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ABSTRACT

Apoptosis occurs widely during brain development, and p73 transcription factors are thought to play essential roles in this process. The p73 transcription factors are present in two forms, the full length TAp73 and the N-terminally truncated DeltaNp73. In cultured sympathetic neurons, overexpression of DeltaNp73 inhibits apoptosis induced by nerve growth factor withdrawal or p53 overexpression. To probe the function of DeltaNp73 in vivo, we generated a null allele and inserted sequences encoding the recombinase Cre and green fluorescent protein (EGFP). We show that DeltaNp73 is heavily expressed in the thalamic eminence (TE) that contributes neurons to ventral forebrain, in vomeronasal neurons, Cajal-Retzius cells (CRc), and choroid plexuses. In DeltaNp73(-/-) mice, cells in preoptic areas, vomeronasal neurons, GnRH-positive cells, and CRc were severely reduced in number, and choroid plexuses were atrophic. This phenotype was enhanced when DeltaNp73-positive cells were ablated by diphtheria toxin expression. However, ablation of cells that express DeltaNp73 and Wnt3a did neither remove all CRc, nor did they abolish Reelin secretion or generate a reeler-like cortical phenotype. Our data emphasize the role of DeltaNp73 in neuronal survival in vivo and in choroid plexus development, the importance of the TE as a source of neurons in ventral forebrain, and the multiple origins of CRc, with redundant production of Reelin.

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DeltaNp73 regulates neuronal survival in vivo

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Apoptosis occurs widely during brain development, and p73 transcription factors are thought to play essential roles in this process. The p73 transcription factors are present in two forms, the full length TAp73 and the N-terminally truncated DeltaNp73. In cultured sympathetic neurons, overexpression of DeltaNp73 inhibits apoptosis induced by nerve growth factor withdrawal or p53 overexpression. To probe the function of DeltaNp73 in vivo, we generated a null allele and inserted sequences encoding the recombining Cre and green fluorescent protein (EGFP). We show that DeltaNp73 is heavily expressed in the thalamic eminence (TE) that contributes neurons to ventral forebrain, in vomeronalan neurons, Cajal-Retzius cells (CRc), and choroid plexuses. In DeltaNp73−/− mice, cells in preoptic areas, vomeronalan neurons, GnRH-positive cells, and CRc were severely reduced in number, and choroid plexuses were atrophic. This phenotype was enhanced when DeltaNp73-positive cells were ablated by diphtheria toxin expression. However, ablation of cells that express DeltaNp73 and Wnt3a did neither remove all CRc, nor did they abolish Reelin secretion or generate a reeler-like cortical phenotype. Our data emphasize the role of DeltaNp73 in neuronal survival in vivo and in choroid plexus development.

Cajal-Retzius cells | p73 | Reelin | thalamic eminence | vomeronalan nerve

Results

Production and Validation of ΔΔNp73 Mutant Mice. ΔΔNp73 transcripts are produced from promoter 2 in the third intron of the p73 gene, and translation is initiated at an AUG in exon 3, followed by splicing to exon 4. To target ΔΔNp73 whilst leaving the TAp73 isoforms unaffected, homology arms corresponding to sequences in intron 3 that flank exon 3 were isolated from PAC clone RPci-21 205D9 (RZPD, Germany). A sequence encoding the Cre recombinase was inserted in phase with the reading frame of the DeltaNp73 protein, using the methionine encoded by the endogenous AUG codon. The Cre sequence was followed by an internal ribosome entry site (IRES) and then by a sequence encoding the EGFP protein (Fig. 1A). Heterozygous and homozygous ΔΔNp73 mutant mice looked healthy and survived. However, homozygous mutants of both sexes had impaired fertility, particularly evident for females that generated only two or three litters. Using reverse transcription–polymerase chain reaction (RT-PCR), we showed that the ΔΔNp73 mRNA was absent in brain extracts from newborn ΔΔNp73 mutant mice, whereas TAp73 transcripts were unaffected, confirming the selective inactivation of the ΔΔNp73 forms (Fig. 1B). When ΔΔNp73 mice were crossed with ROSA26R reporter mice, we observed blue CRc in the marginal zone of the embryonic hemispheres, showing that the Cre sequence knocked in the locus was functional (Fig. 1C and Fig. 2 B and F). We also detected spontaneously fluorescent CRc in vibratome sections, demonstrating endogenous expression of EGFP from the knocked-in gene (Fig. 1D). Cre activity in the targeted locus was further demonstrated in crosses with mice that express DTA conditionally (15), which resulted in the ablation of all fluorescent cells (Fig. 1E).

Multiple Populations of ΔΔNp73-Positive Cells in the Forebrain. We studied expression of ΔΔNp73 in heterozygous mice from E11.5 to adult, by observing the fluorescence related to EGFP expression, sterility, increased susceptibility to spontaneous and induced neoplasia, and subtle abnormalities of the granule cell layer in the dentate gyrus, but it does not affect development of CRc (13, 14).

To study the function of ΔΔNp73 in vivo, we inactivated it specifically in mice, while inserting in the locus sequences that encode the recombining Cre and the enhanced green fluorescent protein (EGFP). Using that new allele, we refine the expression canvas and demonstrate the role of ΔΔNp73 in cell survival in vivo. Our data emphasize the importance of the thalamic eminence (TE) as a largely unsuspected source of neurons destined for ventral forebrain, as well as the multiple origins of CRc and their redundant production of Reelin.
Fig. 1. Generation and validation of DeltaNp73 mutant mice. (A) Genomic organization of the p73 locus showing the two promoters that drive transcription of TAp73 and DeltaNp73. A cassette encoding Cre and EGFP was inserted in frame with the start codon of DeltaNp73 in exon 3. (B) RT-PCR reactions on wild-type (+/+) and DeltaNp73+/− brain extracts at P0, using primers specific for DeltaNp73 and TAp73 isoforms. Note the normal amplification of TAp73 (the 591-bp fragment) and absence of DeltaNp73 transcripts in DeltaNp73+/− mutants (353 bp). (C) betaGal histochemistry on whole forebrain of a LacZ/DeltaNp73 mouse at P0, showing labeled cells in the hemispheric marginal zone and choroid plexuses (ChPl, arrowhead). (D, E) Fluorescence microscopy at P0 detects EGFP signal from the knocked-in sequence in the marginal zone at P0 in DeltaNp73+/− mice (D) and absence of positive cells after genetic ablation in DTA/DeltaNp73 mice (E).

by using immunohistofluorescence with an anti-GFP antibody, as well as in double heterozygous mice obtained by crossing DeltaNp73 mutant males with ROSA26R and ROSA-YFP reporter females (LacZ/DeltaNp73 and YFP/DeltaNp73). Results obtained with all approaches were consistent and confirmed previous studies with in situ hybridization (2, 16). At E11.5 and E12.5, a prominent population of DeltaNp73-positive cells was found in a rostral area located around the insertion of the olfactory bulb, the retrobulbar area (Fig. 2A and B, arrowheads). From this position, cells appeared to migrate in the dorsal and ventral–basal cortical marginal zone (Fig. 2B–D). A second focus of DeltaNp73 positive cells was the cortical hem, from where positive cells also spread in the marginal zone, primarily in medial cortical regions (Fig. 2C and D and Fig. 3A–D). A third zone was seen at the junction between presumptive pyriform and neocortices (Fig. 2A and Fig. 3A). At E13.5 and E14.5, these cells surrounded axons of the lateral olfactory tract. A fourth contingent of DeltaNp73-positive cells appeared at E11.5–E12.5 in a ventral region of the embryonic diencephalon, at the border between ventral diencephalon and telencephalon (Fig. 2B). Fluorescent neurons from this region formed a stream directed toward the ventral forebrain (Fig. 2D and E, Fig. 3C and D). The number of fluorescent cells decreased progressively with development, and no DeltaNp73-positive cell was found at birth. This area was also positive for calretinin and Tbr1 (Fig. S1), showing that it corresponds to the thalamic eminence (TE) (17). A fifth positive population was detected in preoptic area (Fig. 3A and L). Previous studies of p73 gene expression referred to a p73-positive region in the basal forebrain as the bed nucleus of stria terminalis (2). However, because there is no specific marker for this neuronal population and because p73 positive cells were found in rostral diencephalon, we prefer to refer to this zone as preoptic areas (POA). At P10, a few positive cells persisted in the cortical marginal zone, olfactory bulbs, and olfactory tubercles (Fig. 2F and Fig. S2 E and F, p73+/− mutant mice display prominent hydrocephalus (8, 18). To assess whether DeltaNp73 could be involved in cerebrospinal fluid (CSF) dynamics, we examined its expression in the ependyma and choroid plexuses. Although no expression was found in ependymal cells, choroid plexuses were heavily DeltaNp73 positive during embryonic development (Fig. 1C, Fig. 2C and D, Fig. 3A–F) and at postnatal stages (Fig. S3 A and B). They were reduced in size in DeltaNp73−/− animals, indicating that some of their epithelial cells died (compare Fig. 3F with 3E). In DTA/DeltaNp73 mice, choroid plexuses were reduced to a few loops enriched in blood vessels. Yet, these animals looked unremarkable and exhibited neither hydrocephalus nor ventricle collapse (compare Fig. S3 C and E with Fig. S3 D and F), indicating that hydrocephalus in p73−/− mice may be a vacuo rather than related to defective CSF dynamics.

DeltaNp73 Is Required for Neuronal Survival. Numerous in vitro studies showed that DeltaNp73 promotes cell survival (6–11). The number of DeltaNp73-positive cells in the marginal zone, TE, and choroid plexuses was similar in heterozygous and homozygous DeltaNp73 mutant mice at early developmental stages (Fig. S2 A and B). However, from E12.5, the number of labeled cells decreased progressively in DeltaNp73−/− as compared with heterozygous animals (compare Fig. 3 B and D with Fig. 3 A and C). Differences became obvious after birth (Fig. 3 E–J and Fig. S2 E and F). At P0, the number of Reelin-positive cells was reduced by half in
DeltaNP73−/− mice (Fig. S2 C and D). These results indicate that DeltaNP73 promotes cell survival in living animals, as predicted from its activity in cell culture. However, CRc are a peculiar transient population, even in normal mice. To assess whether DeltaNP73 is also required for survival of other cells, we looked at other populations that express DeltaNP73, namely cells of the vomeronasal organ (VNO) and the preoptic area (2). Using endogenous EGFP expression, many DeltaNP73-positive cells were seen in the preoptic region of heterozygous animals at P0, but their number was reduced to almost nothing in DeltaNP73−/− homozygotes (Fig. 3 K and L). Strong DeltaNP73 related signal was demonstrated in a large subset of sensory neurons in the VNO, as well as in their axons and terminals in the accessory olfactory bulb (Fig. A4 A and B). In DeltaNP73−/− mice, VNO axons and terminals, visualized by staining with horseradish peroxidase (HRP)–coupled soybean agglutinin (19), were considerably reduced (Fig. 4 C and D). The time-limited fertility of DeltaNP73 mutant mice and the abnormalities of the vomeronasal system prompted us to examine GnRH neurons. These neurons are generated in olfactory placodes and are believed to use vomeronasal axons to migrate to their final destination in the preoptic region and hypothalamus (20, 21). As shown in Fig. 4 E and F, the number of GnRH positive neurons, detected at P0 using in situ hybridization, was dramatically diminished in DeltaNP73−/− mutant, as compared with wild-type animals.

To understand better the effects of DeltaNP73 on neuronal survival, we assessed apoptosis by immunohistochemistry for activated caspase-3, at E13.5. Whereas no caspase-3–positive cells could be detected in CRc in WT mice, either in the cortical marginal zone or in the cortical hem, a few of these cells were clearly present in both locations in DeltaNP73 homozygous mice (compare Fig. 5 B and D with Fig. 5 A and C). Those caspase-3–positive cells expressed GFP, confirming that DeltaNP73 deficient cells undergo apoptosis (Fig. S4). Moreover, in the trigeminal ganglion, where physiological apoptosis occurs, the number of caspase-3–positive profiles was drastically increased in mutant as compared with wild-type samples (Fig. 5 E and F). These observations show that DeltaNP73 has antiapoptotic properties in vivo.

Genetic Ablation of CRc. Like Reelin, p73 is heavily expressed in, and widely considered a marker of, CRc in various species (2, 22–24). To estimate the percentage of CRc that express DeltaNP73, we produced LacZ/DeltaNP73 mice by crossing DeltaNP73-Cre male mice with ROSA26R females, and compared the number of cells positive for betaGal and Reelin in the cortical marginal zone at P0 (Fig. 6A). In all, 98% (317/325) of betaGal positive cells were also positive for Reelin, indicating that DeltaNP73 expression is largely restricted to Reelin-positive neurons. On the other hand, 73% (317/433) of Reelin-positive cells were betaGal positive, showing that about one in four CRc never express DeltaNP73 during their development. The number of CRc positive both for Reelin and betaGal increased in gradient from the medial to the lateral and basal cortical fields. To genetically ablate CRc expressing DeltaNP73, we crossed DeltaNP73-Cre with ROSA-DTA mice to generate DTADeltaNP73 animals. GFP visualization and Reelin immunohistochemistry in DTADeltaNP73 mice showed that all EGFP-DeltaNP73−/− positive cells were removed (Fig. 1E), and that the number of Reelin-positive CRc was substantially reduced in marginal zones (Fig. 6D). A large contingent of CRc that are generated in the cortical hem and spread in the medial and lateral
cortical marginal zone derive from Wnt3a-positive precursors (16). To reduce further the number of CRc and the production of Reelin, we generated mice that bear combinations of the four alleles DeltaNp73-Cre, Wnt3a-Cre, DTA, and reeler. In these mice, CRc deriving from DeltaNp73 and Wnt3a precursors express Cre and should be genetically ablated, and Reelin production in persisting Reelin-positive cells is reduced by half. In all genotypes, the architectonics of the cerebral cortical plate was unremarkable, unlike that in reeler mutant mice (Fig. S5). To estimate the relative concentrations of Reelin in the dorsal telencephalon, we carried out Western blot analyses of extracts from various genotype combinations at E13.5, the early cortical plate stage (Fig. 6B). Although the actin signal was similar in all samples, the Reelin signal was dramatically decreased in DTA/DeltaNp73 (Fig. 6B, lane 2), DTA/Wnt3a & Reelin*+/– (lane 3), and in DTA/Wnt3a&DeltaNp73 & Reelin*+/– (lane 4), as compared with the wild type (lane 1). However, the Reelin signal was consistently detected, even in quadruple heterozygotes. We then estimated the number of Reelin-positive cells in the cortical marginal zone using Reelin immunohistochemistry. Compared with wild-type brains (Fig. 6C), the number of CRc was reduced by 35% in DTA/Wnt3a (Fig. 6E), by 72% in DTA/DeltaNp73 (Fig. 6D), and by 84% in DTA/Wnt3a&DeltaNp73 (Fig. 6F). To further validate the activity of DTA, we performed double in situ hybridization for Reelin and p73 and found that 210/279 (75%) of Reelin-positive cells coexpressed p73, which is consistent with the proportion of CRc ablated in DTA/DeltaNp73 mice (Fig. S6). Because of the high density of Reelin-positive cells in the hippocampal formation, we found it impossible to count the number of cells that escaped genetic ablation in DTA/Wnt3a and DTA/DeltaNp73 mice. In

Discussion

In this work, we selectively inactivated the DeltaNp73 isoforms by inserting a cassette encoding the recombinase Cre along with EGFP. Using these reporters, we refine the expression pattern of p73 during development, identify the thalamic eminence (TE) as a contributor of neurons to the ventral forebrain, and confirm the multiple sources of CRc. When compared with wild-type littermates, homozygous DeltaNp73 mutant mice display increased cell death in all p73 expressing cells. The number of CRc, POA, GnRH and VNO neurons is markedly reduced, and choroid plexuses are atrophic, yet the lamination of the cerebral cortex is normal. Genetic ablation of DeltaNp73 positive cells severely damages choroid plexuses, but does not affect survival or result in any overt neurological phenotype.

DeltaNp73, a Marker of the Thalamic Eminence. A large number of strongly DeltaNp73 positive cells are found in the ventral diencephalon at E11.5–E13.5. Contrary to CRc, these cells do not co-express Reelin, which is also detected in the diencephalon but at a more dorsal location, in presumptive reticular nuclei, including future zona incerta (25). Although the identity of these ventral diencephalic DeltaNp73-positive cells remains poorly defined, our observation that their number decreases rapidly while streams of cells with similar features are directed to the ventral telencephalon,
suggests strongly that they migrate and contribute to these areas rather than degenerating locally. The diencephalic DeltaNp73-positive region is also labeled with calretinin and Tbr1 antibodies and thus corresponds to the TE (17). That view receives support from comparative embryological observations. The TE is prominent in amphibians (26), and strongly DeltaNp73-positive cells are present in the embryonic reptilian ventral diencephalon (23). It is tempting to propose that the TE corresponds to the transient diencephalic perireticular nuclei (27), and that TE-derived cells might function as guidepost cells for axonal tracts in the internal capsule, such as the thalamocortical tract. Some support for that view is provided by the observation that thalamocortical connections fail to develop in Celsr3/Dnk5/6 mice, in which Celsr3 is inactivated in a wide zone that encompasses the TE (28). Recently, a stream of Dbx1-positive cells, referred to as POA, was shown to originate in a diencephalic zone and to migrate to the amygdala (29). This diencephalic region is strongly reminiscent of the TE described here, including in its contributing neurons to the ventral forebrain. Neuronal migration from diencephalon to telencephalon is not widely investigated, and our DeltaNp73 mutant mouse provides a useful tool for further studies of the TE and its contribution during development.

The p73 Gene Family in Cell Death and Survival. The first genetic evidence for the involvement of p53 gene family in apoptosis came from the observation that approximately 25% of p53−/− females die in utero of exencephaly because of reduced cell death (30). This phenotype is reminiscent of that observed in mutants of Apaf-1, caspase 3, and caspase 9, all members of the mitochondrial cell death pathway. In p73−/− knock-out mice, in which all p73 isoforms are inactivated, the number of neurons of the superior cervical ganglion (SCG) is reduced by half (2, 7). In cultured SCG neurons, NGF removal results in neuronal death and decreased levels of DeltaNp73 proteins. Moreover, DeltaNp73 over expression rescues SCG neurons from NGF withdrawal induced apoptosis, and thwarts the effects of p53 overexpression, indicating that DeltaNp73 has prosurvival properties in SCG neurons, and that these properties are exerted, at least partially, by balancing the proapoptotic activity of p53 (7). Our in vivo study fully supports the role of DeltaNp73 in neuronal survival. In p73−/− mice, the neural phenotype is much more severe than that observed in TAp73 and DeltaNp73 mutant mice. The massive loss of cortical neurons, hydrocephalus, and shortened lifespan described in p73−/− mice (8, 12) are found neither in TAp73 (14, 31) nor in DeltaNp73−/− mice (this work). Usually, such differences are attributed to redundancy between closely related genes. However, many studies in cell culture have shown that TAp73 and DeltaNp73 have opposing rather than redundant effects on cell survival. Perhaps TAp73 and DeltaNp73, in addition to their reported opposing roles, may also act redundantly, and alterations in gene dosage may have an impact on the stoichiometry of complexes containing p73 as well as p53 and p63. Finally, the two known promoters that drive expression of TAp73 and DeltaNp73 may not be the only ones, and other, as yet uncharacterized alternative promoters may exist in the p73 locus.

DeltaNp73 in the Vomeronasal System. The vomeronasal nerve is atrophic and the number of GnRH-positive hypothalamic neurons is drastically reduced in DeltaNp73−/− mice. These mice, particularly females, become prematurely infertile. The vomeronasal system is known to modulate sexual behavior and aggression, as well as pheromone responses (32). We did not observe any unusual sexual or aggressive behavior in DeltaNp73−/− mice. However, behavioral features related to VNO dysfunction require the complete removal of the system and the presence of residual vomeronasal neurons and terminals may thus prevent the appearance of behavioral traits in our mutant mice. On the other hand, vaginal plugs were observed in infertile females, indicating that the poor fertility in DeltaNp73−/− mice could be due either to endocrine dysfunction or to impaired pheromone perception by the VNO. A thorough endocrinological study of the hypothalamo-pituitary-gonadal axis would be needed to understand this better. Finally, it is worth noting that TAp63 and TAp73 play important roles in regulating the genomic stability of the female germ line during meiosis (31, 33), a feature that remains to be investigated in DeltaNp73 mutants.

DeltaNp73, Reelin, and Cajal-Retzius Cells. CRc appear early in telencephalic marginal zones, and most disappear after birth in rodents (16, 34). They have multiple origins, notably in the medial ganglionic eminence, cortical hem, ventral pallium, and retrobulbar area, and migrate in subpial location by tangential routes (22, 35–39). Previous work showed that the loss of CRc cells in p73−/− mice (2) and in Wnt3a-DTA/Emx1 hem-ablated mice (16), is compatible with normal neuronal layering of the cerebral cortex, unlike in Reelin-deficient (reeler) mice. These findings indicate that Reelin production is redundant during murine brain development and that death of most CRc is not sufficient to remove it completely. Using Cre-mediated genetic ablation, we find that 35%, and 72% of Reelin positive are removed in DTA/Wnt3a, and DTA/ DeltaNp73 respectively. Furthermore, we show that Reelin is still detectable in the E13.5 dorsal telencephalon of embryos in which both Wnt3a and DeltaNp73 positive CRc have been genetically ablated, and Reelin-dependent dosage was reduced by 50%. Wnt3a seems to remove more CRc than in Wnt3a-DTA/Emx1 mice in which very few CRc seemed to escape ablation in dorsal telencephalon, although no quantification was performed in that study (16). One possible explanation for this apparent discrepancy could be that Wnt3a-Cre may be less efficient than Wnt3a-DTA, so that some Wnt3a-positive cells escaped genetic ablation in our crosses.

We find that 70–75% of Reelin-positive CRc co-express p73, a proportion similar to that ablated in DTA/DeltaNp73 mice, showing that our DTA allele is effective. In DTA/DeltaNp73&Wnt3a, more than 80%, but not all, of CRc were removed, yet reelin was still detectable. We suggest that residual Reelin is secreted by DeltaNp73- and Wnt3a-negative cells. Dbx1 is another CRc marker the expression of which overlaps that of DeltaNp73, particularly in basal forebrain (29, 37); some Dbx1-positive CRc might be negative for DeltaNp73 and Wnt3a and might contribute to the 16% of Reelin-positive CRc that persist after genetic ablation and to residual reelin detected in Western blot. Another possible source of reelin are neurons migrating from the ganglionic eminence (38), in which Reelin mRNA and protein are detected from E12.5. There is evidence that, in the murine cortex, very low concentrations of Reelin, even when secreted ectopically, suffice to normalize the reeler phenotype (40), suggesting that residual Reelin is sufficient to allow normal development. A subsidiary question that stems from these findings is why murine CRc produce such high levels of apparently redundant and unnecessary Reelin. Thus far, however, this intriguing question has received no satisfactory answer (24).

Materials and Methods

Animals. All animal experiments were carried out in accordance with national and institutional animal ethical guidelines. In addition to the DeltaNp73 mutant strain described below, the following mutant mice were used: Cre reporter mice ROSA26R (41) and ROSA26-eYFP (42), reeler (Orleans allele) (43), Wnt3a-Cre (16), and conditional DTA (15). To describe genotypes in conditional mutant mice, we use the short notation “anyGenecre”; for example, DTA/DeltaNp73 stands for mice that are heterozygotes for DTA and Cre driven by DeltaNp73, in which DTA is activated conditional to DeltaNp73 expression (28).

Targeting of DeltaNp73. DeltaNp73 mutant mice were generated by conventional gene-targeting procedures. The targeting construct contained a Cre-ires-Ef1α cassette inserted from the 3′ homology region (Mm4.39308.37; nucleotides 7931161–7933301), which ends with the ATG codon of exon 3′, a Neo selection cassette flanked with FRT sites, the 3′ homology region (Mm4.39308.37; nucleotides 7920072–7923789), and a DTA negative selection cassette flanked with FRT sites (Mm4.39308.37; nucleotides 7923789–7931161), which ends with the ATG codon of exon 5′. In addition to the Cre reporter mice, mice were crossed to ROSA26R (41) and ROSA26-eYFP (42), reeler (Orleans allele) (43), Wnt3a-Cre (16), and conditional DTA (15). To describe genotypes in conditional mutant mice, we use the short notation “anyGenecre”; for example, DTA/DeltaNp73 stands for mice that are heterozygotes for DTA and Cre driven by DeltaNp73, in which DTA is activated conditional to DeltaNp73 expression (28).
cassette. The construct was electroporated into R1 ES cells to isolate heterozygous ES cells. Injected blastocysts were transferred to pseudopregnant CD1 female mice, and a colony was generated from chimeric animals and maintained by intercrosses. For further information see SI Materials and Methods.

RT-PCR. Total RNA was extracted using NucleoSpin RNA II kit (Macherey-Nagel). Contaminating genomic DNA was removed by treatment with DNase (Macherey-Nagel). RNA was converted to single-stranded cDNA using the ImProm-II reverse transcriptase (Promega) with random primer (0.5 μg/ml) in 20 μl of 1X ImProm-II buffer containing 6 mM MgCl2, 0.5 mM each dNTP, and 200 recombinant RNasin ribonuclease inhibitor. For subsequent PCR amplification, cDNA samples were incubated with 500 nM of each of the sense and antisense primers and 1 unit of recombinant Go Taq polymerase (Promega) in 20 μl of 1X PCR buffer. For further information see SI Materials and Methods.

Histology. Animals were deeply anesthetized before sacrifice. Postnatal mice were fixed by transcardial perfusion with paraformaldehyde (PFA, 4% in PBS) and were fractionated by sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE), followed by transfer to nitrocellulose membranes. Reelin was detected using the G10 antibody (44), and the anti-beta actin antibody (Sigma) was used as loading control.

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