Zfp64 participates in Notch signaling and regulates differentiation in mesenchymal cells

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Introduction

Skeletal tissue is composed of many types of mesenchymal cells, which originate from common pluripotent progenitor cells. Various signaling molecules participate in directing these cells to specific differentiation pathways. Among these, bone morphogenic protein (BMP) has a crucial role in the regulation of myogenic and osteogenic lineage cells, inhibiting myogenic differentiation and promoting osteogenic differentiation (Katagiri et al., 1994). During the regulatory processes of osteoblast differentiation, BMP2 induces the expression of the runt-domain transcription factor 2 (Runx2), which is essential in regulating the expression of osteoblast-related genes, such as those for alkaline phosphatase (ALP), type I collagen, osteopontin and osteocalcin (Ducy, 2000; Komori, 2005). This major signaling cascade in osteogenesis is modified by other signaling pathways, including hedgehog, Wnt and Notch signaling (Komori, 2005; Lee et al., 2006; Nobta et al., 2005).

Notch signaling is a developmentally conserved cell-to-cell communication mechanism that regulates the differentiation of diverse tissues and cell types. Notch signaling exerts diverse effects on cell differentiation, acting to maintain stem cells in an undifferentiated state, but also promoting terminal differentiation (Wilson and Radtke, 2006). Reflecting its complex nature, contradictory data on the role of Notch signaling in osteoblast differentiation have been reported, in which Notch signaling either inhibits (Deregowski et al., 2006; Sciaudone et al., 2003; Shindo et al., 2003) or promotes osteoblastic cell differentiation (Nobta et al., 2005; Tezuka et al., 2002). The multiplicity of the Notch functions suggests the presence of complex mechanisms of signal modification and crosstalk with other signaling pathways, which have yet to be elucidated.

Notch signaling is initiated by ligand-mediated proteolytic cleavage, which facilitates the nuclear translocation of the Notch intracellular domain (NICD). The NICD forms a transcription complex with several cofactors and then activates downstream targets, such as the HES-HEY of family transcription factors. NICD consists of several distinct functional modules, including the RAM domain, ankyrin repeats, nuclear localization motifs, a transactivation domain and a PEST-containing domain (Ehebauer et al., 2006). The RAM domain associates with the DNA-binding factor CSL (CBF1/Su(H)/Lag), leading to the displacement of the co-repressors and the recruitment of the coactivator protein Mastermind to the ankyrin repeats (Ehebauer et al., 2006; Fryer et al., 2004; Nam et al., 2003). The ankyrin repeats also interact with Ski-interacting protein (SKIP) (Zhou et al., 2000) or Deltex (Matsumo et al., 1998) to facilitate Notch signaling. The PEST-containing region is required for ubiquitylation by Sel-10 ubiquitin ligase and subsequent protein degradation, which mediates the rapid turnover of NICD (Gupta-Rossi et al., 2001; Oberg et al., 2001; Wu et al., 2001). The hyperphosphorylation of several conserved serine residues within this motif seems to be important for NICD ubiquitination (Fryer et al., 2004; Gupta-Rossi et al., 2001; Wu et al., 2001). In some cases of T-cell acute lymphocytic leukemia, the absence of the PEST domain increases the stability of NICD, causing an excessive Notch-signal transduction phenotype (Weng et al., 2004). These data highlight that the C-terminal region of Notch is a regulatory element in Notch protein turnover, but the exact mechanism remains to be elucidated. We hypothesized that the PEST-containing region acts as a binding site for some crucial factors that regulate Notch signaling. To identify such factors, we performed yeast-two-hybrid screening using the Notch1 C-terminal PEST-containing region.

In this study, we identified zinc finger protein 64 (Zfp64) as interacting with the intracellular domain of Notch1, and demonstrated that Zfp64 acts as a coactivator of NICD. Interestingly, Zfp64 is a downstream target of Runx2 and mediates the myogenic and osteogenic differentiation of C2C12 cells. Possible roles of Zfp64 in mesenchymal cell differentiation are discussed.

Summary

Notch signaling is required for multiple aspects of tissue and cell differentiation. In this study, we identified zinc finger protein 64 (Zfp64) as a novel coactivator of Notch1. Zfp64 is associated with the intracellular domain of Notch1, recruited to the promoters of the Notch target genes Hes1 and Hey1, and transactivates them. Zfp64 expression is under the control of Runx2, and is upregulated by direct transactivation of its promoter. Zfp64 suppresses the myogenic differentiation of C2C12 cells and promotes their osteoblastic differentiation. Our data demonstrate two functions of Zfp64: (1) it is a downstream target of Runx2 and, (2) its cognate protein acts as a coactivator of Notch1, which suggests that Zfp64 mediates mesenchymal cell differentiation by modulating Notch signaling.

Supplementary material available online at http://jcs.biologists.org/cgi/content/full/121/10/1623/DC1

Key words: Notch, Runx2, Zinc finger protein 64
Results
Identification of Zfp64 as an NICD-interacting factor
We used the C-terminal PEST-containing region of mouse Notch1 (amino acids 2487-2531) fused to a GAL4 DNA-binding domain as the bait for yeast-two-hybrid screening. Approximately $2 \times 10^6$ clones from a mouse embryonic-day-11 cDNA library were screened for interaction with the bait. From about 1000 highly interacting clones, 100 randomly selected clones were sequenced. Zfp64 was identified as two independent clones of Zfp64 isoform D.

At least four alternative splicing variants (isoforms A, B, C and D) have been listed in the GenBank database. Isoforms B and C have minor differences relative to isoform A, with deletions of a few amino acids. By contrast, isoform D has a unique C-terminal region that is derived from genomic DNA used only by isoform D. Mouse and human Zfp64 isoform D has 13 C2H2-type zinc-finger motifs, in which high homology is apparent between the regions spanning zinc-finger motifs 2 to 4 and the region spanning the zinc-finger motifs 5 to 7 (Fig. 1). Motifs 4 and 7 (represented as 4’ in Fig. 1) of the human Zfp64 isoform D are highly homologous to zinc-finger motifs 5 and 6 of the other isoforms. This organization suggests that isoform D derived from the ancestral Zfp64 by genomic duplication. A similar structure is also observed in the mouse Zfp64 isoform D. Interestingly, the Conserved Domain Search algorithm (NCBI, default setting) showed that zinc-finger region 7 to 9 of isoform D (which does not appear in the other isoforms) has substantial structural homology to the SPF1 putative transcriptional-repressor domain that regulates the G2-M transition (COG5189, NCBI). Therefore, the genetic duplication seems to have added to isoform D not only the extra and different sets of zinc-finger motifs, but also a new functional domain for transcriptional regulation. Both of the clones isolated by the yeast-two-hybrid screen were C-terminal fragments that correspond to the isoform-D-specific region. The clone that encodes a Zfp64-isoform-D-specific fragment, spanning the eighth zinc-finger motif of the C-terminus, was chosen for further analysis (hereafter referred to as Zfp-C’). Several other transcription factors were also identified as being highly interacting clones. These included Sp6 and SKIP, both of which have been suggested to form a transcription complex with NICD (Hubbard et al., 1996; Zhou et al., 2000). Most of the other candidate clones were nuclear molecules. However, no factors known to participate in the protein degradation process were isolated.

Zfp64 associates with NICD
To confirm the interaction between Zfp64 and NICD, we performed a yeast-two-hybrid assay using Zfp64 derivatives and the PEST-containing region. The open-reading frame of Zfp64 isoform D was cloned and ligated into pGADT7, which encodes the GAL4 activation domain. Zfp-C’ (the isoform-D-specific C-terminal region), Zfp-N (the N-terminal region shared by all the isoforms) and Zfp-C (the isoform-A, B, C-specific C-terminal region) were also created and ligated into pGADT7. The PEST-containing region interacted with Zfp64, Zfp-C’ and Zfp-C but not with Zfp-N (Fig. 2A). Zfp64 showed no interaction with the vector without the insert or with lamin C, which is known to have no specific interaction with most proteins (Fig. 2A). Protein synthesis in yeast was validated by western blot analysis (Fig. 2B).

This result suggested that all the isoforms of Zfp64 interact with NICD. In this study, we focused our analysis on the isoform D. We tested the interaction between N-terminal hemagglutinin (HA)-tagged Zfp64 and Myc-tagged PEST proteins using an in-vitro-translation system. Immunoprecipitation and western blot analysis revealed that Zfp64 associates with the PEST-containing region (Fig. 2C). We examined the subcellular localization of Zfp64 by transfecting green fluorescent protein (GFP)-tagged constructs into U2OS cells. GFP-Zfp64 was mainly observed in the nuclei, showing a cellular localization similar to those of GFP-NICD and GFP- CSL (supplementary material Fig. S2A). Western analysis revealed both Zfp64 and NICD in the cytoplasmic and nuclear protein extracts, whereas CSL was mostly detected in the nuclear extract (supplementary material Fig. S2B). The nuclear-to-cytoplasmic protein ratios determined by densitometric analysis demonstrated that the cytoplasmic localization of Zfp64 was greater than that in the nucleus when it was coexpressed with NICD, whereas its nuclear localization was dominant when it was coexpressed with CSL and NICD. More NICD was detected in the nucleus when it was coexpressed with CSL or Zfp64 (supplementary material Fig. S2C). These results imply that Zfp64 colocalizes with NICD in the process of NICD nuclear translocation by CSL. We co-transfected constructs encoding N-terminal FLAG-tagged NICD or NICD lacking the PEST region (NICD-p) together with HA-tagged Zfp64 into HEK293 cells, and performed immunoprecipitation analysis and western blotting. The preliminary experiment, using EDTA-containing buffer for cell lysis and washing, yielded negative results for Zfp64-NICD association. Nonreducing SDS-PAGE yielded a band pattern identical to that observed under reducing conditions (data not shown), suggesting that the tertiary structure of Zfp64 had been disrupted in the lysis buffer and that Zn$^{2+}$ are required for the preservation of its structure. Therefore, we used a lysis buffer without EDTA, with or without Zn$^{2+}$. In this procedure, Zfp64 was efficiently recovered by the immunoprecipitation of NICD (Fig. 2D). Zfp64 was also recovered by the immunoprecipitation...
of NICD-p in the buffer with zinc-ion, but not in the buffer without zinc-ion. These results suggest that Zfp64 associates with NICD and that the PEST-containing region is essential for their efficient association, although the region other than the PEST-containing region is also capable of mediating their association. We tried to detect an association between endogenously expressed NICD and Zfp64, but the expression of NICD was insufficient for successful immunoprecipitation, even after coculture with Delta-like-1-expressing HeLa cells (data not shown). Therefore, we overexpressed NICD and examined whether endogenous Zfp64 is co-precipitated with NICD. We used U2OS cells, because the endogenous expression of Zfp64 is relatively high and adenosine-mediated gene transfer is very efficient in these cells. Endogenous Zfp64 was detected in the precipitant with NICD (Fig. 2E). Collectively, these results indicate that Zfp64 associates with NICD, mainly through the PEST-containing region.

Expression of Zfp64 in tissues and cell lines

We examined the expression of Zfp64 in tissues and cell lines. Whole-mount in-situ hybridization (ISH) on mouse embryos at 11 days post conception (dpc) revealed that Zfp64 is expressed in the subepithelial mesenchymal cells, including somites and limb buds (Fig. 3A). ISH using the probe in the sense orientation yielded no significant staining (data not shown). The same expression pattern was observed in a chick embryo at the corresponding developmental stage (HH stage 22), further supporting the validity of the ISH result (Fig. 3B,D). Chick Hey1 expression is shown for comparison, which was prominent in the somites (Fig. 3C), whereas Zfp64 was expressed in a broader region of the mesenchymal cells, including the somites. On embryonic day 6 (HH stage 28-29), Zfp64 expression was prominent in the limb bud, although its expression was ubiquitous in the mesenchyme (Fig. 3E,F). Section ISH on 13.5 dpc mouse embryos revealed that most tissues and organs expressed...
Zfp64. Because its expression is almost ubiquitous at this developmental stage, both in epithelial and mesenchymal cells, we show its expression in several representative tissues. In the dermis, Zfp64 expression was prominent in the dermal basal cells and subepithelial mesenchymal cells (Fig. 3G). Zfp64 expression was observed in satellite cells, whereas its expression was weak in striated muscles (Fig. 3H). Zfp64 was expressed in osteoblasts and hypertrophic chondrocytes (Fig. 3I).

Immunohistochemical staining demonstrated the same patterns of expression: the abovementioned cells exhibited distinct nuclear staining (Fig. 3J,K,L). RT-PCR analysis of various organs from an adult mouse revealed ubiquitous expression of Zfp64 (Fig. 3M). Northern blot analysis confirmed Zfp64 expression in the brain, spleen, liver, and heart (supplementary material Fig. S3). Zfp64 expression was detected in diverse mesenchymal cell lines in culture, including fibroblastic (NIH3T3), myogenic (C2C12), chondrogenic (ATDC5), and osteogenic cells (MC3T3-E1, Kusa-A1, U2OS). C2C12 cells showed the strongest expression compared with that in other cell lines, when measured by realtime RT-PCR. Zfp64 expression was detected in RD-C2 cells established from the calvaria of newborn Runx2-knockout mice (Liu et al., 2007) (Fig. 3N). The expression of Zfp64 in C2C12 and U2OS cells was confirmed by immunoblotting and immunocytochemistry (Fig. 3P,Q).

Zfp64 transactivates Notch target genes
To investigate the effect of Zfp64 on Notch signal transduction, we first performed a Hey1 and Hes1 promoter assay. Hes1-luc or Hey1-luc reporter plasmid was co-transfected with Zfp64 or constitutively active Notch constructs into U2OS cells. Zfp64 transactivated both the Hes1 and Hey1 promoters in a dose-dependent manner (Fig. 4A,B). The transactivation activity of Zfp64 was comparable with that of the constitutively active Notch constructs (Fig. 4C,D). NICD-p, which lacks the PEST sequence of Notch, showed reduced transactivation activity compared with that of NICD (Fig. 4C,D), but this might not be biologically significant because NICD-p showed higher transactivation activity than NICD at different plasmid concentrations (0.5 μg, data not shown). N-EGF, the

Fig. 3. Zfp64 is expressed in a broad range of mesenchymal tissues. (A,B) Whole-mount in-situ hybridization using a (A) mouse dpc 11 embryo and (B) embryonic day 3.5 (HH stage 22) chick embryo. (C) Chick Hey1 expression. (D) Section view of B. (E) Zfp64 expression in an E6 (HH stage 28-29) embryo. (F) Section view of E. (G,H,I) In-situ hybridization to embryonic day 18.5 mouse embryo. Zfp64 is expressed in (G) the basal layer of the dermis and subepithelial mesenchymal cells, (H) chondrocytes and (I) osteoblasts. (J,K,L) Immunohistochemical staining of an embryonic day 18.5 mouse embryo using anti-Zfp64 antibody shows nuclear staining in an expression pattern similar to that seen in G-I. (M) Zfp64 expression in adult organs. Ubiquitous expression of Zfp64 was observed by RT-PCR. (N) Zfp64 expression in mesenchymal cell lines, measured by real-time PCR. *, Since U2OS cells are a human cell line, the PCR primers were different from those used for the other cell lines. (O) Western blot of C2C12 or U2OS cell lysates using anti-Zfp64 antibody. At least two bands of different molecular mass were observed. The band of the higher molecular mass appears to correspond to isoform A and/or C, and the small protein appears to correspond to isoform B and/or D of Zfp64. (P) Immunocytochemistry of C2C12 and U2OS cells using anti-Zfp64 antibody.
membrane-bound form of constitutively active Notch, which lacks all the epidermal growth factor (EGF) repeats but retains the Lin/Notch repeats, also transactivated the Hes1 and Hey1 promoters (Fig. 4C,D). When graded amounts of Zfp64 and NICD or NICD-p were co-transfected, Zfp64 stimulated the Hes1 and Hey1 promoters additively with NICD (Fig. 4E,F), but the additive effects of Zfp64 on NICD-p were weak (Fig. 4G,H).

We measured the mRNA expression of Hes1 and Hey1 in U2OS cells following overexpression of Zfp64. Real-time RT-PCR 24 hours after adenovirus-Zfp64 (AdZfp64) transfection showed that Zfp64 upregulated Hes1 and Hey1 expression twofold compared with that of cells transfected with adenovirus-GFP (AdGFP) (Fig. 4I,J). Furthermore, co-culture with cells that were constitutively overexpressing Delta1 revealed that cells transfected with Zfp64 reacted more robustly to Delta1 stimulation than untransfected cells (Fig. 4K,L). Notably, co-culture with cells that do not overexpress Delta1 led to downregulation of Hes1 and upregulation of Hey1. We could not specify the reason for Hes1 downregulation, but Hey1 upregulation appears to be owing to endogenous BMP production by HeLa cells, because this cell line is known to secrete substantial amounts of BMPs, and Hey1 has also emerged as a downstream target of BMP signal transduction, as discussed below. Collectively, these results indicate that Zfp64 promotes Notch signal transduction and upregulates expression of Hes1 and Hey1.

To examine whether this upregulation is caused by the direct binding of Zfp64 to the promoter regions of Hes1 and Hey1, we used chromatin immunoprecipitation (ChIP)-PCR analysis on U2OS cells transfected with the mock or HA-Zfp64 plasmid using anti-HA antibody. PCR revealed the specific amplification of promoter fragments of Hes1 and Hey1 in the HA-Zfp64-transfected cells, but not in the mock-transfected cells (Fig. 4M,N). We assumed that co-transfection with Zfp64 and NICD might increase Zfp64 recruitment to the Hes1 and Hey1 promoters. However, the ChIP sample of cells co-transfected with Zfp64 and NICD yielded approximately the same or slightly reduced amounts of PCR products. This might be the result of the antagonizing effect of excess amounts of NICD, which captures Zfp64 to form an inefficient transcription complex. We concluded that Zfp64 is recruited to the promoters of Hes1 or Hey1, and that it transactivates these Notch target genes.
Runx2 upregulates Zfp64 expression

Because Zfp64 has been suggested as a downstream target of Runx2 (Gaikwad et al., 2001), we performed an in silico promoter analysis using the Eldorado software (Genomatix). Eldorado predicted that the core promoter for human Zfp64 spans from around the –800 position to the transcription initiation site. Two ose2 Runx2-binding elements were identified in forward and reverse orientations within this region (Fig. 5A). Eldorado also predicted the promoters for mouse and rat Zfp64 in both of which a single ose2 element was identified. The other transcriptional motifs shared by human, mouse, and rat Zfp64 promoters include cbf1- and hey1-binding motifs (Fig. 5B). Although the numbers and locations of these motifs differ in the three species, the conservation of these motifs suggests that Zfp64 expression is under the control of the Runx2 and Notch signaling pathways.

To explore the regulatory mechanism of Zfp64 expression, we cloned the putative human Zfp64 core promoter region and examined its transactivity by luciferase assay. The Zfp64 promoter was activated by Runx2 in a dose-dependent manner (Fig. 6A). Real-time RT-PCR revealed that Zfp64 was significantly upregulated 24 hours after adenovirus-Runx2 (AdRunx2) transfection into MC3T3-E1, C2C12 and RD-C2 cells (Fig. 6B).

To investigate the contribution of each ose2 element to Zfp64 promoter activity, we created reporter constructs with a deletion or mutation in the ose2 elements. These reporter plasmids were cotransfected with mock or Runx2 plasmids and a luciferase assay was performed. Zfp-luc-m2, which has a mutation in the proximal ose2 element, showed Runx2-dependent transactivation, whereas Zfp-luc-d1 and Zfp-luc-d2, which lack the distal ose2, as well as Zfp-luc-m1, which has a mutation in the distal ose2, showed no distinct transactivation by Runx2 (Fig. 6C), suggesting that Runx2 mainly acts on the distal ose2 element in the human Zfp64 promoter. These results indicate that Runx2 upregulates Zfp64 by transactivating the Zfp64 promoter.

Since Runx2 expression is under the control of BMP signaling and is known to be upregulated by BMP2, we treated MC3T3-E1 cells and RD-C2 cells, both of which were derived from mouse calvarial cells, with 100 ng/ml human recombinant BMP2 protein (rBMP2) and examined the change of expression of Runx2, Zfp64, Hey1, and Hey2. Runx2 expression was not altered by BMP2 on day 2, but was upregulated on day 4 in MC3T3-E1 cells (Fig. 6D). The change in Zfp64 expression was similar to that of Runx2; it was unchanged on day 2 and was upregulated on day 4 in MC3T3-E1 cells, whereas Zfp64 expression was largely unchanged in RD-C2 cells that lack Runx2 expression. Hey1 expression was slightly upregulated on day 2 and day 4, although statistical significance was not confirmed. These results indicate that BMP signaling acts to upregulate Zfp64 through Runx2 upregulation. Hey1 upregulation by BMP2 was not prominent, and Hey1 seems to be a direct target of BMP signaling as well as the Notch signaling, therefore, we could not assess the Runx2-Zfp64-dependent contribution of BMP signaling upon Notch signaling.

Zfp64 is involved in the regulation of mesenchymal cell differentiation

To explore the roles of Zfp64 in myogenic differentiation, we established a C2C12 cell line that carries the NICD gene under the control of a tetracycline-inducible promoter. Twelve hours after transduction with AdGFP or AdZfp64, NICD expression was induced by the addition of doxycycline to the culture medium. Twelve hours after NICD induction, myogenic differentiation was induced by reducing the serum concentration in the culture medium from 20% to 2% (day 0). Doxycycline-induced NICD expression was strongly maintained on day 6, and a substantial level of Zfp64 expression was maintained on day 2 and was upregulated on day 4 in MC3T3-E1 cells (Fig. 7A), although this expression was attenuated compared with that on day 2. On day 2, the expression of MyoD and Myog, the key myogenic transcription factors, was significantly downregulated in the cells expressing Zfp64 or NICD (Fig. 7C).

Western blot analysis revealed that the expression of sarcomeric actin-α and smooth muscle actin was attenuated in the cells expressing Zfp64 or NICD, and that the cells expressing both Zfp64 and NICD showed a lower level of expression than that of the single-gene-transfected cells (Fig. 7A). The expression of desmin was not

Fig. 5. Zfp64 promoters. (A) The sequence of the putative promoter of human Zfp64 and the consensus transcription-factor-binding motifs. White and black squares indicate the core elements in the forward and reverse orientations, respectively. (B) Interspecies comparison of Zfp64 promoters. The transcription-factor-binding motifs are indicated by white squares (forward orientation) or black squares (reverse orientation).
Zfp64 participates in Notch signaling

detected in the cells expressing NICD, and was attenuated in the cells expressing Zfp64 (Fig. 7A). C2C12 cells without the overexpression of Zfp64 and NICD generated numerous myotubes. However, myotube formation was significantly inhibited in the cells expressing Zfp64 or NICD (Fig. 7D). The cells overexpressing both Zfp64 and NICD showed the greatest reduction in these muscle-related factors and in myotube formation.

To examine the contribution of endogenous Zfp64 expression to myogenic differentiation, we delivered a small interfering RNA (siRNA) specific for Zfp64 isoform D, with an adenoviral vector (AdsiZfp64). The efficiency of the knockdown effect was confirmed by western blot and real-time PCR analysis (Fig. 7B). Recovery in Mef2C and MyoD expression were observed in NICD-expressing cells following AdsiZfp64 transfection (Fig. 7C), although no changes in myotube formation were apparent (Fig. 7D). These results indicate that Zfp64 inhibits myogenic differentiation.

We next investigated the role of Zfp64 in the BMP2-induced osteoblastic differentiation of C2C12 cells. C2C12 cells were treated with a low dose (20 ng/mL) of rBMP2 after 12 hours of transfection using adenovirus vector, and osteogenic markers were examined after 72 hours. Transfection with AdZfp64 increased the ALP activity of C2C12 cells (Fig. 7E). Conversely, AdsiZfp64 transfection led to a decrease in ALP activity (Fig. 7E). Transfection with AdZfp64 upregulated the mRNA for type I collagen (Col1a1), osteocalcin (Ocn), and osteopontin (Opn), whereas transfection with AdsiZfp64 caused the downregulation of Col1a1 and Opn expression (Fig. 7F). These results suggest that Zfp64 positively regulates osteogenic differentiation. In order to examine whether this phenotype is due to Notch signaling activation, we assessed the contribution of Hey1 in the regulation of osteogenic differentiation by Zfp64 using Hey1-deficient calvarial (HDC) cells that had been established from the calvarial cells of a Hey1-knockout mouse (Minamizato et al., 2007). We focused on analysis of Hey1 for the following reasons: (1) It is reported to be a regulator of osteogenic differentiation (de Jong et al., 2004; Zamurovic et al., 2004). (2) Zfp64 upregulated Hey1 more efficiently than Hes1 in our experiments. The ALP activity of HDC cells was raised by AdZfp64 transfection and was reduced by AdHey1 transfection (Fig. 7G), which implicates that the rise in ALP activity by AdZfp64 transfection is not via Hey1 upregulation. Col1a1 was upregulated by Hey1, but not by Zfp64 in the HDC cells (Fig. 7H), which implicates that the upregulation of Col1a1 by Zfp64 is the consequence of Hey1 upregulation. Similarly, Opn expression seems to be mediated by Zfp64, at least in part, through upregulation of Hey1. Ocn expression was reduced by AdHey1 transfection but was not affected by AdZfp64 in the HDC cells (Fig. 7H). Altogether,
these results indicate that the effects of Zfp64 on osteogenic differentiation can be attributed partially to Hey1 upregulation, but other mechanisms appear to be involved in the effects of Zfp64.

**Discussion**

We have demonstrated by yeast-two-hybrid, and in vitro and in vivo binding assays that Zfp64 associates with NICD mainly through the PEST-containing region. The PEST sequences of Notch1 and Notch2 are highly homologous to that of *Drosophila* Notch and are well-conserved beyond these species. By contrast, the PEST sequence of Notch3 shows low similarity to *Drosophila* Notch, and the PEST motif in Notch4 comprises completely different amino acid residues. Considering that the PEST-domain-containing regions of Notch1 and Notch2 have maintained a specific motif against mutation pressure rather than substituting it with other PEST-domain sequences (as seen in Notch3 and Notch4), it is plausible that this motif is used for interactions with some factors that are essential for Notch function.

The primary purpose of our yeast-two-hybrid screen was to identify factors that modify Notch signaling, possibly by regulating Notch protein stabilization or degradation. However, our yeast-two-hybrid experiments yielded no factors related to protein degradation. Instead, several nuclear molecules were isolated as interaction partners. The PEST signal for degradation might be hidden during its interaction with nuclear transcription factors until it is exposed for degradation, after the transcription complex dissociates. This would allow a better control of protein turnover because the protein degradation signal is unmasked in a timely manner to target the protein for degradation.

Zfp64 contains tandem repeats of the C2H2 zinc-finger motifs. A C2H2 zinc finger comprises a pair of cysteine residues in the β-sheet and two histidine residues in the α-helix, which bind Zn2+ and interact with the major groove of DNA or RNA. In addition to...
its nucleic-acid-binding capacity, a zinc-finger domain can function in protein-protein interactions (Mackay and Crossley, 1998). Because Zn\(^{2+}\) is definitely required to stabilize the tertiary structure of the zinc-finger motif, failure to detect the association in the presence of EDTA suggests that metal ions are crucial for maintenance of the correct protein conformation of Zfp64 and its association with NICD. We observed interaction between Zfp64 and NICD-p, although it was weak compared with that between Zfp64 and NICD. This suggests that association with Zfp64 is mediated not just by the PEST-containing region but also by another region. NICD has been proposed to form a dimer through their ankyrin repeats (Nam et al., 2007). However, NICD-p might have associated with endogenous NICD, which, in turn, associates with Zfp64. This might explain the weak association between Zfp64 and NICD-p. Further studies will be required to clarify this point.

The promoter assay and also real-time PCR revealed that Zfp64 upregulates the expression of Hes1 and Hey1, the direct targets of Notch. The effects of Zfp64 on Hes1 and Hey1 transcription were additive to those of NICD, but were attenuated in combination with NICD that lacked the PEST-containing region (NICD-p). Furthermore, a ChIP assay showed the recruitment of Zfp64 to the promoters of Hes1 and Hey1. These data suggest that Zfp64 is incorporated into the transcription complex with NICD and contributes to an increase in its transcriptional activity. Therefore, the basic function of Zfp64 might be to strengthen the effects of Notch signaling. It should be noted that our knockdown experiments imply that Zfp64 is not an indispensable factor in Notch signaling. Instead, it might have an additional role in aiding signal transduction.

Gaikwad et al. screened a subtraction library for genes that were significantly downregulated in the tooth germ of Runx2-knockout mice, and reported that Zfp64 is a tooth-specific downstream target of Runx2 (Gaikwad et al., 2001). We showed that the expression of Zfp64 is under the direct control of Runx2, through the ose2 elements in the Zfp64 promoter. This suggests that Runx2 positively acts on Notch signaling through Zfp64 upregulation. What is the biophysiological significance of this mechanism?

BMP-regulated Runx2 expression has a pivotal role in the transdifferentiation of mesenchymal stem cells. Runx2 regulates the transcription of numerous genes and thereby controls osteoblast development from mesenchymal stem cells (Komori, 2005). Runx2 also suppresses the myogenesis of primary myoblasts and induces their transition to an osteoblastic lineage (Gersbach et al., 2004). Notch signaling exerts a similar effect on myogenesis, by antagonizing MyoD activity and suppressing myoblast differentiation (Kopan et al., 1994; Noziger et al., 1999). BMP4-mediated inhibition of myoblast differentiation requires functional Notch signaling and seems to coincide with the upregulation of Hes1 and Hey1 expression (Dahlqvist et al., 2003). This seems to be achieved without Hes1 activity (Shawber et al., 1996) but the role of another target gene product, Hey1, in blocking myogenesis is yet to be elucidated.

Our data suggest that the upregulation of Zfp64 expression by Runx2 directs cells to follow an osteoblastic lineage rather than a myogenic lineage. Because the synergistic effects of NICD and Zfp64 were observed in our overexpression experiments, the inhibition of myogenic differentiation appears to be achieved, at least partially, through the activation of Notch signal transduction. However, our data also imply a Notch-independent action of Zfp64, and we do not assume that its Notch-dependent action is the only mechanism involving Zfp64 function, considering that Zfp64 exerts its effects in the absence of any forced expression of NICD or Notch signal stimulation. Other interacting partners for Zfp64 have been suggested in a systematic yeast-two-hybrid screening strategy, such as using several nuclear factors, including transducin-like enhancer protein 1/Groucho (Stelzl et al., 2005). The study of other interaction partners might shed light on the Notch-independent functions of Zfp64.

Zfp64 stimulated ALP activity and the mRNA expression of osteogenic marker genes in C2C12 cells. This indicates that Zfp64 is involved in osteoblast differentiation, possibly as a factor downstream from Runx2. Several lines of evidence have demonstrated that Notch signaling is involved in osteoblast differentiation, but the manner in which Notch signaling either inhibits osteoblast differentiation (Deregowski et al., 2006; Sciaudone et al., 2003; Shindo et al., 2003) or promotes it (Nobta et al., 2005; Tezuka et al., 2002) has yet to be elucidated. These multiple effects of Notch signaling have been observed in other cell types, such as blood, skin, and gut epithelium, in which Notch signaling determines binary cell fates or induces terminal differentiation processes, as well as maintains stem cells in a proliferative and pluripotent state (Wilson and Radtke, 2006). These opposing functions appear to be, at least in part, the outcomes of crosstalk with other signaling pathways, such as the Wnt, hedgehog and BMP pathways (Itoh et al., 2004; Wilson and Radtke, 2006).

Both BMP and Notch signaling have crucial roles in the development of various tissues and in the regulation of cell differentiation. Recently, several mechanisms that coordinate the two signaling pathways have been proposed. For example, Smad isoforms form a complex with NICD (Dahlqvist et al., 2003; Sun et al., 2005; Takizawa et al., 2003) in the presence of the coactivators P/CAF and p300, which stabilize the Smad-NICD complexes and promote Notch signal transduction (Itoh et al., 2004; Takizawa et al., 2003). Consequently, Hey1 is synergistically induced by the activation of the Notch and BMP signaling pathways, and Hey1 is thought to be a three-way switch by receiving signals from the Notch and the BMP signaling pathways (Itoh et al., 2004). Another example of BMP and Notch interplay is seen in the downstream transcription factors of the two signaling pathways. Hes1 associates with Runx2 and potentiates Runx2-dependent transcription (McLarren et al., 2000). The association of Hes1 with Runx2 is mediated by the retinoblastoma protein pRb, which further increases Runx2 transactivity in osteoblasts (Lee et al., 2006). We have also reported that the multimodular regulatory protein CCN3/Nov has dual functions that affect both the Notch and BMP signaling pathways. CCN3/Nov interacts with both Notch1 and BMP2, thereby stimulating Notch signal transduction and antagonizing the BMP2 signaling pathway (Minamizato et al., 2007; Sakamoto et al., 2002). In this study, we suggest that Zfp64 is an additional factor that mediates the interplay between the two signaling pathways. The abundant repertoire of mechanisms that coordinate the two signaling pathways should allow for the delicate regulation of the downstream events. This might explain the enigmatic behaviors of the two signaling pathways, which can – depending on the context – act either synergistically or antagonistically.

Materials and Methods

Genes

NICD was generated by PCR from mouse Notch1 cDNA using primers EcoR1-N5353 and Nhe1-Sal1-Xho1, and was cloned into EcoR1-Sal1 site of pCMVTag2B (Stratagene). The NICD fragment in pCMVTag2B was digested with Nhe1 and ligated into the Nhe1-Xho1 site of pCDNA6/V5-HisC (Invitrogen) to create N-terminal FLAG-tagged/C-terminal V5 tagged NICD (Flg-NICD-V5). For NICD without the PEST region, Flg-NICD-V5 was digested with Nhe1-Apa1 and the insert was ligated...
into the Nhel/Apal site of pCDNA6/V5-HisB(NICD-p). The PEST-containing region (from T2487 to T2517) was obtained by PCR using primers EcoR1-1781 and XmaI and was cloned into the EcoR1/SalI site of pGKBT7/gpGBKT7-C3, a DNA for murine Zfp64 isoform D (GenBank accession number BC004695) was provided by the MRC geneservice (Hinxton, UK). Zfp64 open reading frame was obtained by PCR using primers EcoR1-1781 and T7 as the plasmid template, and was ligated into the BamHI/SalI DNA3/N-terminal HA tag expression vector (HA-Zfp64, or described as Zfp64). The EcoR1-SacI fragment from HA-Zfp64 was ligated into pGADT7. For Zfp64-N, the primers EcoR1-mZf109 and mZf1327-Sal1 were used for PCR and the amplified fragment was digested with EcoR1-SalI and was ligated into EcoR1-XhoI site of pGADT7 (Clontech). Zfp-C was cloned by PCR, and reamplified by PCR using the primers XhoI mZf132 and XmaI and was ligated into EcoR1-XhoI site of pGADT7-Rec. N-EF-G has been previously described (Sakamoto et al., 2005).

For the knockdown experiment, micro RNAs (miRNAs) targeting the isoform-specific coding region of pGADT7 was created using the BLOCK-it Polli miR RNAi Expression Vector Kits (Invitrogen). The sequences of pre-miRNA oligonucleotides (miR-Zfp64up and miR-Zfp64down) are given in supplementary material Fig. S1. Mouse C57BL/6J cDNA was provided from RIKEN GenBank courtesy of T. Honjo (Department of Immunology and Genomic Medicine, Kyoto University, Japan). Mouse Hey1 has been previously described (Minamizato et al., 2007). GFP-Flag M2 (Sigma), anti-Myc (Clontech) and anti-V5 (Invitrogen) antibodies.

Yeast-two-hybrid screening

Yeast-two-hybrid screening was performed using Matchmaker two-hybrid system 3 (Clontech) according to the manufacturer’s instructions. AH109 yeast cells were transformed with pGBK77-PEST and were mated with the Y187 cells transformed with mouse 11-day embryo cDNA library (Matchmaker Pretransformed cDNA library, Clontech). Approximately two million diploid cells were spread on SD dropout (-Ade/-His/-Leu/-Trp) plates and incubated. Candidate clones were re-plated on SD dropout plate with α-X-gal to confirm the bait-prey interactions. The plasmids were extracted from true-positive clones that yielded distinct blue coloration, amplified in E. coli and then submitted to DNA sequencing. For confirmation of protein interaction, bait constructs in pGBK77 and prey constructs in pGADT7 were transformed into AH109 and Y187 respectively, the transformants were grown and mated together. Mated cultures were spread on SD dropout plates and incubated, pGBK77 without an insert and pGBK77-Lam, which contains the gene for human lamin C, were used as negative controls.

Cell culture, transfection, in vitro translation and protein extraction

All cell lines (DMBA transformed NIH3T3 cells and p53- and p16-inhibitor-stromyecyn, except C2C12 cells, were, which were maintained in DMEM with 20% FCS. Transfection was performed using Geneshuttle 40 (Qiogene) or FuGene 6 (Roche). The cells were lysed 48 hours after transfection with HNTZ buffer (10 mM HEPES pH 7.4, 150 mM NaCl, 1% Triton X-100, 0.02 mM Zn acetate) containing 1× protease inhibitor cocktail (Sigma) or RIPA) (50 mM Tris pH 8.0, 150 mM NaCl, 1% NP-40, 0.5% sodium deoxycholate, 0.1% SDS, 0.05 mM Zn acetate). For extraction of cytoplasmic protein, HKMZ1 (10 mM HEPES pH 7.9, 10 mM KCl, 1.5 mM MgCl2, 0.02 mM Zn acetate, 0.06% IGEPAL CA-630 (Sigma) was used, followed by nuclear protein extraction with HNMGZ (20 mM HEPES pH 7.9, 150 mM NaCl, 1% NP-40, 0.1% SDS, 0.05 mM Zn acetate, 25% glycerol).

In vitro transcription and translation were performed using a TNT coupled reticulocyte lysate system (Promega).

Immunoprecipitation and western blot analysis

Immunoprecipitation was conducted using anti-FLAG M2 affinity gel (Sigma), Profound Myc tag IP-Co-IP Kit (Pierce) or anti-V5 agarose (GenTex) for 1 hour or overnight at 4°C. The beads were washed four times with RIPAZ buffer. SDS-PAGE was performed using 1× sample buffer containing 10% β-mercaptoethanol. The proteins were transferred to the nitrocellulose membrane (Hybond-ECL, Amersham). Nonspecific binding was blocked with 2% blocking solution (Amersham) in TBST (10 mM Tris pH 7.6, 150 mM NaCl, 0.1% Tween 20) and incubated with an antibody for 1 hour or overnight. The membranes were washed four times with TBST each for 5 minutes. For the antibodies that have not been coupled to peroxidase, incubation with secondary antibody was conducted. Chemiluminescent detection was performed using an ECL Advance Chemiluminescence Detection Kit (Amersham). The following antibodies were used in this study: anti-Zfp64 (Orbigen), anti-actin (SC-8432, Santa Cruz), anti-sarcromer-2 (clone 5C5, Sigma), anti-desmin (CloneD33, DAKO), anti-α-skeletal muscle actin (Clone 1A4, DAKO), anti-HA (clone 3F10, Roche), anti-Flag M2 (Sigma), anti-Myc (Clontech) and anti-V5 (Invitrogen) antibodies.

In-situ hybridization and immunohistochemistry

Whole-mount in-situ hybridization, embryos were fixed in 4% paraformaldehyde-PBS for 24 hours, decaclified in 10% EDTA at 4°C for one week, embedded in paraffin and sectioned in 4 μm thick. For mouse Zfp64, the open reading frame was used as a template for the digoxigenin-labeled RNA probe. For chick Zfp64 and Hey1, cDNA fragments for RNA probe templates were PCR amplified using the primer sets z22020/z22573 and z22572/z22020. Immunohistochemical staining was performed on formalin-fixed, EDTA-decaclified and paraffin-embedded sections. Epitope retrieval was performed in 10 mM Tris (pH 9.0) supplemented with 1 mM EDTA for 20 minutes at 120°C in a autoclave machine. Endogenous peroxidase activity was killed in 10% hydrogen peroxide/methanol and nonspecific binding was blocked in 10% horse serum/TBST. Incubation with anti-Zfp64 antibody was done overnight at 4°C. After washing, the sections were incubated with biotin-conjugated anti-IgY antibody (Abcam) and then with peroxidase-conjugated streptavidin. The antigen-bound peroxidase activity was visualized with diaminobenzidine substrate.

Northern blot analysis, RT-PCR and real-time PCR

Total RNA was extracted using a NucleoSpin RNA II Kit (Macherey-Nagel). Northern blot analysis was performed using a digoxigenin-labeled RNA probe according to the Dig Application Manual for Filter Hybridization (Roche). Total RNA was reverse transcribed using oligo-RT primer and real-time PCR was performed using a LightCycler ST300 system (Roche) with a Platinum SYBR Green qPCR SuperMix UDG Kit (Invitrogen). Primers used for the real-time PCR are listed in the supplementary material Fig. S1. Expression levels of each gene were normalized to r18s rRNA expression using delta-delta Ct method.

Recombinant adenovirus production and infection

HA-Zfp64 and the mRNA-Zfp64 knockdown construct were cloned into pDNA-CMV (Clontech) and were recombinated by Cre recombinase into pLP-AdenoX (Clontech). Adenovirus production was carried out according to the manufacturer’s instruction. Adenovirus (Ad5GF) and adenovirus (Ad5Zfp64) have been previously described (Hirata et al., 2003). The viral titers of AdZfp64 were evaluated in HEK293 cells by immunocytostaining using anti-Hexon antibody (Clontech). Adenovirus transduction was done at multiplicity of infection (MOI) of 50 in HEK293. Using Ad5GF, we confirmed that MOI 50 is sufficient to achieve virtually 100% infection of C2C12 cells.

Luciferase-activity assay

The Zfp64-luc reporter vector and its derivatives were created as described above (Genes section). The original HE11 promoter fragment was a gift from R. Kaye (Institute for Virus Research, Kyoto University, Japan) and has been described previously (Sakamoto et al., 2002). Hey1-luc was kindly provided by M. Gessler (Biocenter, University of Würzburg, Germany). The total amounts of the plasmids for transfection was equalized to 0.3 μg by adding the mock plasmid. Transfections were done into U2OS cells on 48 well plates and the luciferase activity was measured 48 hours after transfection. All transfections were carried out in triplicate and the experiments were repeated at least twice. Statistical analysis was performed using Excel 2003 (Microsoft).

Chromatin immunoprecipitation (ChIP) assay

U2OS cells were spread on 24-well plates and were transfected with Zfp64 over and NICO. CHIP assay was performed basically according to the protocol provided by Abcam (available online at http://www.abcam.com/ps/pdf/protocols/chip_protocold.pdf). In brief, cells were fixed in 1% formaldehyde for 5 minutes, washed twice with PBS, 1% glycine, washed twice with cold 1% Triton X-100, 0.1% SDS, 0.05% Triton X-100, exposed to RNase A, washed again before addition of 1× Proteinase K/0.1 M NaCl. After digestion, the DNA was purified and precipitated on 5% sodium dodecyl sulfate (SDS)-polyacrylamide gel. The PCR primers used were 5′-ATGGGACAGAGGGTCCCCCG-3′ and 5′-ATGCTTTGCGCCTGCTCTG-3′ for Zfp64.

Immuocytoaining

For myotube staining, cells were fixed with methanol for 5 minutes, blocked in TBST supplemented with 10% horse serum for 10 minutes and incubated with mouse antibody against sarcomeric actin (clone 5C5, Sigma, dilution 1:200) for 30 minutes. After washing, the cells were incubated with Alexa-Fluor-488-conjugated goat anti-
mouse IgG (Molecular Probes, dilution 1:500) and DAPI Solution (Dojindo, Japan, dilution 1:10,000) for 10 minutes. After brief washing, cells were visualized under a fluorescent microscope (Axioskop2, Zeiss). For Zfp64 staining, cells were fixed with PBS supplemented with 4% paraformaldehyde and endogenous peroxidase activity was quenched by 10% hydrogen peroxide. Peroxidase-conjugated anti-IgY antibody (Chemicon) was used as a secondary antibody.

Alkaline phosphatase (ALP) staining and ALP-activity assay

Cells were fixed with methanol for 5 minutes and stained in NBT/BCIP substrate (Wako Chemical, Japan) at 37°C for 1 hour and absorbance at 405 nm was measured. The values were normalized to the protein concentrations.

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References

**Primers for cloning**

EcoR1-N5353         TCGAATTC
N7671-Sall-Xba1     GGGTCTAGAGTTCGACCTTTTTAATGCGCTCTTGAAGT
EcoR1-N7450         AGGAATTCCCATCAGACGACAGT
N7623-Sall          AAGTCGAC
EcoR1-mZf109        CGAATTC
T7                  TAATACGACTCACTATAGGG
mZf1327-Sall        GGGGACAACGTTGCGAGCGACCAGGT
mZf1119             GATCTGTCCCTACCAGCGTC
mZf1941             GTTCGTCTTCAACCTCACT
R1-mZf1326          CAAGAATTC
Nhel-Rx1           CGCTAGCTGGGACCTGCAAG
Rx1791-Sall         TTAGTCGAC
EcoR1-CSL6          AAAGAATTC
CSL1586-Xba1-Xho1   GCTAGCTTTCTCCCGTTGAAAGAG
hgZf51231           AACCTGGCTTTGCAGCAG
hgZf52118           CAGGAAGGAGACAGGGAGTG
mZfp64              GCAAGGTCACAGGGATGACT / CCCACACAGCTCAGTTCAG
hZfp64              TGAGATGCCACAAGAAGCAG / GAAGGCCTGTGAAGTTGGAG
mMyoD               CGACTGCTTTCTTCACCACA / GAGAGCTGCGCTACGGAAAC
mMef2C              TTATCCCACCTGGCAGCAAGAA / AGGGTCATTGCAAGTGGA
mHes1               GAGTGCATGAACGAGGTG     /  AGGTCATGGCGTTGATCTG
hHes1               GCGGACATTCTGGAAATGACA  /  CGTTCATGCACTCGCTGAAG
mHey1               AGCAGTGAGGTGAAGGGAGA   /  AACGGTGAAATCCGTGAGAC
hHey1               GATGACCCTGTATCACTTGAAG / CCGAAATCCAAAATCCCGATAG
mCol1a *             CCAAGAGGGAGGCACATA / AGGGGCGAGCAGTCTCCTAA
mOsc                 CCAAGCAGGAGGGCAATA / AGGGGCAACAGGATGCTC
mOpn                 GTGATAGCTTGGCTTTATGGACT / CTGGGACACGGGATGAC
mRunx2               ATCCATCCACTCCACCAG / AGAGAAGGCGAGGAGGA
18SrRNA              GTAACCGTCGTTACCACATT / CTGACATGCAAGGCAG
hgHs521/hgHs747     GGTGCTGATAACAGCGGAAT / TCAGCTGGCAATTCTCTTT
hgHy519/hgHy686     TGGGAAAGGATGGTTGAG / TGGAGCTGCTTCATGCTG

**Primer sets for real time PCR or ChIP**

mZfp64              GCAAGGTCACAGGGATGACT / CCCACACAGCTCAGTTCAG
hZfp64              TGAGATGCCACAAGAAGCAG / GAAGGCCTGTGAAGTTGGAG
mMyoD               CGACTGCTTTCTTCACCACA / GAGAGCTGCGCTACGGAAAC
mMef2C              TTATCCCACCTGGCAGCAAGAA / AGGGTCATTGCAAGTGGA
mHes1               GAGTGCATGAACGAGGTG     /  AGGTCATGGCGTTGATCTG
hHes1               GCGGACATTCTGGAAATGACA  /  CGTTCATGCACTCGCTGAAG
mHey1               AGCAGTGAGGTGAAGGGAGA   /  AACGGTGAAATCCGTGAGAC
hHey1               GATGACCCTGTATCACTTGAAG / CCGAAATCCAAAATCCCGATAG
mCol1a *             CCAAGAGGGAGGCACATA / AGGGGCGAGCAGTCTCCTAA
mOsc                 CCAAGCAGGAGGGCAATA / AGGGGCAACAGGATGCTC
mOpn                 GTGATAGCTTGGCTTTATGGACT / CTGGGACACGGGATGAC
mRunx2               ATCCATCCACTCCACCAG / AGAGAAGGCGAGGAGGA
18SrRNA              GTAACCGTCGTTACCACATT / CTGACATGCAAGGCAG
hgHs521/hgHs747     GGTGCTGATAACAGCGGAAT / TCAGCTGGCAATTCTCTTT
hgHy519/hgHy686     TGGGAAAGGATGGTTGAG / TGGAGCTGCTTCATGCTG

Restriction sites are underlined.

*This primer set was purchased from Nippon Gene Research Laboratories (Cat. No.484583). The primer sequences were not open to public.*
A

GFP-Zfp64

GFP-CSL

GFP-NICD

B

Zfp64

CSL

NICD

IB: HA

IB: Flg

IB: V5

C

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