{I}).

β-Catenin Is Essential for Nanog-Mediated Conversion of Pre-iPSCs into iPSCs

Stepwise modulation of the Wnt pathway is necessary for reprogramming mouse embryonic fibroblasts (MEFs) into iPSCs (Aulicino et al., 2014; Ho et al., 2013). Furthermore, Nanog is necessary for pre-iPSCs to become iPSCs (Silva et al., 2009). However, whether the Wnt pathway and Nanog cooperate in this conversion has not been studied.

MEFs stably carrying a GFP reporter for Nanog were infected with the mouse transcription factors Oct4, Klf4, Sox2, and c-Myc (OKSM) (Figure 2H). In pre-iPSCs positive for SSEA-1 and negative for Nanog (Figure S2D^{I}), we upregulated Nanog using a Mek inhibitor (Silva et al., 2008), and at the same time, we inhibited the Wnt pathway by adding Dkk1 (Figures 2H and S2E^{I}). There was a significantly reduced number of iPSCs generated from pre-iPSCs, while iPSCs were efficiently generated without inhibition of the Wnt pathway (Figures 2I–2K and S2F^{I}–S2H^{I}). We then further showed that inhibition of the Wnt pathway impairs the activity of Nanog in the late phase of reprogramming, as although Nanog was overexpressed in pre-iPSCs, the addition of Dkk1 drastically decreased iPSC number (Figures S2I^{I}–S2K^{I}).

Next, we investigated whether deletion of β-catenin in pre-iPSCs impairs their conversion into iPSCs. MEFs$^{\beta\text{-cat fl/fl}}$ were infected with OKSM (Figure 2L). The β-catenin gene was deleted in pre-iPSC colonies positive for SSEA-1 and negative for Nanog (Figures S2L^{I} and S2M^{I}). The deletion was not complete, however. After induction of Nanog with Mek inhibitor, pre-iPSCs$^{\beta\text{-cat }-/-}$ failed to become iPSCs, and there were no clones positive for Nanog and negative for β-catenin (Figures 2M and S2N^{I}). The few Nanog-positive clones selected (Figure 2M) were also positive for β-catenin, which indicated that they derived from MEFs that escaped β-catenin deletion. These were indistinguishable from iPSCs generated from pre-iPSCs$^{\beta\text{-cat fl/fl}}$ (Figures 2M and S2O^{I}). These data demonstrate that β-catenin is essential in the conversion of pre-iPSCs into iPSCs in establishing Nanog-mediated ground-state pluripotency.

β-Catenin Fluctuates Synchronously with Nanog in Serum+LIF Medium

Nanog fluctuates in ESCs cultured in serum+LIF medium (Chambers et al., 2007; MacArthur et al., 2012). We therefore investigated whether, apart from controlling reprogramming of somatic cells, the above-described Nanog regulation of Dkk1 affects β-catenin distribution and dynamics in ESCs.

In immunofluorescence experiments, there were heterogeneous levels of total and active β-catenin in E14Tg2a cultured in serum+LIF, with active β-catenin localized also in the nucleus, as expected (Figure 3A). Single cells expressing more Nanog also expressed high total and active β-catenin (Figure 3A), with high correlation (r = 0.78; Figure 3A). β-catenin-GFP was also heterogeneously expressed in EL55 cells, with these expressing high levels of β-catenin and Nanog, or low levels of both, as indicated by the correlation plot (r = 0.76; Figure 3B). Overall, these data indicate correlated heterogeneity of β-catenin and Nanog in ESCs cultured in serum+LIF.

We next investigated the dynamics of β-catenin in population studies and with time-lapse single-cell imaging. EL55 cultured in serum+LIF showed 45% ± 10% of GFP-positive cells, 15% ± 10% of GFP-negative cells, and a population with intermediate GFP levels (Figure 3C, Hβ-cat, Lβ-cat). Sorted Hβ-cat (GFP+) had higher levels of both β-catenin and Nanog with respect to

(D and E) Reprogramming efficiency comparing Nanog overexpression in β-catenin Δ/Δ background (ΔN4) and in β-catenin fl/fl background (N1), counting AP+ (D) and GFP+ (E) colonies. (E, inset) Representative GFP clone.

(F and G) Reprogramming efficiency stabilizing β-catenin with Chiron (3 μM, 24 hr) in βgeo/+ cells, counting AP+ (F) and GFP+ (G) colonies. (G, inset) Representative GFP clone.

(H) Scheme of iPSC generation. MEFs$^{\text{Nanog-GFP}}$ were infected with OKSM. Nanog-negative pre-iPSCs were cultured in ESC medium with the Mek inhibitor PD0325901 (Meki, 1 μM) ± Dkk1 (50 ng/ml).

(I and J) Immunofluorescence of pre-iPSCs grown in ESC medium containing Meki and Dkk1 (I) and of pre-iPSCs grown in ESC medium plus Meki (without Dkk1), converted into iPSCs (J).

(K) Percentage of Nanog-GFP+ iPSCs over total pre-iPSC clones.

(L) Scheme of iPSC generation from MEFs$^{\beta\text{-cat flox/flox}}$ after infection with OKSM. β-catenin was deleted in Nanog-negative pre-iPSCs with tamoxifen (1 μM). Pre-iPSCs ±tamoxifen were cultured in ESC medium with Meki to stabilize Nanog.

(M) Percentages of Nanog+ iPSCs over total pre-iPSC clones.

Data are means ± SEM (n = 5). $p > 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.0001$. Scale bars represennt 200 μm (C, E, and G inset) and 25 μm (I and J).

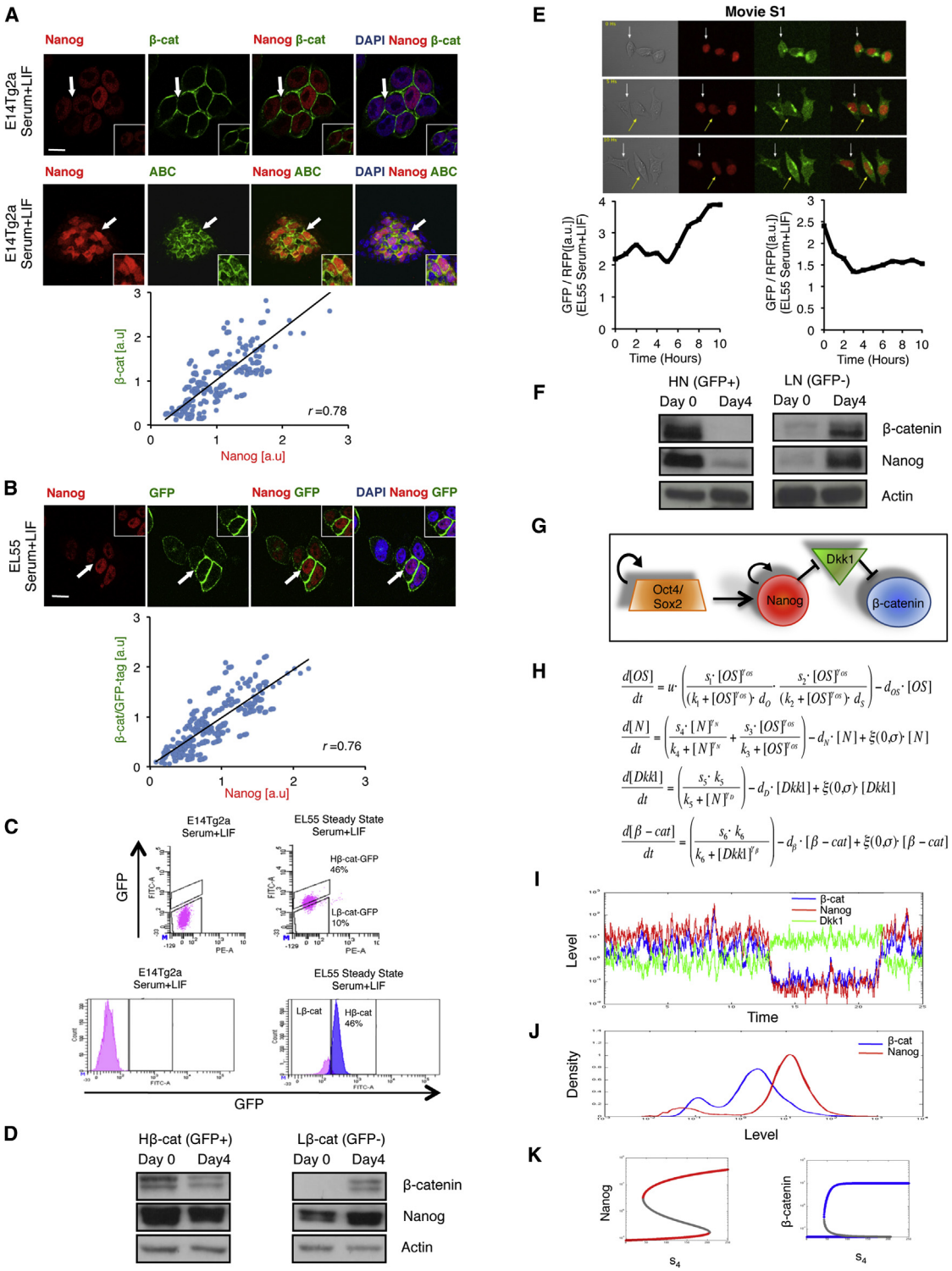

Figure 3. Correlated Fluctuations of β-Catenin and Nanog in ESCs Cultured in Serum+LIF Medium

(A and B) Immunofluorescences of total β-catenin, active β-catenin (ABC) and Nanog in E14Tg2a and EL55 cells cultured in serum+LIF. Arrows indicate zoomed regions with correlated expression of β-catenin and Nanog. The correlation plots of endogenous (A) and GFP-tagged (B) β-catenin with Nanog are shown (*r*, Pearson correlation coefficient).

(C) GFP distribution of the EL55 clone in serum+LIF analyzed by FACS. Hβ-cat, high β-catenin; Lβ-cat, low β-catenin.

(D) Western blot of GFP-positive (Hβ-cat) and GFP-negative (Lβ-cat) EL55 cells from FACS sorting (day 0) and 4 days of culture (day 4).

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sorted Lβ-cat (GFP−) cells (Figure 3D, day 0). Levels of pluripotency genes were comparable (Figures S3A and S3B).

Next, we asked whether β-catenin spontaneously fluctuates over time, as had already been reported for Nanog. Hβ-cat (GFP+) and Lβ-cat (GFP–) fluorescence-activated cell sorting (FACS)-sorted cells passed from both Nanog and β-catenin "high states" to "low states" and vice versa, after 4 days of culture (Figure 3D).

We then analyzed β-catenin fluctuations using time-lapse single-cell imaging. The GFP signal was normalized against stably expressed red fluorescent protein fused to histone H2B (H2B-RFP). Unsynchronized EL55 cells cultured in serum+LIF showed increases and decreases in GFP levels over time (Movie S1; Figures 3E and S3C).

Finally, we showed correlated dynamics of Nanog and β-catenin in TNGA cells. FACS-sorted GFP+ (HN) had high levels of β-catenin, while GFP− (LN) cells had almost no β-catenin accumulation (Figure 3F, day 0). GFP+ cells had decreased levels of both β-catenin and Nanog at day 4. Symmetrical dynamics were observed in the GFP− population (Figure 3F). These data indicate that the levels of β-catenin and Nanog are dynamically interconnected in ESCs cultured in serum+LIF.

A Mathematical Model Recapitulates Nanog- and β-Catenin-Correlated Fluctuations

Different models have been proposed to explain Nanog dynamics (Fidalgo et al., 2012; Glauche et al., 2010; Kalmar et al., 2009; Navarro et al., 2012). To recapitulate the two different substates of Nanog and β-catenin in serum+LIF, we modeled the system as a bistable one, in which the low and high states of Nanog, and consequently of β-catenin, are both stable and the transition from one to the other is due to noise. Of note, gene expression noise is a major determinant of the distribution of Nanog in stem cells (Wu and Tzanakakis, 2012).

Oct4, Sox2, Nanog, Dkk1, and β-catenin interactions are considered in our model. The topology encompasses a positive autofeedback loop of Oct4-Sox2 heterodimer (Glauche et al., 2010), which activates Nanog expression (Rodda et al., 2005), and a positive autofeedback loop of Nanog (Loh et al., 2006; Mullin et al., 2008) (Figures 3G and S3D). Nanog has also been suggested to fluctuate because of autorepression (Fidalgo et al., 2012; Navarro et al., 2012). Here, we described the system using a minimal topology that encompasses bistability, as we mainly focused on the effects of Nanog fluctuations on β-catenin through Dkk1 repression, rather than on the regulation that controls the dynamics of Nanog.

We used first-order degradation kinetics and Hill functions for the transcriptional interactions. The model includes stochastic terms, implemented as zero-mean Gaussian processes, which are added to the equations for Nanog and β-catenin (Figure 3H). Starting from parameter values reported before (Abranches et al., 2013; Glauche et al., 2010), we measured the half-life of β-catenin (Figures S3E and S3F; Table S1) and modified the transcription rates and the amplitude of noise to fit the distribution of Nanog and β-catenin in TNGA and EL55 cells, respectively.

When simulating over time, a typical trajectory of Nanog, Dkk1, and β-catenin is presented (Figure 3I); due to noise, in serum+LIF, cells can switch from one steady state to the other, with correlated Nanog and β-catenin dynamics in antiphase with the Dkk1 ones. Simulating the model for a high number of cells and estimating the Kelner density (Cao et al., 1994), we recapitulated the stationary GFP distribution of TNGA and EL55 cells (Figures 1E, 1F, steady-state conditions, and Figure 3J). We captured the distributions observed in the two cell lines and the distances between the positive and negative states. Figure 3K shows typical bistability continuation plots; continuing the steady state on s_4 (the maximal rate of the autofeedback of Nanog), two saddle-node bifurcations delimit the bistability region.

β-Catenin Protein Is Heterogeneous in ESCs Cultured in 2i+LIF Medium

Recent reports have shown that Nanog and other members of the pluripotency network do not fluctuate when ESCs are cultured in 2i+LIF medium (Ying et al., 2008). We therefore asked whether β-catenin heterogeneity is also abrogated in ESCs cultured in 2i+LIF.

Nanog was overall homogeneously expressed in E14Tg2a cells, and instead, β-catenin was heterogeneous, with some cells accumulating more β-catenin in the nucleus and in the membranes than other cells in the same clone (Figure 4A). Furthermore, the correlation between Nanog and β-catenin levels was much lower in ESCs cultured in 2i+LIF (r = 0.51), as compared to serum+LIF (r = 0. 78) (Figures 3A and 4A). In EL55 cells cultured in 2i+LIF, although β-catenin-GFP fully colocalized with endogenous β-catenin with correlated expression (r = 0.98; Figure S4A), it was heterogeneously expressed, poorly correlating with Nanog (r = 0.56; Figure 4B).

Single-cell time lapses of EL55 cells cultured in 2i+LIF showed increases or decreases of GFP levels over time (Movies S2 and S3; Figures 4C, S4B, and S4C), which clearly demonstrated that β-catenin can fluctuate in ESCs in 2i+LIF.

In addition, we studied the dynamics of the pathway activity using TOP-dGFP, a well-known Wnt reporter carrying destabilized GFP (Biechele and Moon, 2008). Only 8% ± 5% of cells were GFP+ in 2i+LIF medium (Figure 4D). Furthermore, after plating the unsorted cells, we observed a variable number of GFP+ cells over time (Figures 4E and S4D), which confirmed the heterogeneous activity of the Wnt/β-catenin pathway. In addition,

(E) Snapshots of live EL55 cell imaging. Quantifications of GFP signal normalized against RFP signal, plotted as a function of time. White arrows, GFP switch off; yellow arrows, GFP switch on.
(F) HN (GFP+) and LN (GFP−) cells FACS sorted from TNGA ESCs and analyzed by western blot. HN, high Nanog; LN, low Nanog.
(G) Topology of the interactions among the Oct4-Sox2 heterodimer, Nanog, Dkk1, and β-catenin.
(H) Differential equations (DEs) model of the network.
(I) Nanog, Dkk1, and β-catenin simulated time course.
(J) Bimodal distribution of Nanog and β-catenin.
(K) Bifurcation plots of the model; red and blue lines indicate stable, while gray lines indicate unstable steady state. Scale bar represents 25 μm.

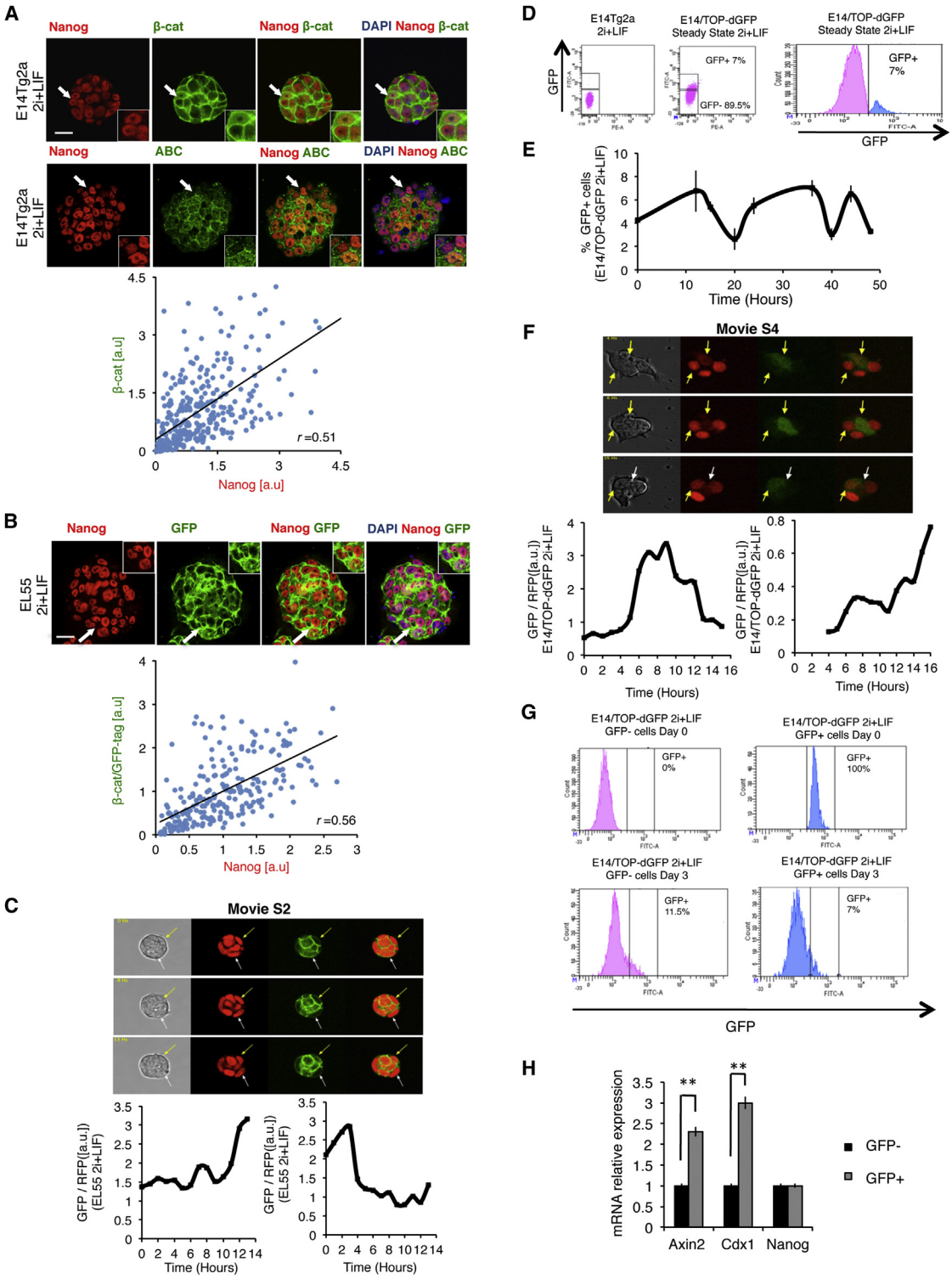

Figure 4. Dynamics of β-Catenin in Mouse ESCs Cultured in 2i+LIF Medium

(A and B) Immunofluorescences of β-catenin, active β-catenin (ABC), and Nanog in wild-type ESCs (E14Tg2a) and EL55 cells cultured in 2i+LIF. Arrows indicate zoomed regions with both correlated and uncorrelated expression of β-catenin and Nanog. The correlation plots of endogenous (A) and GFP-tagged (B) β-catenin with Nanog are shown (*r*, Pearson correlation coefficient).

(C) Snapshots of live EL55 cells imaged in 2i+LIF. Quantification of GFP normalized against RFP signal is plotted. White arrows, GFP switch off; yellow arrows, GFP switch on.

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time-lapse single-cell imaging of E14/TOP-dGFP showed switching on and off of the reporter over time, as well as fluctuations between the two states (Movie S4; Figures 4F and S4E).

Finally, the TOP-dGFP reporter was activated 3 days after culturing FACS-sorted GFP− population in 2i+LIF, while it was inactivated in sorted GFP+ cells (Figure 4G). Target genes were active only in the sorted GFP+ cells, while Nanog did not change in both populations (Figure 4H).

Overall, these data indicate that β-catenin and its target genes can fluctuate in ground pluripotency state.

DISCUSSION

Crosstalk between the Wnt/β-catenin pathway and Nanog is important for ESC physiology. Here, we show that Nanog represses an important negative regulator of the Wnt pathway, Dkk1, and in turn indirectly activates β-catenin. This is essential for the function of Nanog during somatic cell reprogramming. On the other hand, we cannot exclude additional regulation by Nanog of other effectors of the pathway or that repression of Dkk1 by Nanog is in cooperation with a recruited repressor complex. Impairment of reprogramming due to lack of Nanog can be rescued by β-catenin stabilization, which implies a key function of β-catenin as a downstream effector of Nanog. Interestingly, there have been similar findings for Esrrb (Festuccia et al., 2012; Martello et al., 2012) and Tet1 and Tet2 (Costa et al., 2013), which are also Nanog-dependent factors in the establishment of pluripotency and reprogramming.

The regulation of Nanog on β-catenin in the reprogramming process is relevant regardless of transcriptional (Nusse, 2008; ten Berge et al., 2011) and nontranscriptional activities of β-catenin (Faunes et al., 2013), which might be synergistic, and therefore may be both important in the control of ESC pluripotency.

We used β-catenin null ESCs and confirmed published data (Lyashenko et al., 2011; Wray et al., 2011) that in the presence of LIF, these cells maintain pluripotency. Other studies have reported that removal of β-catenin affects pluripotency (Faunes et al., 2013). These divergences are probably due to the different strategies used to generate the lines.

Nanog is heterogeneous in serum+LIF, but only under feeder-free conditions, while it is homogeneous in 2i+LIF medium (Cahan and Daley, 2013; Smith, 2013), although some variability is expected (Faddah et al., 2013). Nanog dynamics were modeled as a single, stable, and high steady state, from which ESCs can escape due to intrinsic noise toward a transient state with low Nanog expression, in an excitable fashion (Kalmar et al., 2009). High and low Nanog states were also shown equally probable, and the dynamics of the transition between these as monotonic (Abranches et al., 2013). Here, we included Dkk1 and β-catenin and demonstrated that Nanog and β-catenin fluctuate synchronously with bistable dynamics due to stochastic noise.

Interestingly, in 2i+LIF medium, β-catenin fluctuates independently of Nanog. Fluctuations are probably regulated by negative feedback loops that result in Wnt pathway activation (Lee et al., 2003), as the 2i medium contains Chiron.

Nanog-dependent fluctuations are stochastic and are due to transcriptional noise; they might be important to prime cells toward differentiation. Upon Wnt pathway activation, fluctuating dynamics of β-catenin are not stochastic, as they can be controlled by negative feedback loops induced by drug treatments. Whether controlled β-catenin dynamics can maintain the ground state of ESC pluripotency remains an open question.

EXPERIMENTAL PROCEDURES

Cell Hybrids

For ESC and neural precursor cell (NPC) cocultures, 1.0×10^6 ESCs were plated onto preplated 1.0×10^6 NPCs. These were cocultured for 4 hr, first for 2 hr in NPC medium and then for 2 hr in ESC medium. The cells were then trypsinized and plated at 1/5 into p100 gelatin-coated dishes in ESC medium. After 72 hr, puromycin or hygromycin were added to the ESC medium for hybrid selection.

Time-Lapse Live Fluorescence Imaging

Images were acquired with a 40× (numerical aperture 0.55) lens using 488 nm and 561 nm excitation. A pinhole size of ~3 Airy units was used to increase signal. Cells were imaged at 37°C in a humidified environmental chamber in 5% CO_2. A time interval of 1 hr was set between time points. Image processing and fluorescence quantification were performed using ImageJ v1.47p.

Mathematical Model Simulation and Analysis

The stability and bifurcation analyses were realized using the software tool *xppaut* (http://www.math.pitt.edu/~bard/xpp/xpp.html). To approximate numerical solutions of the stochastic differential equations, we applied the Euler-Maruyama method. Stochastic simulations were implemented using the programming language C++. Density plots were generated under the MATLAB platform (MathWorks).

SUPPLEMENTAL INFORMATION

Supplemental information includes Supplemental Experimental Procedures, four figures, one table, and four movies and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2014.08.011.

AUTHOR CONTRIBUTIONS

M.P.C., L.M., and E.P. designed the experiments and data analysis. L.M., E.P., U.D.V., and B.S.E. performed experiments. M.I. designed the tagging strategy. L.M. developed the mathematical model. M.P.C., L.M., and E.P. wrote the manuscript. M.P.C. supervised the project.

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(D) GFP distribution in E14/TOP-dGFP by FACS. GFP+, high TOP-dGFP activity; GFP−, low TOP-dGFP activity.
(E) Time course of unsorted E14/TOP-dGFP grown in 2i+LIF and analyzed by FACS.
(F) Snapshots of live single E14/TOP-dGFP cell imaging and quantifications of GFP signal versus RFP. White arrows, GFP switch off; yellow arrows, GFP switch on.
(G) FACS analysis of GFP+ and GFP− cells sorted from E14/TOP-dGFP and cultured in 2i+LIF for 3 days.
(H) qPCR of Axin2, Cdx1, and Nanog in GFP+ and GFP− cells sorted from E14/TOP-dGFP cultured in 2i+LIF. Data are means ± SEM (n = 5). **$p < 0.01$. Scale bar represents 25 μm.

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