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KAT-Independent Gene Regulation by Tip60 Promotes ESC Self-Renewal but Not Pluripotency

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Highlights

- The Tip60 acetylase (KAT) activity is dispensable for gene regulation in ESCs
- Tip60-p400 complex limits chromatin accessibility independently of its KAT activity
- The Tip60 KAT activity is necessary for induction of differentiation genes
- Tip60 KAT mutant mice exhibit developmental defects later than null mutants

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In Brief

Acharya et al. show that the Tip60 (Kat5) lysine acetyltransferase regulates gene expression and self-renewal independently of its KAT activity in mouse ES cells. The KAT activity is necessary for differentiation and post-implantation mouse development. Therefore, Tip60 has KAT-independent (early) and KAT-dependent (later) functions that are essential for development.

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KAT-Independent Gene Regulation by Tip60 Promotes ESC Self-Renewal but Not Pluripotency

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SUMMARY
Although histone-modifying enzymes are generally assumed to function in a manner dependent on their enzymatic activities, this assumption remains untested for many factors. Here, we show that the Tip60 (Kat5) lysine acetyltransferase (KAT), which is essential for embryonic stem cell (ESC) self-renewal and pre-implantation development, performs these functions independently of its KAT activity. Unlike ESCs depleted of Tip60, KAT-deficient ESCs exhibited minimal alterations in gene expression, chromatin accessibility at Tip60 binding sites, and self-renewal, thus demonstrating a critical KAT-independent role of Tip60 in ESC maintenance. In contrast, KAT-deficient ESCs exhibited impaired differentiation into mesoderm and endoderm, demonstrating a KAT-dependent function in differentiation. Consistent with this phenotype, KAT-deficient mouse embryos exhibited post-implantation developmental defects. These findings establish separable KAT-dependent and KAT-independent functions of Tip60 in ESCs and during differentiation, revealing a complex repertoire of regulatory functions for this essential chromatin remodeling complex.

INTRODUCTION
Embryonic stem cells (ESCs)—cells derived from the inner cell mass of the early blastocyst—have been utilized as an in vitro model of differentiation due to their pluripotency and unlimited capacity for self-renewal in culture (Keller, 2005). A complex array of signaling pathways and transcription factors control ESC fate, promoting self-renewal in the presence of either leukemia inhibitory factor (LIF) or inhibitors of differentiation-promoting kinases MEK1/2 and Gsk3β (Ying et al., 2008). In addition to transcription factors, a number of chromatin regulatory proteins help control the expression of pro-self-renewal and pro-differentiation genes (Chen and Dent, 2014). Although dozens of chromatin regulators necessary for ESC self-renewal or differentiation have been identified, the specific contributions of many chromatin regulatory proteins to ESC self-renewal and differentiation are poorly understood, due to the redundant and context-dependent contributions of most chromatin modifications to gene expression (Rando and Chang, 2009).

Previously, we showed that RNAi-mediated knockdown (KD) of components of the well-conserved Tip60-p400 (also called NuA4) chromatin regulatory complex resulted in multiple defects in ESC pluripotency (Fazzio et al., 2008a). ESCs depleted of Tip60-p400 subunits exhibit cell and colony morphologies indicative of differentiation and reduced expression of some pluripotency markers. However, Tip60-p400-depleted cells are also defective in normal ESC differentiation, forming small, abnormal embryoid bodies under differentiation conditions that fail to upregulate some markers of differentiated cells (Chen et al., 2013; Fazzio et al., 2008a). Consistent with this self-renewal defect, homozygous knockout of the Tip60 gene in mouse results in embryonic lethality at approximately the blastocyst stage (the stage at which ESCs are derived) (Hu et al., 2009). Tip60+/− blastocysts are morphologically abnormal and fail to hatch from the zona pellucida when cultured in vitro. No post-implantation Tip60−/− embryos were observed, demonstrating an absolute requirement for Tip60 at or before this stage.

Tip60-p400 has two biochemical activities that contribute to its functions within the nucleus. The Tip60 subunit is a lysine acetyltransferase (KAT) that targets histones H4 and H2A, H2A variants, and non-histone proteins (Ikura et al., 2000; Keogh et al., 2006; Squatrito et al., 2006; Xu and Price, 2011). Histone acetylation near gene promoters or enhancers is strongly associated with gene expression, consistent with Tip60’s known function as a co-activator that collaborates with numerous transcription factors (Squatrito et al., 2006). In addition to its role as a co-activator, Tip60 also directly regulates the activities of numerous transcription factors through acetylation of lysine residues (Farria et al., 2015). Finally, besides regulation of transcription, Tip60 plays important roles in DNA damage repair, senescence, and apoptosis (Doyon et al., 2004; Ikura et al., 2000; Kusch et al., 2004; Xu and Price, 2011; Jiang et al., 2011; Sykes et al., 2006; Tang et al., 2006; Van Den Broeck et al., 2012). Importantly, the KAT activity of Tip60 has been shown to be essential for its role in each of these processes.
The second chromatin remodeling activity found within the Tip60-p400 complex is catalyzed by the p400 subunit (gene name: Ep400). The p400 protein, like its homologs in other eukaryotes, catalyzes ATP-dependent incorporation of histone H2A variant H2A.Z into chromatin via exchange of H2A-H2B dimers within nucleosomes for free H2A.Z-H2B dimers (Gévy et al., 2007; Mizuguchi et al., 2004). Interestingly, p400 was recently shown to incorporate histone H3 variant H3.3 into chromatin (Pradhan et al., 2016). H2A.Z and H3.3 are often enriched near gene regulatory regions, consistent with a role for p400 (like Pradhan et al., 2016). H2A.Z and H3.3 are often enriched near gene regulatory regions, consistent with a role for p400 (like Pradhan et al., 2016). H2A.Z and H3.3 are often enriched near gene regulatory regions, consistent with a role for p400 (like Pradhan et al., 2016).

How does Tip60-p400 promote ESC self-renewal and pre-implantation development? Tip60-p400 binds near the promoters of both active genes and lowly expressed developmental genes in ESCs and acetylates the promoter-proximal histones of both groups (Chen et al., 2013, 2015; Fazzio et al., 2008a; Ravens et al., 2015). Given the well-established activating roles of histone acetylation, these data imply that Tip60-p400 may drive expression of highly expressed housekeeping and pluripotency genes but that its developmental targets are resistant to this activation, possibly due to the repressive activities of Polycomb complexes or other factors (Alaio et al., 2013; Simon and Kingston, 2013). However, this model is unlikely to be correct, since Tip60-p400 is largely dispensable for transcriptional activation in ESCs, and instead functions mainly to repress its developmental targets (Chen et al., 2013; Fazzio et al., 2008a, 2008b). Therefore, either the Tip60 KAT activity must inhibit transcription of developmental genes in ESCs, or repression of these genes by Tip60-p400 is KAT independent.

Here, we show that Tip60 functions independently of its KAT activity to repress differentiation genes in ESCs and promote ESC self-renewal. Consistent with this repressive function, Tip60 limits promoter-proximal chromatin accessibility at many Tip60 target genes, and this function is similarly KAT independent. By contrast, KAT-deficient ESCs are impaired for differentiation, revealing a critical role for the Tip60 KAT activity in pluripotency. Upon induction of differentiation, KAT mutant ESCs exhibit defects in production of mesoderm and endoderm cell types, due to reduced induction of numerous key drivers of differentiation. Unlike Tip60 null mice (Hu et al., 2009), KAT-deficient mutant mice proceed past the blastocyst stage, consistent with the ability of KAT mutant ESCs to self-renew. However, KAT mutant mice exhibit post-implantation developmental defects beginning around the start of gastrulation, analogous to the ESC differentiation defect observed in vitro. Together, these findings establish separable KAT-independent and KAT-dependent roles of Tip60 in pluripotency and embryonic development that are both essential but that act at different stages.

RESULTS
Tip60 KAT Activity Is Dispensable for Gene Regulation and Self-Renewal in ESCs
Tip60 is one of several histone acetyltransferases (HATs) that acetylate the N-terminal tails of histones H4 and H2A, whereas p400 is one of two SWI/SNF (switch/sucrose non-fermentable) family ATPases that mediate H2A.Z deposition (Altaf et al., 2009; Lalonde et al., 2014). To test the importance of these activities in ESCs, we generated independent ESC lines with homozygous mutations encoding amino acid substitutions in the acetyl coenzyme A (CoA)-binding site of Tip60 (Tip60hypo) or the ATP-binding pocket of p400 (Ep400hypo, Figures S1A and S1B), both of which were previously shown to block enzymatic activity (Ikura et al., 2000; Xu et al., 2010). We confirmed that these mutations broadly reduced H4 acetylation and H2A.Z deposition, respectively, in ESCs (Figures S1C and S1D). Since Tip60 or Ep400 depletion in ESCs causes loss of self-renewal (Fazzio et al., 2008a), we utilized previously validated short hairpin RNAs (shRNAs) (Chen et al., 2013) to perform acute KD of Tip60 or Ep400, along with an Ep400 hypomorphic mutant (Ep400hypo) that exhibits reduced levels of p400 protein (Figure S1E), for comparison. Surprisingly, Tip60hypo and Ep400hypo lines had normal ESC morphology and maintained expression of pluripotency markers such as alkaline phosphatase (AP; Figure 1A), and stage-specific embryonic antigen 1 (SSEA-1) (Figure S1F), whereas Tip60 KD or Ep400hypo cells exhibited reduced AP and SSEA-1 staining and flattened colonymorphologies, as observed previously (Chen et al., 2015; Fazzio et al., 2008a), Tip60hypo and Ep400hypo cells proliferated more rapidly than Tip60 KD and Ep400hypo cells (Figure 1B), although Tip60hypo cells proliferated slightly less rapidly than wild-type controls. Finally, to test for functional redundancy, we constructed double-homozygous mutant Tip60hypo Ep400hypo lines. As with the single mutants, these lines expressed markers of pluripotent stem cells and normal ESC colony morphology, similar to that of Tip60hypo single mutants (Figures S1F and S1G). These data suggest that loss of Tip60 KAT activity and p400 ATP-dependent nucleosome remodeling activity have minimal effects on ESC maintenance.

To test whether gene expression is altered in Tip60hypo and Ep400hypo mutant ESCs, in spite of their normal self-renewal, we performed RNA sequencing (RNA-seq) on biological replicates of Tip60hypo and Ep400hypo mutants, along with positive and negative controls. Consistent with previous findings (Chen et al., 2013; Fazzio et al., 2008a), Tip60 KD and Ep400hypo cells each exhibited upregulation of numerous genes enriched for developmental factors and downregulation of a smaller group of genes (Figures 1C–1F; Figures S2A and S2B). In contrast, few genes were significantly altered in Tip60hypo, Ep400hypo, or Tip60hypo Ep400hypo double mutants (Figures 1C–1F; Figures S2C–S2F). These data demonstrate that, while Tip60 and p400 are necessary for gene regulation and self-renewal in ESCs, their catalytic activities are dispensable for these processes.

KAT-Independent Regulation of Promoter-Proximal Chromatin Accessibility by Tip60
Since KATs function mainly as co-activators of gene expression, we next focused on how Tip60 functions independently of its KAT activity to repress transcription in ESCs. We confirmed normal expression of Tip60 and p400 in Tip60hypo Ep400hypo ESCs (Figure S3A) and found that Tip60hypo and Ep400hypo ESCs assemble intact Tip60-p400 complexes with compositions...
similar to that of wild-type cells, in contrast to p400hypo

but minimal changes in accessibility in KAT-deficient ESCs (Figure S3B).

Given its size (∼1.5 MDa; 17 core subunits), we considered the possibility that binding of the Tip60-p400 complex reduces the accessibility of underlying chromatin, regardless of its enzymatic functions. To test this possibility, we performed an assay for transposase-accessible chromatin followed by high-throughput sequencing (ATAC-seq) (Buenrostro et al., 2013) to quantify changes in chromatin accessibility at Tip60-binding sites. In Tip60KD control ESCs (expressing wild-type Tip60), chromatin accessibility is higher at Tip60-binding sites than flanking regions (Figures 2A and 2B), consistent with the observed enrichment of Tip60 near gene regulatory elements (Chen et al., 2013; Fazzio et al., 2008a, 2008b; Ravens et al., 2015). Interestingly, we observed significantly increased chromatin accessibility upon Tip60 KD but minimal changes in accessibility in KAT-deficient ESCs (Figures 2A and 2B). Clustering of these data identified two prominent patterns of chromatin accessibility, segregated primarily by whether the Tip60-binding sites were promoter-proximal or -distal (Figure 2C). Examination of promoter-proximal regions of Tip60 target genes revealed that Tip60 KD increased chromatin accessibility within a several-hundred base-pair window extending from the promoter into the gene body, corresponding to Tip60-p400 binding sites on chromatin (Figure 2D) (Chen et al., 2013, 2015; Ravens et al., 2015). In contrast, KAT-deficient ESCs were minimally affected. Unlike promoter-proximal regions, chromatin accessibility at gene-distal Tip60-binding sites was relatively unaltered by Tip60 KD or KAT mutation (Figure 2E). Consistent with these findings, KAT-deficient Tip60 bound to Tip60-p400 target genes at levels similar to those of wild-type (Figure S3C). These data demonstrate Tip60 functions independently of its KAT activity to regulate promoter-proximal chromatin accessibility in ESCs.

Tip60 KAT Activity Is Necessary for Differentiation and Post-implantation Development

Consistent with the self-renewal defect of Tip60 KD ESCs (Fazzio et al., 2008a), Tip60 homozygous null (Tip60−/−) mice die at the peri-implantation stage: Tip60−/− blastocysts fail to hatch and survive in culture, and no post-implantation Tip60−/− embryos can be recovered (Hu et al., 2009). Since Tip60KD ESCs self-renew normally, we next tested whether the Tip60 KAT activity is also dispensable for mouse development. To this end, we generated and intercrossed Tip60+/− heterozygous mice to produce Tip60+/− homozygous mice (see Experimental Procedures for details). However, we recovered no Tip60+/− pups at birth (χ² = 40.45, p < 0.001), suggesting that Tip60 KAT activity is essential for development (Figure 3A).

To elucidate the developmental defect of Tip60−/− animals, we examined the morphology of embryos at multiple stages. Tip60−/− embryos were recovered as late as 10.5 days post-fertilization (embryonic day [E]10.5; Figure 3A) but were much smaller than Tip60+/− or Tip60+/+ littermates (Figure 3B) and exhibited morphological abnormalities as early as E6.5 (Figures S4A–S4C). The contrasting phenotypes between Tip60−/− and Tip60+/+ mice reveal an essential KAT-independent role for Tip60 in pre-implantation development, as well as an essential KAT-dependent role in early post-implantation development.

The phenotypes of Tip60+/− embryos are evident at or just before gastrulation, where the three primary germ layers are established, suggesting that, although Tip60+/− ESCs self-renew normally, they may not differentiate properly. We tested this
possibility using embryoid body differentiations of control, Tip60 KD, and Tip60/ci/ci ESCs. Previously, we showed that KD of Tip60, Ep400, or (Tip60-p400 subunit) Dmap1 resulted in defects in embryoid body (EB) formation (Chen et al., 2013; Fazzio et al., 2008a), suggesting that Tip60-p400 is required for this initial step of differentiation. In contrast, Tip60/ci/ci ESCs efficiently formed EBs, which expanded in culture at near-wild-type levels, although modest differences in EB morphology were observed relative to Tip60/KD cells (Figures 3C and 3D). However, induction of mesodermal and endodermal markers was delayed and/or reduced in Tip60/ci/ci EBs (Figure 3E), compared to Tip60/KD controls. These data suggest that the Tip60 KAT activity is important for specification of mesodermal and endodermal cell types in vitro.

To test whether the ESC differentiation defects were recapitulated in vivo, we stained post-implantation Tip60/ci/ci embryos for T (also known as Brachyury), a marker of cells migrating through the primitive streak to become mesodermal or endodermal cell types (Herrmann, 1991; Rivera-Pérez and Magnuson, 2005). Although T staining of Tip60+/+ and Tip60/ci/+ embryos was evident at E6.5 and strong at E7.5, Tip60/ci/ci embryos exhibited reduced staining at both stages (Figures 3F and 3G). These data show that gastrulation is delayed or impaired in Tip60/ci/ci embryos. This phenotype could result from impaired lineage commitment, poor migration of cells through the primitive streak, or other factors. Regardless, this developmental defect is consistent with the impaired induction of early mesodermal and endodermal markers observed for KAT-defective ESCs in vitro.

**Impaired Expression of Multiple Drivers of Differentiation in KAT-Deficient ESCs**

What is the molecular basis for the in vivo and in vitro developmental defects of Tip60/ci/ci mutants? These phenotypes could result from failure to upregulate key lineage-specific transcription factors and/or a disruption in signaling pathways that promote lineage commitment. To address these possibilities, we compared the changes in gene expression during a time course of differentiation of control (Tip60+/+) and Tip60/ci/ci ESCs using RNA-seq on biological replicate samples. We
observed differences in both the timing and levels of markers of mesoderm and endoderm (Figure 4A; e.g., FoxA2, Gata4, Sox17, T, Hand1, and Flk1), expanding on our preliminary analyses (Figure 3E). Next, we used k-means clustering to identify groups of genes induced early or late during differentiation in Tip60fl/+ control cells and characterized the effects of the KAT mutation on their induction. We observed 1,338 genes of this type that mainly fall into three clusters based on the timing of their expression peak (Figure 4B). In Tip60ci/ci cells, we observed reduced or delayed induction of numerous genes with key roles in differentiation, including developmental transcription factors and mediators of growth factor signaling, within each of the three clusters (Figure 4B).

To test whether impaired induction of key signaling proteins hindered activation of their downstream targets, we examined activation of the FGF/MEK/ERK (fibroblast growth factor/mitogen-activated protein kinase/extracellular signal-regulated kinase) and TGF-β (transforming growth factor β) pathways using antibodies recognizing the phosphorylated (and activated) forms of ERK1/2 and Smad2/3, respectively (Tsang and Dawid, 2004; Whitman and Mercola, 2001). These factors act downstream of FGF and BMP (bone morphogenetic protein) signaling in differentiating ESCs and embryos and are critical for differentiation (Sui et al., 2013). Although Smad2/3 phosphorylation was unaltered in differentiating Tip60ci/ci ESCs, we observed impaired ERK phosphorylation in these mutants after 6 days of differentiation (Figure 4C).

Together, these data suggest that the differentiation defect observed in Tip60ci/ci ESCs is due to at least two overlapping defects: delayed or reduced activation of ERK and impaired induction of key developmental transcription factors.

**DISCUSSION**

Here, we showed that Tip60 functions in ESC gene regulation and self-renewal, as well as pre-implantation development, independently of its KAT activity. This finding was unexpected,
because Tip60 depletion or knockout leads to a self-renewal defect in ESCs and pre-implantation lethality in mice (Fazzio et al., 2008a; Hu et al., 2009). Furthermore, KAT-impaired mutants of esat1, the yeast homolog of Tip60, are severely growth impaired (Selleck et al., 2005), suggesting that the critical cellular functions of this KAT are dependent on its acetylation activity. The fact that Tip60 is largely a repressor of transcription in ESCs (Fazzio et al., 2008a), and that this repressive function is independent of its KAT activity, suggests that Tip60 regulates ESC gene expression in a manner that is distinct from other well-studied KATs, at least in part. Consistent with its role as a broadly acting repressor of transcription in ESCs, we found that Tip60 functions by a KAT-independent mechanism to limit chromatin accessibility directly over its promoter-proximal binding sites at many target genes. Additional studies will be necessary to determine whether Tip60 also performs this function in somatic cell types.

In contrast, the Tip60 KAT activity is essential during ESC differentiation and post-implantation development. Consequently, these findings demonstrate separable, essential functions of Tip60: its KAT-independent function is sufficient for Tip60’s essential role in ESC self-renewal and pre-implantation development, and its KAT-dependent function is required for post-implantation development and ESC differentiation. Interestingly, we found that the ATP-dependent histone exchange activity of p400 was also dispensable for gene regulation and self-renewal in ESCs, revealing that the Tip60-p400 complex represses differentiation genes in ESCs independently of its known chromatin-remodeling activities (Figure 4D). These findings necessitate a re-evaluation of current models of gene regulation by this essential chromatin regulatory complex.

What is the role of the Tip60 KAT activity during development? Given the defect of KAT-deficient ESCs and embryos in lineage specification, one possibility is that histone acetylation at differentiation genes in ESCs (as observed previously; Fazzio et al., 2008a) facilitates their upregulation when differentiation is induced. This provides a potential explanation for the counterintuitive role of Tip60 in the repression of differentiation genes in ESCs: occupancy of Tip60-p400 at differentiation gene promoters helps repress these genes by reducing chromatin accessibility, while acetylation at these loci may allow more rapid induction after binding of differentiation-specific transcription factors. Together, these data show that not all functions of Tip60 are reliant on its KAT activity, and they raise the possibility that KAT-independent gene regulation by Tip60 plays important roles in additional cell types.

**EXPERIMENTAL PROCEDURES**

**Antibodies**

Antibodies used in this study were as follows: p400 (A300-541A; Bethyl Laboratories); StainAlive SSEA-1 (09-0067; Stemgent); Smad2/3 (8685; Cell Reports 19, 671–679, April 25, 2017)
Cell Lines
Mouse ESC lines were derived from E14 (129/Ola) (Hooper et al., 1987) and grown as described previously (Chen et al., 2013). Tip60<sup>ci/ci</sup> ESCs were derived from floxed Tip60-HSF cells (Chen et al., 2013) by introduction of Cre recombinase (Addgene, 20781) to loop out a fused version of wild-type Tip60 exons 11–14, leaving a mutant exon 11 that harbors two substitution mutations (Q377E and G380E) that eliminate acetyl-CoA binding (Ikura et al., 2000) (Figure S1A).

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SUPPLEMENTAL INFORMATION
Supplemental Information includes Supplemental Experimental Procedures, four figures, and three tables and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2017.04.001.

AUTHOR CONTRIBUTIONS

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Chromatin Immunoprecipitation
Chromatin immunoprecipitation and deep sequencing were performed as described previously (Chen et al., 2013; Hainer et al., 2015). Chromatin immunoprecipitation (ChiP)-qPCR was performed using SYBR FAST (KAPA Biosystems), with primers described previously (Fazzio et al., 2008a).

RNA-Seq
Strain-specific library construction and RNA-seq were performed by Applied Biological Materials and the UCLA Clinical Microarray Core for ESCs and differentiating ESCs, respectively. Data analysis is described in the Supplemental Experimental Procedures.

ATAC Sequencing
ATAC sequencing (ATAC-seq) was performed essentially as described previously (Buenrostro et al., 2013, 2015). Two independent ATAC reactions per biological replicate were performed, using 35,000 and 70,000 ESCs each. After library preparation, the two reactions were found to have indistinguishable distributions of fragment sizes and were, therefore, combined for sequencing. (Therefore, each biological replicate consisted of two ATAC reactions.) Data analysis is described in the Supplemental Experimental Procedures.

Statistical Methods
For non-genomic in vitro experiments, two-tailed t tests were used to calculate statistical significance. A chi-square test was used to evaluate genotypes of offspring from Tip60<sup>ci/ci</sup> intercrosses. Adjusted p values were calculated for RNA-seq data using DEseq2. Significance of differences in ATAC-seq read enrichment were calculated by a hypergeometric test using the dhyper package in R.

ACCESSION NUMBERS
The accession number for the deep-sequencing data reported in this paper is GEO: GSE85505.

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