

Role of *Pax3/7* in the tectum regionalization

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SUMMARY

Pax3/7 is expressed in the alar plate of the mesencephalon. The optic tectum differentiates from the alar plate of the mesencephalon, and expression of *Pax3/7* is well correlated to the tectum development. To explore the function of *Pax3* and *Pax7* in the tectum development, we misexpressed *Pax3* and *Pax7* in the diencephalon and ventral mesencephalon. Morphological and molecular marker gene analysis indicated that *Pax3* and *Pax7* misexpression caused fate change of the alar plate of the presumptive diencephalon to that of the mesencephalon, that is, a tectum and a torus semicircularis were formed ectopically. Ectopic tectum in the diencephalon appeared to be generated through sequential induction of *Fgf8*, *En2* and *Pax3/7*. In ventral

mesencephalon, which expresses *En* but does not differentiate to the tectum in normal development, *Pax3* and *Pax7* misexpression induced ectopic tectum. In normal development, *Pax3* and *Pax7* expression in the mesencephalon commences after *Otx2*, *En* and *Pax2/5* expression. In addition, expression domain of *Pax3* and *Pax7* is well consistent with presumptive tectum region in a dorsoventral axis. Taken together with normal expression pattern of *Pax3* and *Pax7*, results of misexpression experiments suggest that *Pax3* and *Pax7* define the tectum region subsequent to the function of *Otx2* and *En*.

Key words: *Pax3*, *Pax7*, *En*, Tectum, Chick

INTRODUCTION

It has been shown that isthmic region acts as an organizer for the mesencephalon and metencephalon, and that *Fgf8* is a candidate organizing molecule (Martinez et al., 1991; Alvarado-Mallart, 1993; Marin and Puellas, 1994; Martinez et al., 1995; Crossley et al., 1996; Joyner, 1996). The optic tectum is a major component of the mesencephalic alar plate derivatives, and has been a focus of attention. *Fgf8*, *Pax2/5* and *En* make a positive feedback loop for their expression to keep organizing activity, and contribute to initiate and maintain the tectum development (Song et al., 1996; Lun and Brand, 1998; Araki and Nakamura, 1999; Funahashi et al., 1999; Okafuji et al., 1999; Ristoratore et al., 1999; Shamim et al., 1999; Liu and Joyner, 2001). However, *Grg4* may antagonize this positive feedback loop (Sugiyama et al., 2000). Now it is accepted that combination of *Otx2*, *En* and *Pax2* defines the tectum region (Nakamura, 2001). Although molecular mechanisms that define the tectum region in the early developmental phase have been well studied, little attention has been paid to downstream factors for the tectum development.

Pax3 and *Pax7* belong to the same *Pax* subfamily, and widely expressed in the nervous system and somites (Jostes et al., 1990; Goulding et al., 1991). In the nervous system *Pax3* and *Pax7* are expressed in the dorsal part of the neural tube (Jostes et al., 1990; Goulding et al., 1991). They are expressed in the whole region of the tectum anlage (Kawakami et al., 1997).

Pax3 mutant mice, *Spotch*, show exencephaly and defects in myogenesis and neural crest cell differentiation (Epstein et al., 1991; Franz, 1993; Tremblay, 1995; Conway et al., 1997). *Pax7* mutant mice also show the defects in myogenesis and neural crest cell differentiation but no defects in the central nervous system (Mansouri et al., 1996). *Pax3* and *Pax7* share their expression domain broadly in the central nervous system, which may explain functional redundancy and rather mild defects in mutant mice. *Pax3* and *Pax7* double mutant mice show severe exencephaly, spina bifida and defects in commissural neurons in the spinal cord, and die by E11.0 (Mansouri and Gruss, 1998).

As *Pax3* and *Pax7* are expressed in the mesencephalic alar plate, the possibility that they are involved in regionalization of the tectum has been suggested (Kawakami et al., 1997; Nomura et al., 1998). A tectum could be induced ectopically in the diencephalic region by transplantation of the isthmus or by misexpression of *En*, *Pax2/5* or *Fgf8*. *Pax7* was always induced where the ectopic tectum structure was formed (Nomura et al., 1998; Araki and Nakamura, 1999). On the other hand when the tectum development was repressed by *Shh* misexpression, *Pax7* expression was repressed in the dorsal mesencephalon (Watanabe and Nakamura, 2000). Therefore, we suspected that *Pax3* and *Pax7* would work to define the identity of the alar plate of the mesencephalon, and that *Pax3* and *Pax7* misexpression would induce an ectopic tectum. *Pax3* overexpression was carried out in the transgenic mice, in which *Pax3* expression was

regulated by *Hoxb4* promoter (Tremblay et al., 1996). In the transgenic mice, however, effects of *Pax3* overexpression on the mesencephalon were not assessed as the *Hoxb4* promoter does not assure expression in the mesencephalon. To explore the roles of *Pax3/7* in tectum development, we carried out misexpression experiments of *Pax3* and *Pax7* in the diencephalon and ventral mesencephalon by *in ovo* electroporation. An ectopic tectum in the diencephalon and ventral mesencephalon was differentiated after *Pax3* and *Pax7* misexpression. A torus semicircularis, which derives from the caudal part of the mesencephalic alar plate and corresponds to the mammalian inferior colliculus, was also differentiated ectopically in the diencephalic region. Analysis of marker gene expression indicated fate change of the diencephalon occurred after sequential induction of *Fgf8*, *En2* and *Pax3/7*. In normal development, *Pax3* and *Pax7* expression in the alar plate of the presumptive mesencephalon commences after *Otx2*, *En* and *Pax2/5*. Thus, results of misexpression experiments, together with normal expression patterns, suggests that *Pax3* and *Pax7* defines the alar plate of the mesencephalon subsequent to determination of the mesencephalon by *Otx2*, *En* and *Pax2/5*.

MATERIAL AND METHODS

Expression vectors

Partial fragment of chick *Pax3* cDNA was isolated from E3 chick brain library, and then this fragment was fused to a C-terminal fragment isolated by 3'RACE to get the full length of *Pax3* cDNA. The full-length of chick *Pax7* cDNA was isolated from E3 chick cDNA by reverse transcription PCR. Primers for N- and C-terminal fragments are 5'-TTGTGACATAGCCCCGAAAACCT-3', 5'-TCTTGCTCGTCCGTTGCTGA-3' and 5'-AGGCGGACCACTTTCACCTGC-3', 5'-TTGCTGGAGTGGGTTGTTGG-3', respectively. These fragments were fused at *StuI* site to make a full length of *Pax7*. *Pax7* was also fused with HA-tag to make *Pax7-HA*. These fragments were inserted in pMiwIII, a derivative of pMiwSV (Suemori et al., 1990; a gift from Dr Kondoh), which has Rous sarcoma virus enhancer and chicken β -actin promoter.

In ovo electroporation

Fertilized chicken eggs from a local farm were incubated at 38°C. *Pax3*, *Pax7* and *Pax7-HA* expression vector (3.0 μ g/ml), β -galactosidase expression vector (MiwZ) (a gift from Dr Kondoh) and the green fluorescence (*GFP*) expression vector (pEGFP-N1, Clontech) (0.5 μ g/ml) were transfected to chick embryos by *in ovo* electroporation at stage 10 (Hamburger and Hamilton, 1951) as previously described (Funahashi et al., 1999). A GFP expression vector was co-transfected to check the efficiency of electroporation. Transfection to the ventral mesencephalon was carried out at stage 13.

Electroporation of this condition does not induce defects in the embryos (Funahashi et al., 1999; Nakamura et al., 2000).

In situ hybridization

Whole-mount *in situ* hybridization was performed as described by Bally-Cuif et al. (Bally-Cuif et al., 1995) or by Stern (Stern, 1998). *In situ* hybridization for sections was carried out as described by Ishii et al. (Ishii et al., 1997). Probes for *Fgf8*, *Lim1* and *Pax6* were described previously (Araki and Nakamura, 1999; Matsunaga et al., 2000). For *Pax3* probe, partial fragment, isolated from cDNA library of E3 chick brain, was used. These fragments were inserted in pBluescript II SK (-) (Stratagene). After linearization, digoxigenin (DIG)-labeled antisense RNA was generated by T3 or T7 RNA polymerase (Stratagene) (Funahashi et al., 1999). For detection,

alkaline phosphatase (ALP)-conjugated anti-DIG sheep-polyclonal antibody (Roche Molecular Biochemicals) was used, and 4-nitroblue tetrazolium chloride (NBT) and 5-bromo-4-chloro-3-indolyl-phosphate (BCIP) (Roche Molecular Biochemicals) were used for the coloring. In some cases, NBT staining was washed out by incubating in dimethylformamide (DMF) at 55°C.

Immunohistochemistry

Anti-*Pax6* rabbit polyclonal antibody (provided by Dr N. Osumi), anti-*Pax7* monoclonal antibody (Developmental Studies Hybridoma Bank; Kawakami et al., 1997), anti-*En2* monoclonal antibody, 4D9 (American Type Culture Collection; Patel et al., 1989) and anti-HA rabbit polyclonal antibody (Berkeley Antibody Company) were used as primary antibodies. Horseradish peroxidase (HRP)-conjugated anti-mouse IgG antibody (Jackson Immuno Research Laboratories) was used as the secondary antibody. For double staining on sections, Alexa488-conjugated anti-rabbit IgG antibody (Molecular Probes) and Cy3-conjugated anti-mouse IgG antibody (Jackson Immuno Research Laboratories) were used as secondary antibodies.

Histology

Embryos were fixed in 4% paraformaldehyde in PBS (phosphate buffered saline), embedded in Technovit (Kulter), serially sectioned at 5 μ m, and stained with Hematoxylin and Eosin. Tiling images were automatically composed by MCID Image analyzer (Imaging Research Inc). β -galactosidase activity was detected on whole-mount embryos as previously described (Katahira et al., 2000).

Tracing retinal fibers with HRP

For tracing of the retinal fibers 30% HRP solution, dissolved in PBS, was injected into the eye using a glass micropipette by air pressure. At 24 hours after injection, the brain was dissected, and the HRP-positive fibers were stained with *p*-cresol-diaminobenzidine method (Streit and Reubi, 1977). After observation of the fiber trajectory, the specimen was embedded in Technovit, and sagittal sections of 5 μ m were prepared.

RESULTS

Expression patterns of *Pax3* and *Pax7* in the prosencephalon and mesencephalon

We first examined expression patterns of *Pax3* and *Pax7* in the prosencephalon and mesencephalon. At stage 10, *Pax3* and *Pax7* expression was detected near the dorsal midline in the neural tube (Fig. 1A,D). *Pax3* and *Pax7* expression extended laterally in the alar plate of the mesencephalon at stage 13 (Fig. 1B,E), and by E2.5 (stage 17), the expression extended more to cover the alar plate of the mesencephalon and the p1 (prosomere1) region (Fig. 1C,F). We adopted the neuromeric criteria presented by Rubenstein et al. (Rubenstein et al., 1994). *Pax3* and *Pax7* were also expressed in the roof plate anterior to p2, but in the anterior midline of the telencephalon only *Pax7* was expressed at stage 17 (Fig. 1F). Around stage 20, *Pax3* and *Pax7* were expressed strongly in the alar plate of the mesencephalon, which is now conspicuous as the tectal swelling. Thereafter *Pax3* and *Pax7* were expressed in the ventricular zone and mantle layer of the tectum (data not shown; Kawakami et al., 1997). Expression of *Pax3* and *Pax7* was also observed in neural crest cells, which shows dot-like staining in Fig. 1A,D.

Pax3 and *Pax7* misexpression caused fate change of the diencephalon to the tectum

To examine the role of *Pax3* and *Pax7* in tectum development,

Pax3 and *Pax7* expression vectors were transfected in the right side of the neural tube from the telencephalon to the metencephalon (Fig. 2).

Pax7 misexpression caused a morphological change in the diencephalon at 48 hours after electroporation ($n=34/56$). An ectopic swelling was generated in the diencephalic region especially in p2 region (Fig. 2A,B). But in p1, swelling was not formed so that the ectopic swelling did not continue to the tectum proper, being interrupted at p1 (Fig. 2A-F). Co-transfection of *Pax7* and *lacZ* expression vector showed that p1 region did not make swelling even though p1 region had been well transfected (Fig. 2A,B).

Lim1 is a good marker expressed in the pretectum (Mastick et al., 1997; Matsunaga et al., 2000). *Lim1* expression remained in the p1 region after *Pax7* misexpression, though expression domain a little narrowed, which indicates that most of the pretectal region retained even after *Pax7* misexpression ($n=5/5$) (Fig. 2G-J).

At E6.5 (stage 27, 5 days after electroporation of *Pax3* expression vector), morphological change was more remarkable (Fig. 2C,D). Histologically, the ectopic swelling was generated in the diencephalic region (Fig. 2E) ($n=4/5$). High power micrograph of this area clearly shows that the ectopic swelling consists of laminar structure that is characteristic of the tectum, though cytoarchitectonic differentiation in the ectopic tectum was behind of the tectum proper (Fig. 2F). In the tectum proper, three layers were prominent in addition to the neuroepithelial layer, and in the ectopic swelling two layers were discernible in addition to the neuroepithelial layer (Fig. 2F).

To examine if the ectopic tectal swelling can receive retinal fibers, we looked at fiber trajectory of retinal axons at E13.5 after *Pax7* misexpression. Fiber tracing with HRP showed that most of retinal fibers innervated the ectopic tectum ($n=3/3$) (Fig. 2K,L). Sagittal sections of this specimen (Fig. 2M-R) show that the ectopic swelling contains well differentiated tectal structure though cytoarchitectonic differentiation was behind of normal tectum. According to LaVail and Cowan (LaVail and Cowan, 1971), the tectum of E12-14 has 12 layers. In the ectopic tectum (Fig. 2P), cell-dense layers of vi and viii are conspicuous; SO (stratum opticum) was easily recognized because retinal fibers had been labeled as shown in Fig. 2L. As the tectum proper at the experimental side was deprived of retinal fibers (Fig. 2L), superficial layers were poorly differentiated (Fig. 2O) as shown by Kelly and Cowan (Kelly and Cowan, 1972). The torus semicircularis (Fig. 2Q,R) that corresponds to the mammalian inferior colliculus (Puelles et al., 1994) was also formed ectopically. Taken together, whole the derivatives of the mesencephalic alar plate were differentiated ectopically. Pretectal nuclei persisted between the tectum proper and the ectopic tectum (Fig. 2N). The pattern of fiber trajectory and histology indicated that ectopic swelling acquired the character of the tectum.

***Pax7* represses *Pax6* expression and induces ectopic tectum by activating the gene cascade for tectum development**

Next we examined effects on marker gene expression

Table 1. Summary of the results of the timecourse analysis of marker gene expression in the diencephalon by *Pax7*-HA misexpression

	Time (hours)						
	6	12	18	24	36	48	96
<i>Pax6</i>		– (3/3)	↓ (2/4)	↓↓ (4/4)		↓↓ (2/2)	↓↓ (4/4)
<i>Fgf8</i>	– (6/6)	↑ (1/4)	↑↑ (5/5)	↑↑ (7/7)	↑↑ (3/3)	↑ (4/9)	– (4/4)
<i>En2</i>			– (3/3)	– (4/4)	↑↑ (7/7)	↑↑ (9/13)	↑ (4/4)
<i>Pax3</i>		– (3/3)	↑ (1/3)	↑ (5/8)		↑ (1/7)	↑↑ (4/4)

Upward arrows represent ectopic induction and downward arrows represent repression. Single arrows represent weak induction or repression. A bar indicates that induction or repression was not detected.

after *Pax7* misexpression. The results of timecourse analysis are summarized in Table 1.

First, we looked at the effects of *Pax7* misexpression on *Pax6* expression. *Pax6* is expressed in the diencephalon and essential for its development (Walther and Gruss, 1991; Stoykova et al., 1996; Stoykova et al., 1997; Grindley et al., 1997; Mastick et al., 1997; Warren and Price, 1997). *Pax6* mutant mice, *Sey*, show fate change of p1 region to the mesencephalon (Mastick et al., 1997). Repression of *Pax6* by *Pax7* was detected by 15 hours after electroporation ($n=1/3$), and repression was observed in all the embryos examined at 24 hours after electroporation ($n=4/4$) (Table 1 and Fig. 3A-C). Repression of *Pax6* was remarkable in the p2 region (Fig. 3C). In the p1

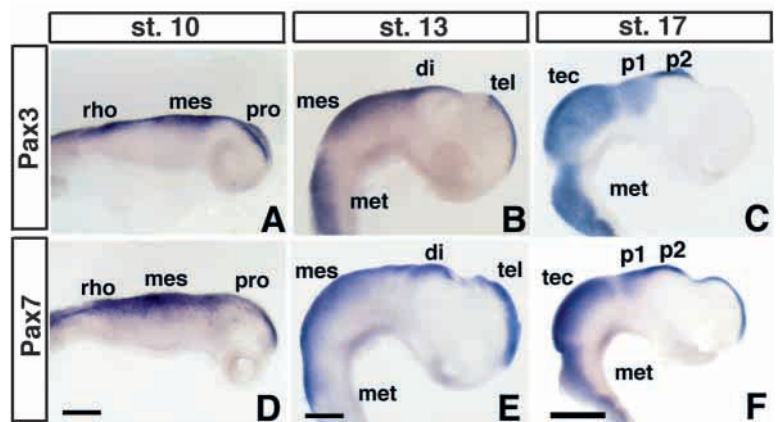


Fig. 1. Normal expression patterns of *Pax3* and *Pax7* in the prosencephalon and the mesencephalon. Whole-mount in situ hybridization for *Pax3* (A-C) and *Pax7* (D-F) at 10-somite stage (A,D), 18-somite stage (HH13) (B,E) and E2.5 (HH17) (C,F). *Pax3* and *Pax7* are expressed near the dorsal midline of the neural tube and in the migrating neural crest cells in the mesencephalic region at stage 10 (A,D). Expression of *Pax3* and *Pax7* commences around stage 13 in the alar plate of the mesencephalon (B,E). In the alar plate, *Pax3* and *Pax7* are expressed posterior to p1/p2 boundary at stage 17. Expression around the roof plate extended rostrally beyond the p1/p2 boundary (C,F). *Pax7* is also expressed in anterior midline of the telencephalon, but *Pax3* is not expressed there. Scale bars: 500 μ m in F; 200 μ m in D,E. di, diencephalon; mes, mesencephalon; met, metencephalon; p1, prosomere 1; p2, prosomere 2; pro, prosencephalon; rho, rhombencephalon; tel, telencephalon.

Fig. 2. *Pax3/7* misexpression changed the fate of the alar plate of the diencephalic P2 region to that of the mesencephalon. (A,B) Morphological change at 48 hours after electroporation of *Pax7*. Horizontal section.

Hematoxylin and Eosin staining (A). X-gal staining of an embryo at 48 hours after co-electroporation of *Pax7* and *lacZ* expression vector (B). White arrowheads show the ectopic swelling in the diencephalon. Note that the ectopic swelling is formed in the p2 region, although expression vectors were uniformly transfected from the telencephalon to the mesencephalon.

(C-F) Morphological change at 5 days after electroporation of *Pax3*. View from the experimental side (C), dorsal view (D). Horizontal section at the plane indicated in C. Hematoxylin and Eosin staining (E). (F) A high power micrograph of boxed area in (E).

Arrowheads on E indicate the ectopic swelling in the diencephalon. Note that ectopic swelling (ect. tec) has the laminar structure similar to the tectum proper (tec). Differentiation of laminar architecture in the ectopic swelling is behind of tectum proper. (G-J) In situ hybridization for *Lim1* to show that pretectum is retained after *Pax7* misexpression. View from the experimental side (G), view from the control side (H) and dorsal view (I) of an E4.0 embryo. (J) Horizontal section at the plane indicated in G. The control side is printed in reverse for the comparison. *Lim1* expression in the pretectum is detected (between arrowheads on panel J).

(K-R) Retinal fiber trajectory and histology of E13.5 embryos after *Pax7* misexpression. Schematic drawing of retinal fiber trajectory (K), and lateral view (L). Horseradish peroxidase was injected into the left eye at E12.5 and the embryo was sacrificed at 24 hours later (E13.5, 12 days after *Pax7* misexpression). Most of retinal fibers innervate the ectopic swelling (arrow), and some of them innervate the tectum proper (arrowhead). After observation of retinal fiber trajectory, the specimen was embedded in Technovit, and sagittal sections were stained with Hematoxylin and Eosin. Approximate planes of M,N are indicated in K. Panels P-R are higher magnifications indicated on M,N. The tectum proper (O) does not contain stratum opticum (SO) as is inferred from L, which may result in maldifferentiation of superficial layers (layer x is barely discernible). The ectopic tectum (P) contains SO, and layers vi, vii, viii, ix are discernible, though its differentiation is behind the normal tectum. Torus semicircularis at the proper site and ectopically differentiated in the diencephalon are shown in Q,R, respectively. We could identify pretectal nuclei (nucleus spiriformis lateralis (Spl) and medialis (Spm), and nucleus principalis precommissuralis (Ppc)). We adopted the criterion of the tectum layers of LaVail and Cowan (LaVail and Cowan, 1971). Scale bars: 2.0 mm in L; 1.0 mm in D,H,I; 500 μ m in A,B,E,J,M,N; 200 μ m in F,R; 100 μ m in O. cont., control side; cer, cerebellum; exp., experimental side; tec, tectum; ect. tec, ectopic tectum; ts, torus semicircularis; ect. ts, ectopically differentiated torus semicircularis.

(M) Horizontal section at the plane indicated in C. Hematoxylin and Eosin staining (E).

(F) A high power micrograph of boxed area in (E).

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(K-R) Retinal fiber trajectory and histology of E13.5 embryos after *Pax7* misexpression. Schematic drawing of retinal fiber trajectory (K), and lateral view (L). Horseradish peroxidase was injected into the left eye at E12.5 and the embryo was sacrificed at 24 hours later (E13.5, 12 days after *Pax7* misexpression). Most of retinal fibers innervate the ectopic swelling (arrow), and some of them innervate the tectum proper (arrowhead). After observation of retinal fiber trajectory, the specimen was embedded in Technovit, and sagittal sections were stained with Hematoxylin and Eosin. Approximate planes of M,N are indicated in K. Panels P-R are higher magnifications indicated on M,N. The tectum proper (O) does not contain stratum opticum (SO) as is inferred from L, which may result in maldifferentiation of superficial layers (layer x is barely discernible). The ectopic tectum (P) contains SO, and layers vi, vii, viii, ix are discernible, though its differentiation is behind the normal tectum. Torus semicircularis at the proper site and ectopically differentiated in the diencephalon are shown in Q,R, respectively. We could identify pretectal nuclei (nucleus spiriformis lateralis (Spl) and medialis (Spm), and nucleus principalis precommissuralis (Ppc)). We adopted the criterion of the tectum layers of LaVail and Cowan (LaVail and Cowan, 1971). Scale bars: 2.0 mm in L; 1.0 mm in D,H,I; 500 μ m in A,B,E,J,M,N; 200 μ m in F,R; 100 μ m in O. cont., control side; cer, cerebellum; exp., experimental side; tec, tectum; ect. tec, ectopic tectum; ts, torus semicircularis; ect. ts, ectopically differentiated torus semicircularis.

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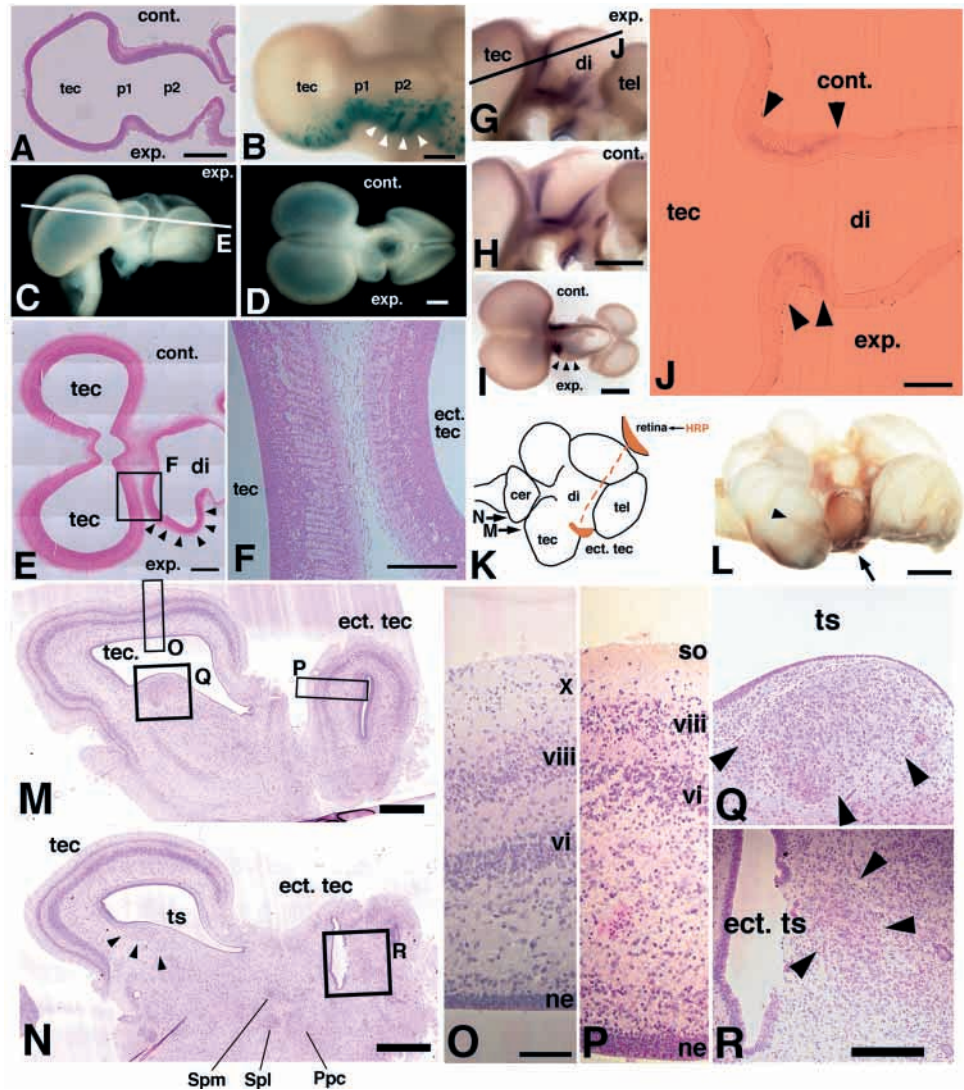
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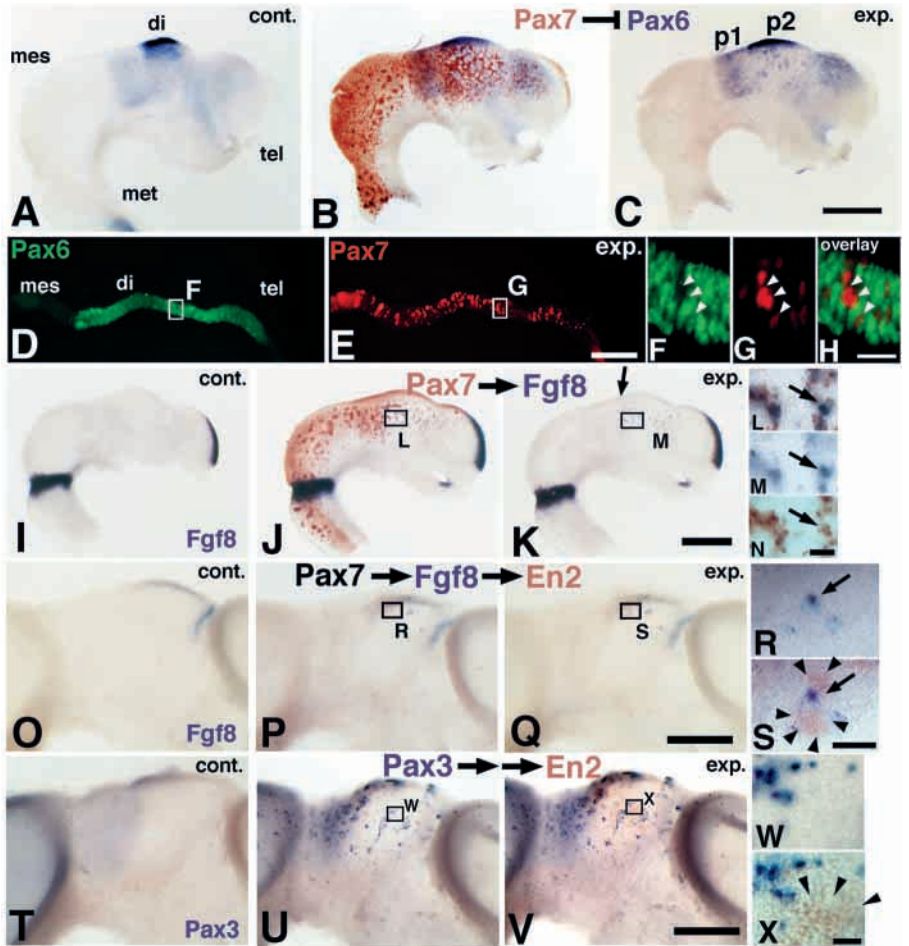


region, *Pax6* expression was not so much affected even when *Pax7* had been misexpressed strongly (Fig. 3A-C). Double staining by immunocytochemistry with specific antibodies for *Pax6* and *Pax7* revealed that *Pax6* was repressed in the cells that had expressed *Pax7*, which indicates that repression is in a cell-autonomous manner ($n=4/4$) (Fig. 3D-H). *Pax7* also repressed *Tcf4*, which is a dorsal diencephalon marker gene (data not shown).

Then, we checked effects on tectum-related genes. *Fgf8* induction by *Pax7* was detected in some embryos by 12 hours after electroporation (Table 1), and in all the embryos by 24

hours after electroporation (Table 1). Induction of *Fgf8* was detected earlier than repression of *Pax6* (Table 1). However, if we take it into consideration that detection of repression is much more difficult than that of induction, induction of *Fgf8* and repression of *Pax6* by *Pax3/7* may have occurred around the same time. Induction of *Fgf8* was always detected rostral to the p1/p2 boundary, that is, in the p2 region, but not in the p1 region ($n=7/7$) (Fig. 3I-N). Double staining for *Fgf8* and *Pax7* shows that *Fgf8* was induced in the *Pax7*-expressing cells, that is, in a cell autonomous manner (Fig. 3L-N). *En2* induction was not detected even at 24 hours after electroporation (Table

Fig. 3. Effects of Pax7 on expression of tectum related genes. (A-H) Cell autonomous repression of *Pax6* by Pax7. In situ hybridization for *Pax6* (blue), the control (A), and the experimental embryos (C) at 24 hours after electroporation. Immunostaining for Pax7 (brown) was also carried out on the same embryo (B). Repression of *Pax6* is rarely detected in the p1 region (C). (D-H) Double immunocytochemical staining for Pax6 (green) and Pax7 (red) 24 hours after Pax7 electroporation. (F,G) High power magnifications of boxed areas in D,E, respectively. (H) A combined image. Pax6 is repressed in the cells that express Pax7 (arrowheads, F-H), indicating that Pax6 is repressed by Pax7 in a cell autonomously. (I-N) Induction of *Fgf8* by Pax7. In situ hybridization for *Fgf8* (blue, I,K), and immunostaining for Pax7 (brown) was added on the same embryo (J) at 24 hours after electroporation. (L,M) Higher power micrographs of the area indicated in J,K, respectively. (N) A micrograph of the same field as M, showing only Pax7 expression. This figure was taken after staining for *Fgf8* was washed away. These figures indicate that induction of *Fgf8* expression by Pax7 is in a cell autonomous manner. The arrows in L-N indicate the same position. (O-S) En2 induction via *Fgf8* after Pax7 misexpression. In situ hybridization for *Fgf8* (blue, O,P), and immunostaining for En2 (brown) on the same embryo (Q) at 48 hours after electroporation. (R,S) High power micrographs of boxed area in P,Q, respectively. The arrows in R,S indicate ectopic expression of *Fgf8*. Arrowheads in S indicate ectopic expression of En2. En2 induction was always detected around *Fgf8*-expressing cells. (T-X) En2 induction after Pax3 misexpression. In situ hybridization for Pax3 (blue, T,U), and immunostaining for En2 (brown) on the same embryo (V). (W,X) High power micrograph of boxed area in U,V. En2 induction was detected adjacent to the Pax3-misexpressing cells, which indicate that En2 was induced in a same manner as after Pax7 misexpression. A,I,O,T are printed in reverse for the comparison. Scale bars: 500 μ m in C,K,Q,V; 200 μ m in E; 25 μ m in H,N,S,X.



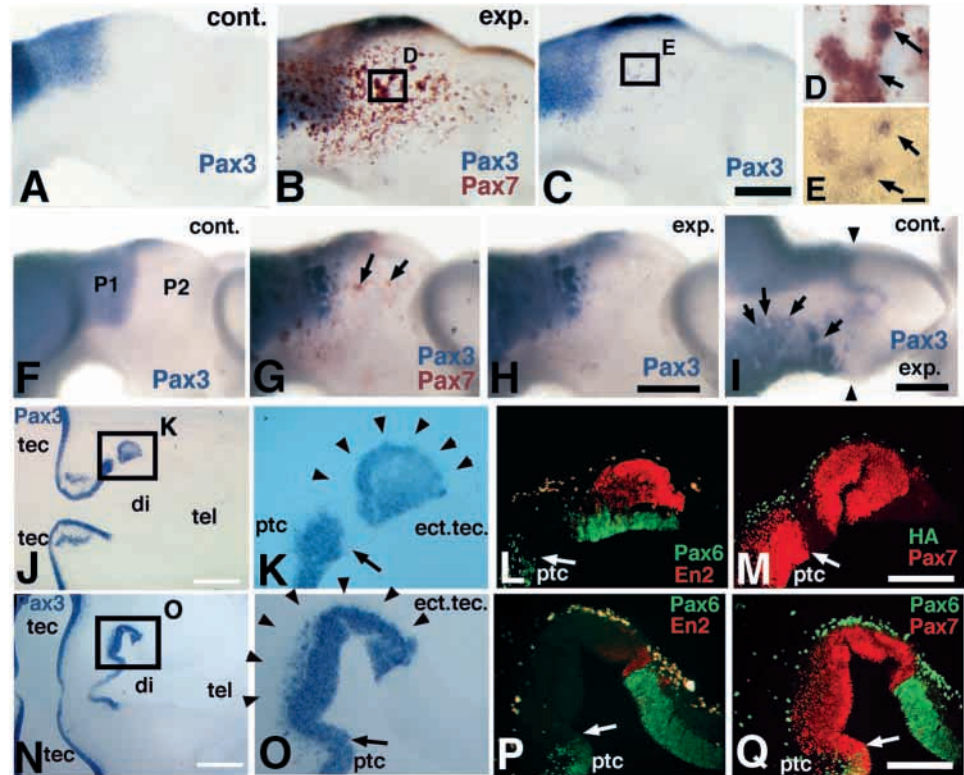
1). By 36 hours after electroporation, En2 was ectopically induced in the alar plate of the diencephalon. Ectopic En2 induction was observed in p2, but not in p1 in the embryos of 48 hours after electroporation ($n=9/13$) (Fig. 3O-S). Double staining for *Fgf8* and En2 shows that En2 was induced in the cells around those in which *Fgf8* had been ectopically induced, suggesting that En2 was induced by *Fgf8*. (Fig. 3R,S). After Pax3 misexpression, En2 was also induced around the Pax3-expressing cells, which indicates that En2 was induced in non cell autonomous manner ($n=3/4$).

Repression of *Otx2* by Pax7 was not recognized at 24 hours after electroporation ($n=3/3$). Ectopic expressions of *En1* and *Pax2* was not detected in the diencephalic region (data not shown). *Pax5* induction was very weakly detected at 48 hours after electroporation, but not detected before 48 hours after electroporation (data not shown).

Next we looked at inter-relationship between Pax3 and Pax7. Pax3 was induced ectopically in the diencephalon by 18 hours after electroporation of Pax7 (Table 1; Fig. 4A-E). Induction was very weak at first, and higher magnification indicates that the induction is cell autonomous (Fig. 4F-I). By 96 hours after

electroporation, when the ectopic swelling became conspicuous, Pax3 expression became strong and covered the whole ectopic swelling (Fig. 4J, N). Serial sections showed that Pax3 was expressed in the ectopic swelling, where En2 had been ectopically induced and Pax6 was repressed (Fig. 4K,L,O-Q). Pax7 also covered whole the ectopic swelling (Fig. 4M,Q). To distinguish induced and exogenous Pax7 expression, we misexpressed HA-tagged Pax7. The ectopic swelling was not stained immunocytochemically by anti-HA antibody at 96 hours after electroporation (Fig. 4M). As expression vector adopted in the present study assures transient expression, it is conceivable that Pax7 expression by introduced expression vector disappeared by this stage. Thus, Pax7 expression seen in the ectopic swelling was not exogenous one, but expression from the host Pax7 gene. Timecourse analysis shows that Pax3 was weakly induced by Pax7 at 18 and 24 hours after electroporation, then Pax3 expression nearly disappeared by 48 hours after electroporation. Then by 96 hours after electroporation, Pax3 expression covered whole the ectopic swelling. These results indicates that there are two modes in Pax3 induction by Pax7

Fig. 4. Interrelationship between *Pax3* and *Pax7*. (A-I) In situ hybridization for *Pax3* (blue) (A,C,E,F,H,I) and in situ hybridization for *Pax3* and immunohistochemistry for *Pax7* (brown) (B,D,G) 24 hours (A-E) and 48 hours (F-I) after electroporation. View from the control side (A,F), view from the experimental side (B,C,G,H), dorsal view (I). The control side is printed in reverse (A,F). High power magnification of boxed area in B,C (D,E). Corresponding arrow in D,E indicates the same position. Arrows in G indicate exogenous expression of *Pax7*. Arrows in I indicate repression of endogenous *Pax3* expression by *Pax7*. Arrowheads in I indicate the line corresponding to p1/p2 boundary. (J-Q) Serial sections of the embryo at 96 hours after electroporation. (J-M) An embryo in which the swelling in the diencephalon is small; (N-Q) an embryo in which the swelling had enlarged. (J,N) In situ hybridization for *Pax3*. (L,P,Q) Double staining by immunohistochemistry for *Pax6* (green) and for *En2* (L,P, red), for *Pax7* (Q, red). (M) Immunohistochemistry for HA-tag (green) and for *Pax7* (red). (K,O) High power magnifications indicated in J,N.



Areas surrounded by arrowheads on panels K and O indicate ectopic swelling, where *Pax3* expression was induced. Arrows in K-M, O-Q indicate the approximate position of the boundary between the ectopic swelling and the pretectum. Exogenous *Pax7* expression which is identified by HA-tag had disappeared at 96 hours after electroporation (M). Green cells in M are mesenchymal cells (stained for HA). *En2* is expressed in almost entire region of the ectopic swelling with rostral-high and caudal-low level when ectopic swelling is small (L). *En2* expression is almost absent by the time the ectopic swelling enlarged, leaving at the rostral tip of the swelling (P). *Pax7* was induced in the ectopic swelling, making a sharp boundary with *Pax6* (Q). This boundary is consistent with the *Pax6/En2* boundary (P). Scale bars: 500 μ m in H,I,J,N; 250 μ m in C; 200 μ m in M,Q; 50 μ m in E. ptc, pretectum.

in the ectopic swelling; one is direct induction by *Pax7*, and the other is indirect and may be induced after the feedback loop of tectum organizing molecules had been turned on.

***Pax7* misexpression expands the territory of the tectum ventrally**

Shh misexpression in the dorsal mesencephalon resulted in repression of *Pax7* expression and fate change of the tectum to the tegmentum (Watanabe and Nakamura, 2000). *Pax7* expression is well correlated with tectum development in a dorsoventral axis (Nomura et al., 1998). Therefore, we misexpressed *Pax3* and *Pax7* in the ventral mesencephalon and analyzed effects on dorsoventral axis.

At E6.5, the tectum and the tegmentum can be distinguished histologically; the tectum shows specific laminar structure as shown previously. After *Pax7* misexpression, tectal structure extended ventrally ($n=3/6$) (Fig. 5A-C). Next we checked effects on marker gene expression for the tectum and tegmentum. Induction of *Pax3* in the ventral mesencephalon was observed at 24 hours after electroporation of *Pax7* ($n=3/3$) (Fig. 5G,H). Higher power micrographs indicate that induction of *Pax3* by *Pax7* is cell autonomous (Fig. 5H',I'). *Pax3* misexpression also expanded the tectal domain ventrally (Fig. 5D-F).

Ectopically induced *Pax3* expression by *Pax7* disappeared

near the floor plate, and *Pax3* expression domain expanded ventrally corresponding to that ventral expansion of the tectal swelling by 48 hours after electroporation ($n=4/6$) (Fig. 5K,L). As *Shh*, a ventralizing factor, emanates from the floor plate, re-specification along dorsoventral axis may have taken place. These results together with those in diencephalon suggest that morphological change in the ventral mesencephalon occurred earlier than that in the diencephalon. In accordance with this idea, differentiation of the ectopic tectum in the diencephalon is behind of the tectum proper (Fig. 2E,F), while no such differentiation gap was found when tectal structure extended ventrally (Fig. 5C,F).

Lim1 is expressed in the ventral mesencephalon at E4.0, and is thought as a good marker for the tegmentum (Watanabe and Nakamura, 2000). At E4.0 (60 hours after electroporation), *Lim1* expression in the ventral mesencephalon made two stripes on the control side; broad lateral stripe and narrow medial stripe (Fig. 5M). On the experimental side, broader stripe was completely missing although narrow stripe remained and the position of narrow stripe did not shift ventrally ($n=2/5$) (Fig. 5M). On the control ventral side, *Pax6* expression band is discernible (Agarwala, 2001). The *Pax6* expression band disappeared after *Pax3* misexpression ($n=3/4$) and after *Pax7* misexpression ($n=4/4$, Fig. 5N).

In normal development, *Pax3* and *Pax7* are expressed almost in an overlapping manner in the mesencephalic alar plate, and *Pax3* and *Pax7* misexpression caused very similar phenotype. These results indicate functional redundancy of *Pax3* and *Pax7* in tectum development as suggested previously from the phenotype of mutant mice (Epstein et al., 1991; Mansouri et al., 1996; Mansouri et al., 1998). Our misexpression study showed that in the dorsal mesencephalon and p1 region, *Pax3* and *Pax7* repressed each other's expression. At the same time, some regulation mechanism to balance total expression level of *Pax3* and *Pax7* by downregulating or by upregulating each other's expression may exist. In *Pax3* mutant mice *Pax7* was upregulated in the somite and neural tube (Borycki et al., 1999).

Pax7 repressed *Pax6* expression in the alar plate of the p2 region, which may mean that *Pax7* repressed diencephalic property to cause re-specification of gene expression cascade toward mesencephalic development. In the p1 region, *Pax6* expression was not affected so much, and most of it differentiated according to its original developmental program, that is, p1 differentiated into the diencephalic pretectum. This difference may be attributed to that both *Pax3/7* and *Pax6* are expressed normally in the p1 region. *Pax3/7* and *Pax6* repress each other's expression (Matsunaga, et al., 2000; present study), but in p1 region there may be some mechanism for each of them to escape from other's repressive effect. As a consequence, forced expression of these genes would not exert strong effect, and would result in separation of ectopically differentiated tectum from the tectum proper at the p1 region.

Role of Pax3/7 in tectum development

The ectopically introduced *Pax7* may turn off the gene expression cascade toward the diencephalic differentiation, by repressing *Pax6* expression. At the same time, or rather earlier induction of *Fgf8* expression took place. *Fgf8* was broadly induced, and subsequently *En2* expression was induced in the p2 region, not in the p1 region. *Fgf8* and *Otx2* are mutually repressive in their expression (Liu et al., 1999; Martinez et al., 1999; Katahira et al., 2000), but weak signal of *Fgf8* does not affect *Otx2* expression (Sato et al., 2001). In the present study, *Otx2* expression was not affected by ectopically induced *Fgf8* so that ectopic swelling in the p2 region may have differentiated into the tectum. If *Fgf8* signal is strong enough to repress *Otx2* expression in the diencephalon, cerebellum would ectopically differentiate (Martinez et al., 1999; Sato et al., 2001). Fate change to the tectum occurred in the region where ectopic *En* was induced, that is, p2 region differentiated into the tectum, but p1 region kept its original fate after *Pax3/7* misexpression. Expression of *Lim1*, pretectum marker gene, and the persistence of the pretectal nuclei also indicated that the pretectum still remained. The results of the present study, those of *En2* misexpression (Araki and Nakamura, 1999) and those in *En1/2* double mutant mice that show complete deletion of the mesencephalon (Liu and Joyner, 2001) all indicate that the neural tissue should express *En* to differentiate into the tectum.

The results of the present study indicate that the tissue should express *Pax3* and *Pax7* followed by *En* expression to differentiate into the tectum. Exogenously introduced *Pax3* or *Pax7* might not be directly involved in the transformation of presumptive diencephalic alar plate to the mesencephalic

property. Introduced *Pax3/7* may first turn off the gene expression program towards diencephalon, then may induce *Fgf8* and *En* expression. At first, *En* expression was found on the entire ectopic swelling, but then, confined to the rostral border of the swelling (see Fig. 4J-Q), which may indicate that the rostrocaudal polarity of the ectopic tectum was established in a mirror image to the tectum proper. Following *En* expression, *Pax3* and *Pax7* expression covered whole the ectopic swelling. The results of transfection experiments with HA-tagged *Pax7* expression vector suggested that expressions of *Pax3* and *Pax7*, covering whole the ectopic swelling, were not expressed from the transfected expression vector, but from the embryonic gene induced sequentially after *En* expression (see Fig. 4L,M). These results together with the chronological order of expression of these genes in normal development indicate that *Pax3* and *Pax7* may take part in mesencephalic development after the *En* expression.

It was suggested that the brain vesicle should express *Otx2*, *En* and *Pax2* to acquire the property to differentiate into the tectum (Nakamura, 2001). We would like to add *Pax3* and *Pax7*, expressed in the mesencephalic alar plate, for the tectum development. *En*, *Otx2* and *Pax2* are expressed or once expressed in both the alar plate and the basal plate of the mesencephalon. In this scenario, addition of *Pax3* or *Pax7* expression at the basal plate may be enough to change its fate to the tectum. This assumption well explains the results that the morphological change was detectable earlier in the basal plate of the mesencephalon than in the diencephalon after *Pax3* and *Pax7* misexpression

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REFERENCES

- Agarwala, S., Sanders, T. A. and Ragsdale, C. W. (2001). Sonic hedgehog control of size and shape in midbrain pattern formation. *Science* **291**, 2147-2150.
- Alvarado-Mallart, R.-M. (1993). Fate and potentialities of the avian mesencephalic/metencephalic neuroepithelium. *J. Neurobiol.* **24**, 1341-1355.
- Araki, I. and Nakamura, H. (1999). *Engrailed* defines the position of dorsal di-mesencephalic boundary by repressing diencephalic fate. *Development* **126**, 5127-5135.
- Bally-Cuif, L., Cholley, B. and Wassef, M. (1995). Involvement of Wnt-1 in the formation of the mes/metencephalic boundary. *Mech. Dev.* **53**, 23-34.
- Borycki, A. G., Li, J., Jin, F., Emerson, C. P. and Epstein, J. A. (1999). *Pax3* functions in cell survival and in *pax7* regulation. *Development* **126**, 1665-1674.
- Conway, S. J., Henderson, D. J. and Copp, A. J. (1997). *Pax3* is required for cardiac neural crest migration in the mouse: evidence from the splotch (*Sp2H*) mutant. *Development* **124**, 505-514.
- Crossley, P. H., Martinez, S. and Martin, G. R. (1996). Midbrain development induced by FGF8 in the chick embryo. *Nature* **380**, 66-68.
- Epstein, D. J., Vekemans, M. and Gruss, P. (1991). Splotch (*Sp2H*), a

- mutation affecting development of the mouse neural tube, shows a deletion within the paired homeodomain of Pax-3. *Cell* **67**, 767-774.
- Franz, T., Kothary, R., Surani, M. A., Halata, Z. and Grim, M.** (1993). The Sploch mutation interferes with muscle development in the limbs. *Anat. Embryol.* **187**, 153-160.
- Funahashi, J.-i., Okafuji, T., Ohuchi, H., Noji, S., Tanaka, H. and Nakamura, H.** (1999). Role of Pax-5 in the regulation of a mid-hindbrain organizer's activity. *Dev. Growth Differ.* **41**, 59-72.
- Goulding, M. D., Chalepakis, G., Deutsch, U., Erselius, J. R. and Gruss, P.** (1991). Pax-3, a novel murine DNA binding protein expressed during early neurogenesis. *EMBO J.* **10**, 1135-1147.
- Grindley, J. C., Hargett, L. K., Hill, R. E., Ross, A. and Hogan, B. L.** (1997). Disruption of PAX6 function in mice homozygous for the *Pax6*Sey-1Neu mutation produces abnormalities in the early development and regionalization of the diencephalon. *Mech. Dev.* **64**, 111-126.
- Hamburger, V. and Hamilton, H. L.** (1951). A series of normal stages in the development of the chick embryo. *J. Morphol.* **88**, 49-92.
- Ishii, Y., Fukuda, K., Saiga, H., Matsushita, S., and Yasugi, S.** (1997). Early specification of intestinal epithelium in the chicken embryo: a study on the localization and regulation of CdxA expression. *Dev. Growth Differ.* **39**, 643-653.
- Jostes, B., Walther, C., and Gruss, P.** (1990). The murine paired box gene, Pax7, is expressed specifically during the development of the nervous and muscular system. *Mech. Dev.* **33**, 27-37.
- Joyner, A. L.** (1996). Engrailed, Wnt and Pax genes regulate midbrain-hindbrain development. *Trends Genet.* **12**, 15-20.
- Katahira, T., Sato, T., Sugiyama, S., Okafuji, T., Araki, I., Funahashi, J.-I., and Nakamura, H.** (2000). Interaction between Otx2 and Gbx2 defines the organizing center for the optic tectum. *Mech. Dev.* **91**, 43-52.
- Kawakami, A., Kimura-Kawakami, M., Nomura, T. and Fujisawa, H.** (1997). Distributions of PAX6 and PAX7 proteins suggest their involvement in both early and late phases of chick brain development. *Mech. Dev.* **66**, 119-130.
- Kelly, J. P. and Cowan, W. M.** (1972). Studies on the development of the chick optic tectum. III. Effects of early eye removal. *Brain Res.* **42**, 263-288.
- LaVail, J. H. and Cowan, W. M.** (1971). The development of the chick optic tectum. I. Normal morphology and cytoarchitectonic development. *Brain Res.* **28**, 391-419.
- Liu, A., Losos, K. and Joyner, A. L.** (1999). FGF8 can activate *Gbx2* and transform regions of the rostral mouse brain into a hindbrain fate. *Development* **126**, 4827-4838.
- Liu, A. and Joyner, A. L.** (2001). EN and GBX2 play essential roles downstream of FGF8 in patterning the mouse mid/hindbrain region. *Development* **128**, 181-191.
- Lun, K. and Brand, M.** (1998). A series of no isthmus (noi) alleles of the zebrafish *pax2.1* gene reveals multiple signaling events in development of the midbrain-hindbrain boundary. *Development* **125**, 3049-3062.
- Mansouri, A., Stoykova, A., Torres, M. and Gruss, P.** (1996). Dysgenesis of cephalic neural crest derivatives in Pax7^{-/-} mutant mice. *Development* **122**, 831-838.
- Mansouri, A. and Gruss, P.** (1998). Pax3 and Pax7 are expressed in commissural neurons and restrict ventral neuronal identity in the spinal cord. *Mech. Dev.* **78**, 171-178.
- Marin, F. and Puelles, L.** (1994). Patterning of the embryonic avian midbrain after experimental inversions: a polarizing activity from the isthmus. *Dev. Biol.* **163**, 19-37.
- Martinez, S., Wassef, M. and Alvarado-Mallart, R. M.** (1991). Induction of a mesencephalic phenotype in the 2-day-old chick prosencephalon is preceded by the early expression of the homeobox gene *en*. *Neuron* **6**, 971-981.
- Martinez, S., Marin, F., Nieto, M. A. and Puelles, L.** (1995). Induction of ectopic engrailed expression and fate change in avian rhombomeres: intersegmental boundaries as barriers. *Mech. Dev.* **51**, 289-303.
- Martinez, S., Crossley, P. H., Cobos, I., Rubenstein, J. L. R. and Martin, G. R.** (1999). FGF8 induces formation of an ectopic isthmus organizer and isthmocerebellar development via a repressive effect on *Otx2* expression. *Development* **126**, 1189-1200.
- Mastick, G. S., Davis, N. M., Andrew, G. L. and Easter, S. S., Jr** (1997). Pax-6 functions in boundary formation and axon guidance in the embryonic mouse forebrain. *Development* **124**, 1985-1997.
- Matsunaga, E., Araki, I. and Nakamura, H.** (2000). Pax6 defines the dimesencephalic boundary by repressing *En1* and *Pax2*. *Development* **127**, 2357-2365.
- Nakamura, H., Watanabe, Y. and Funahashi, J.-i.** (2000). Misexpression of the genes in the brain vesicles by in ovo electroporation. *Dev. Growth Differ.* **42**, 199-201.
- Nakamura, H.** (2001). Regionalisation of the optic tectum: combinations of gene expression that define the tectum. *Trends Neurosci.* **24**, 32-39.
- Nomura, T., Kawakami, A., and Fujisawa, H.** (1998). Correlation between tectum formation and expression of two PAX family genes, PAX7 and PAX6, in avian brains. *Dev. Growth Differ.* **40**, 485-495.
- Okafuji, T., Funahashi, J.-i., and Nakamura, H.** (1999). Roles of Pax-2 in initiation of the chick tectal development. *Brain Res. Dev. Brain Res.* **116**, 41-49.
- Patel, N. H., Martin-Blanco, E., Coleman, K. G., Poole, S. J., Ellis, M. C. Kornberg, T. B. and Goodman, C. S.** (1989). Expression of *engrailed* proteins in arthropods, annelids, and chordates. *Cell* **58**, 955-968.
- Puelles, L., Robles, C., Martinez de la Torre, M. and Martinez, S.** (1994). New subdivision schema for the avian torus semicircularis: neurochemical patterns in the chick. *J. Comp. Neurol.* **340**, 98-125.
- Ristoratore, F., Carl, M., Deschet, K., Richard-Parpailion, L., Boujard, D., Wittbrodt, J., Chourrout, D., Bourrat, F. and Joly, J. S.** (1999). The midbrain-hindbrain boundary genetic cascade is activated ectopically in the diencephalon in response to the widespread expression of one of its components, the medaka gene *Ol-eng2*. *Development* **126**, 3769-3779.
- Rubenstein, J. L., Martinez, S., Shimamura, K. and Puelles, L.** (1994). The embryonic vertebrate forebrain: the prosomeric model. *Science* **266**, 578-580.
- Sato, T., Araki, I. and Nakamura, H.** (2001). Inductive signal and tissue responsiveness to define the tectum and the cerebellum. *Development* **128**, 2461-2469.
- Shamim, H., Mahmood, R., Logan, C., Doherty, P., Lumsden, A. and Mason, I.** (1999). Sequential roles for Fgf4, En1 and Fgf8 in specification and regionalisation of the midbrain. *Development* **126**, 945-959.
- Song, D. L., Chalepakis, G., Gruss, P. and Joyner, A. L.** (1996). Two Pax-binding sites are required for early embryonic brain expression of an Engrailed-2 transgene. *Development* **122**, 627-635.
- Stern, C. D.** (1998). Detection of multiple gene products simultaneously by *in situ* hybridization and immunohistochemistry in whole mounts of avian embryos. *Curr. Top. Dev. Biol.* **36**, 223-243.
- Stoykova, A., Fritsch, R., Walther, C. and Gruss, P.** (1996). Forebrain patterning defects in *Small eye* mutant mice. *Development* **122**, 3453-3465.
- Stoykova, A., Götz, M., Gruss, P. and Price, J.** (1997). Pax6-dependent regulation of adhesive patterning, *R-cadherin* expression and boundary formation in developing forebrain. *Development* **124**, 3765-3777.
- Streit, P. and Reubi, J. C.** (1977). A new and sensitive staining method for axonally transported horseradish peroxidase (HRP) in the pigeon visual system. *Brain Res.* **126**, 530-537.
- Suemori, H., Kadokawa, Y., Goto, K., Araki, I., Kondoh, H. and Nakatsuji, N.** (1990). A mouse embryonic stem cell line showing pluripotency of differentiation in early embryos and ubiquitous beta-galactosidase expression. *Cell. Differ. Dev.* **29**, 181-186.
- Sugiyama, S., Funahashi, J.-i. and Nakamura, H.** (2000). Antagonizing activity of chick Grg4 against tectum-organizing activity. *Dev. Biol.* **221**, 168-180.
- Tremblay, P., Kessel, M. and Gruss, P.** (1995). A transgenic neuroanatomical marker identifies cranial neural crest deficiencies associated with the Pax3 mutant Sploch. *Dev. Biol.* **171**, 317-329.
- Tremblay, P., Pituello, F. and Gruss, P.** (1996). Inhibition of floor plate differentiation by Pax3; evidence from ectopic expression in transgenic mice. *Development* **122**, 2555-2567.
- Walther, C. and Gruss, P.** (1991). Pax-6, a murine paired box gene, is expressed in the developing CNS. *Development* **113**, 1435-1449.
- Warren, N. and Price, D. J.** (1997). Roles of Pax-6 in murine diencephalic development. *Development* **124**, 1573-1582.
- Watanabe, Y. and Nakamura, H.** (2000). Control of chick tectum territory along dorsoventral axis by Sonic hedgehog. *Development* **127**, 1131-1140.