Two regulatory genes, *cNkx5-1* and *cPax2*, show different responses to local signals during otic placode and vesicle formation in the chick embryo

Heike Herbrand¹, Sarah Guthrie², Thorsten Hadrys¹, Sonja Hoffmann¹, Hans-Henning Arnold¹, Silke Rinkwitz-Brandt¹ and Eva Bober¹,*

¹Department of Cell and Molecular Biology, Technical University Braunschweig, Spielmannstrasse 7, 38106 Braunschweig, Germany
²Department of Developmental Neurobiology, United Medical and Dental Schools, Guy’s Hospital, London SE1 9RT, UK

*Author for correspondence (e-mail: e.bober@tu-bs.de)

Accepted 9 December 1997: published on WWW 22 January 1998

SUMMARY

The early stages of otic placode development depend on signals from neighbouring tissues including the hindbrain. The identity of these signals and of the responding placodal genes, however, is not known. We have identified a chick homeobox gene *cNkx5-1*, which is expressed in the otic placode beginning at stage 10 and exhibits a dynamic expression pattern during formation and further differentiation of the otic vesicle. In a series of heterotopic transplantation experiments, we demonstrate that *cNkx5-1* can be activated in ectopic positions. However, significant differences in otic development and *cNkx5-1* gene activity were observed when placodes were transplanted into the more rostral positions within the head mesenchyme or into the wing buds of older hosts. These results indicate that only the rostral tissues were able to induce and/or maintain ear development. Ectopically induced *cNkx5-1* expression always reproduced the endogenous pattern within the lateral wall of the otocyst that is destined to form vestibular structures. In contrast, *cPax2* which is expressed in the medial wall of the early otic vesicle later forming the cochlea never resumed its correct expression pattern after transplantation. Our experiments illustrate that only some aspects of gene expression and presumably pattern formation during inner ear development can be established and maintained ectopically. In particular, the dorsal vestibular structures seem to be programmed earlier and differently from the ventral cochlear part.

Key words: Homeobox, *Nkx5-1* gene, *Pax2*, Inner ear, Otic induction, Chick

INTRODUCTION

The first morphologically discernible structures of inner ear development in the chick embryo are the otic placodes, which arise as two ectodermal thickenings lateral to the prospective rhombomeres 5 and 6 at the 3- to 5-somite stage. The placodes subsequently invaginate to form the otic pit at about the 12- to 14-somite stage and eventually the closed otic vesicles at the 24- to 30-somite stage (Knowlton, 1967; Anniko and Wikström, 1984). Transplantation experiments in amphibia and chick have demonstrated that the hindbrain plays a critical role in the development of the inner ear (Waddington, 1937; Yntema, 1955). It has also been suggested that the mesoderm underlying the auditory field may be important, however, it is unclear whether this influence is direct or mediated via neural induction (review: Van de Water and Represa, 1991). Several genes have been identified which are expressed during early ear development in the mouse, although their functions are largely unknown (review: Fekete, 1996). Gene inactivations generated either by homologous recombination, by chemical mutagenesis or by spontaneous mutations suggested that some genes expressed in the neighbouring hindbrain are involved in the molecular control of otic development. For instance, mice carrying mutations in the *FGF3*, *Hoxa-1* or *kreisler* genes exhibit disrupted development of the hindbrain and malformations of the inner ear in line with the general concept of inductive interactions between hindbrain and otic placode (Mansour et al., 1993; Mark et al., 1993; Frohman et al., 1993; McKay et al., 1994; Cordes and Barsh, 1994). In no case, however, have the genes been identified that directly respond to the inductive hindbrain signals and may therefore be involved in interpreting these signals. Recently, a battery of genetic loci affecting inner ear development has also been identified in the zebrafish by extensive genetic screens (Malicki et al., 1996; Whitfield et al., 1996). Further analysis and cloning of the identified mutated genes should greatly support and extend our understanding of the molecular processes governing the inner ear development in vertebrates.

We have previously isolated mouse homologs of *Drosophila NK* genes (Bober et al., 1994a). One of them, *Nkx5-1*, is specifically expressed in the otic placode and vesicle. At E8.5 to E10.5 the only additional expression domain is in the first branchial cleft (Rinkwitz-Brandt et al., 1995). In this study, we investigated whether *Nkx5-1* gene expression might depend on interactions with the hindbrain during otic placode and vesicle formation. Since the chick presents a suitable model for
investigation of tissue interactions, we first isolated the chick Nkx5-1 homologue (cNkx5-1) and analysed its expression pattern. In contrast to the mouse Nkx5-1 gene, which is also expressed in the branchial region, cNkx5-1 transcripts were found exclusively in the otic placode and vesicle. We monitored cNkx5-1 expression in a series of transplantation experiments to establish the spatial and temporal requirements for the cNkx5-1 gene activation in correlation with early inner ear development. Our experiments demonstrate that the normal, regionalized cNkx5-1 expression pattern can be established in otic vesicles after transplantation of early placodes to ectopic positions. However, as has also been documented previously, inner ear morphogenesis cannot be faithfully restored in the absence of the normal local environment (Van de Water and Represa, 1991; Swanson et al., 1990). In line with this fact, we found that the expression pattern of the paired box gene Pax2 which is involved in the development of the cochlea (Torres et al., 1996) was not maintained in transplanted otocysts. Thus Nkx5-1 and Pax2, associated with vestibular and cochlear development, respectively (Rinkwitz-Brandt et al., 1996; Hadrys et al., 1998; Torres et al., 1996), seem to differ in their susceptibility to local environmental cues.

**MATERIALS AND METHODS**

**Library screening, cloning and sequencing**

Chick Nkx5-1 and Pax2 clones were isolated by screening a genomic DNA library prepared in lambda Fix II vector (Stratagene, Heidelberg) with a hybridisation probe consisting of a 1.1 kb StuI-EcoRI fragment from the 3’ region of the mouse Nkx5-1 cDNA (Bober et al., 1994a) and a 1.4 kb EcoRI fragment of the mouse Pax2 cDNA (Dressler et al., 1990; kindly provided by P. Gruss). Four independent overlapping lambda phages were isolated using the mouse Nkx5-1 cDNA probe. cNkx5-1 coding sequences were identified by Southern blot hybridisation. Following subcloning by standard procedures (Maniatis et al., 1982), sequences were determined by the dideoxy-procedure on both strands of appropriate DNA subfragments using the DNA sequencing kit (USB, Cleveland, OH). A 1.3 kb SacI-XbaI Pax2 genomic fragment containing exon sequences was identified by sequencing, subcloned and used for generation of antisense RNA transcripts for whole-mount in situ hybridisation (see below).

**Cloning of cNkx5-1 cDNA fragments by RT-PCR and the 5′ cDNA sequences by RACE**

mRNA was isolated from otic vesicles of E3 chicken embryos using the Micro-Fast Track mRNA kit (Invitrogen, Leek). 100 ng mRNA were treated with RNase-free DNaseI, phenol purified and used for the first cDNA strand synthesis with an oligo (dT) primer and AMV Reverse Transcriptase (Boehringer Ingelheim Bioproducts, Heidelberg) in a total volume of 25 μl. 1 μl of this reaction was amplified using 1 unit Taq-Polymerase (Boehringer Ingelheim Bioproducts, Heidelberg) and 25 pmol of oligonucleotide primers, which are indicated in the cNkx5-1 sequence (Fig. 1) and correspond to two different exons of the mouse Nkx5-1 gene. The 25 μl reaction mixture contained 1.5 mM MgCl2, 50 mM KCl, 10 mM TrisHCl pH 9.0, 0.1% Triton X-100 and 1 mM dNTP. Usually 35 cycles of amplification (denaturation for 30 seconds at 94°C, annealing 30 seconds at 55°C, elongation 60 seconds at 72°C) were performed. The amplification products were isolated from agarose gels, subcloned and sequenced.

The 5′ cDNA sequences were cloned by a RACE procedure using a 5′ RACE kit (GIBCO-BRL, Egggenstein). Briefly 50 ng mRNA and 2.5 pmol of the cNkx5-1-specific oligonucleotide (653-675): 5′-GGACTCGAGCTGGAAGACCTGG-3′ were used for the first strand synthesis and tailed with an oligo d(T). Using three nested gene-specific primers: (308-327) 5′-CAGCGAGTCGCCGCTCAAGG-3′, (302-322) 5′-AGTCGCCGCTCAGAGCGAAAG-3′, (282-302) 5′-CGCGGCCGGATCTCAAGG-3′ cDNA fragments were synthesized in three subsequent amplification steps and identified by hybridisation with an internal cNkx5-1-specific oligonucleotide (239-268): 5′-GATCTCCACCTGCGAGAG-3′. The reaction products were subcloned into the pGem-T vector (Boehringer Ingelheim Bioproducts, Heidelberg). We were not able to clone the entire 5′ Nkx5-1 cDNA probably due to the high content of GC sequences, which hindered the elongation reaction.

**Embryo preparation**

Fertilized chick (Gallus gallus) eggs were incubated at 37.8°C and 50% humidity. Embryos were staged according to Hamburger and Hamilton (1951). Since there is a three-somite difference between each consecutive early stage, i.e. a stage 10 embryo possesses 10 somites, stage 11 embryo 13 somites etc., we subdivided the stages in + (stage 10+ means 11-somite embryo) and – (stage 10– means 9-somite embryo).

**Transplantation of otic vesicles to ectopic locations**

Embryos were washed thoroughly in Hanks’ Balanced Salt Solution (HBSS, Gibco) and then transverse body sections containing the region of rhombomere 5/6 and the outlying tissues were cut using tungsten needles. Otic placodes were removed using needles during brief immersion of the body sections in a solution of 1 mg/ml Dispase (Grade II, Boehringer Manheim Biochemicals). Placodes were then washed several times in HBSS before transplantation into host embryos.

Eggs containing host embryos were windowed, several drops of Ringer solution added and embryos visualized by sub-blastodermal injection of India Ink (Pelican Fount, 1 : 15 in Ringer). The vitelline membrane was dissected away from the desired region of the embryo and a region of tissue including the ectoderm and underlying mesenchyme was removed using tungsten needles. An isolated placode was then added to the host embryo using a pipette and the tissue manoeuvred into place using needles. No care was undertaken to preserve the orientation of the transplant. Windows in operated eggs were sealed using tape (Beiersdorff) and returned to the incubator for 2 additional days in most cases. In one series of experiments, the incubation time was extended to 4 days. After incubation embryos were fixed in 4% Paraformaldehyde/PBS overnight and submitted to whole-mount in situ hybridisation. The transplantation procedures are outlined in Fig. 4.

Nearly 50% of the operated embryos were viable and showed no obvious developmental deviations. Ectopic otic vesicles were seen on the surface of about 20% of those embryos by morphological scrutiny. Another 15% developed vesicles in deeper tissue layers which were revealed on vibratome sections after in situ hybridisation. Embryos with no recognizable transplanted tissue were not included in further analysis. To ensure that otic development was not affected by the operation procedure itself sham transplantations were performed. In stage 10-12 chick embryos otic placodes were removed using tungsten needles and replaced by placodes isolated from isochronic donor quail embryos. Operated embryos were allowed to develop as usual and processed for antibody staining using a quail-specific antibody QCPN obtained from the Developmental Studies Hybridoma Bank maintained by the Department of Biology at the University of Iowa, Iowa City, IA. In succesfully transplanted, normally developed embryos, the otic tissue on the operated side was entirely of quail origin and showed no abnormalities as compared to the control unoperated side. In parallel controls using chick hosts and donors, no changes in expression of cNkx5-1 and cPax2 genes were observed due to the operation (results not shown).
Whole-mount in situ hybridisation

Whole-mount in situ hybridisation experiments were performed as previously described (Bober et al., 1994b). An antisense RNA probe corresponding to the 850 bp fragment from the carboxyterminal end of the cNkx5-1 coding region (nucleotides 415-1265) was used for hybridisation. An antisense RNA cPax2 probe was generated from the 1.3 kb SacI-XhoI fragment cloned into the Bluscript KS vector (Stratagene). This probe included exon sequences outside the conserved paired box and corresponded to amino acids 228-287 encoded by the mouse Pax2 cDNA (Dressler et al., 1990).

Embryos were embedded in a mixture of 0.5% gelatine, 30% albumin, 20% sucrose and 2% glutaraldehyde and sectioned at 30 μm using the Leica Jung Autocut vibratome. Sections were photographed under a Zeiss Axiovert microscope with Nomarski optics. Whole-mount embryos were photographed under a Wild M10 stereomicroscope.

RESULTS

The coding sequence of the chick Nkx5-1 gene

Fig. 1 shows the coding region of the chick cNkx5-1 gene in comparison with the corresponding mouse cDNA. The longest product obtained by RACE procedure ended 33 bp downstream of the putative ATG initiation codon (arrow in Fig. 1). This methionine is the first ATG codon in frame with the homeodomain but the surrounding nucleotides conform poorly with the Kozak consensus sequence for translation initiation and no in frame stop codon was found in the near upstream region. Thus, the definitive NH2-terminus of the 5’ cNkx5-1 protein needs further evaluation. The derived cNkx5-1 protein sequence revealed a homeodomain that was identical to that encoded by the mouse Nkx5-1 gene. Sequences downstream and upstream of the homeodomain are also strongly conserved in both species with more than 80% identity. The boundary between the first and second exon is also perfectly conserved in mouse and chick (arrowhead in Fig. 1). This sequence conservation and the conserved gene structure strongly suggest that both genes represent true orthologs.

The chick Nkx5-1 gene is an early marker for inner ear development

Whole-mount chick embryos at stages 8 to 17 have been analysed for cNkx5-1 expression by in situ hybridisation using digoxigenin-labeled antisense RNA probes. By this technique, cNkx5-1 transcripts were first detectable at stage 10, at the anterior aspect of the otic placode (Fig. 2A); the rostral part of the developing inner ear continues to express the highest level of the cNkx5-1 transcripts in the forming otic vesicle (Fig. 2B,C) until about stage 15 in the closing vesicle. The posterior part of the otic vesicle is almost devoid of cNkx5-1 hybridisation signal as shown on vibratome sections at stage 10 (Fig. 3A-C), 12 (Fig. 3D-F), and 14 (Fig. 3G-I). At stage 17, no posterior restriction of the cNkx5-1 expression exists (Figs 2D-F, 3J-L).

During the early morphogenetic movements of the otic placode, which result in the formation of the otic pit and later the otic vesicle, cNkx5-1 expression displays a changing pattern. As mentioned above, cNkx5-1 signals form a gradient along the anteroposterior axis, which originates at the most anterior part of the otic anlage. In addition, there is a changing distribution within the mediolateral plane. At first, the cNkx5-1 expression domain lies medially, adjacent to the neural tube (Fig. 3B,E). At stage 14, when the walls of the vesicle are almost closed, the cNkx5-1 signal extends to the lateral wall (Fig. 3G,H). Later, cNkx5-1 expression is confined exclusively to the lateral wall of the otic vesicle, which does not contact the neural tissue (Figs 2E, 3J-L).

Expression of cNkx5-1 in the inner ear anlage was visible in the chick embryo usually after 2-6 hours of staining reaction. The only additional signal that could be observed after prolonged dye reaction (8-12 hours) was a very faint staining in the lens and in the branchial region (not shown). In contrast, in the mouse, the first branchial cleft presents a dominant, albeit transient expression domain (Rinkwitz-Brandt et al., 1995). Whether the lack of the strong cNkx5-1 expression in the first branchial cleft in the chick is the only significant difference of Nkx5-1 expression in these two species needs further analysis at later stages.

cNkx5-1 gene can be activated in otic placode transplants to anterior positions

The early cNkx5-1 expression domain is adjacent to the neighbouring neural epithelium of the hindbrain. This prompted us to investigate whether cNkx5-1 transcriptional activation and/or its maintenance depends on signals from the hindbrain. Placodes of various stages were transplanted to rhombomere 1/2 or midbrain levels of isochronic hosts or to the wing buds of heterochronic older hosts and cNkx5-1 expression was analyzed in these ectopic locations (Fig. 4).

Embryos, including those without macroscopically recognizable otic vesicles, were submitted to in situ hybridisation and subsequently sectioned on the vibratome to ensure that the transplants were not lost, as sometimes ectopic vesicles could only be identified after sectioning of the specimen.

Transplantation of otic placodes to rostral locations yielded two different results depending on the age of the donor embryos. Placodes younger than stage 10 gave rise to ectopic vesicles in the majority of cases (8 out of 11 successful transplantations; see Table 1). However, these vesicles were always smaller than those of the endogenous controls and displayed no signs of continuing morphogenesis as judged by lack of endolymphatic duct formation (Fig. 5 and not shown). Half of these transplants (4) switched on the cNkx5-1 gene, whereas the other half of ectopic vesicles (4) were negative for cNkx5-1 gene activity. Fig. 5 presents examples of ectopic vesicles positive (Fig. 5C) and negative (Fig. 5F) for cNkx5-1 transcripts. No clear correlation was apparent between the presence of cNkx5-1 expression and either the location of the transplant or its age at the time of transplantation. Interestingly, one of the three transplants that did not form vesicles was slightly positive for cNkx5-1 (not shown) indicating that cNkx5-1 could be activated and maintained independently of vesicle formation at least for some time period. It cannot be completely ruled out that variations in ectopic cNkx5-1 expression that were observed in transplants younger than stage 10 were caused by the operation procedure. However, in the light of results with placodes at stages 10-12 that maintained cNkx5-1 expression very faithfully (see below), such influence is highly unlikely. Nevertheless, better orthotopic controls, which include simultaneous detection of quail marker and specific gene expression, should be established.

Transplantation of placodes at stage 10 and older to
Fig. 1. Sequence comparison of mouse and chick Nkx5-1 cDNAs. The chick sequence includes only the coding regions estimated by comparison of the cNkx5-1 genomic sequence with sequences of the RT PCR and RACE products. The 3' untranslated region of the gene is not included in the figure. The mouse cDNA sequence (Bober et al., 1994a) constitutes the region overlapping with the corresponding chick sequence. The homeodomains are boxed, the identical amino acid residues shaded grey, and the conservative exchanges are in white boxes. The asterisk marks the stop codon, the arrowhead marks the intron-exon boundary, which is conserved in both species, and the arrow indicates the end of the longest RACE product for the chick Nkx5-1 cDNA. The primers used for the amplification of the RT-PCR products (192-213, 304-324 and 653-675) are shown in grey outlined boxes. Accession number for chick Nkx5-1 is Y15989, EMBL Nucleotide sequence Database.
rhombomeres 1/2 or midbrain position resulted in the formation of ectopic vesicles in every successful operation (Table 1). In contrast to the results obtained with younger transplants in which nearly 30% (3 out of 11) of successfully transplanted placodes did not form ectopic vesicles, we never found such cases in the older group of transplants. This can be interpreted that beginning at stage 10 otic placodes are already committed to form vesicles even in anterior ectopic positions, although a permissive environment seems to be required (see below). All ectopic vesicles formed in this age category expressed \( cNkx5-1 \) (Fig. 6; Table 1). Although significantly higher numbers of experiments were performed with placodes at stage 10 and older (21 individual successful transplantations versus 11 transplantations of placodes younger than stage 10), we never observed an ectopic vesicle lacking the \( cNkx5-1 \) signal in this group (Table 1). This was in a sharp contrast to the results obtained with placodes younger than stage 10 in which 50% of ectopic vesicles were \( cNkx5-1 \) negative (Fig. 5; Table 1).

The characteristic pattern of \( cNkx5-1 \) distribution was retained in all ectopic otic vesicles which formed in the anterior locations and were \( cNkx5-1 \) positive. As in endogenous vesicles, the \( cNkx5-1 \) signal was always confined to the lateral wall of the ectoptopic otocysts (Figs 5C, 6C,F). In some cases, the ectopic expression domain appeared even broader than in the endogenous control (compare Fig. 6E to F) but in no case was \( cNkx5-1 \) signal observed in the medial vesicle wall. This correct pattern formation was apparently not influenced by the age, shape or location of the ectopic vesicles. It was also independent of the original orientation of the placodes, since the transplanted placodes where positioned at random in the host embryo.

Despite the correct spatial distribution of \( cNkx5-1 \) transcripts, morphogenesis of the inner ear did not proceed normally. Although a small percentage of the ectopic vesicles underwent initial morphogenesis as judged by the evagination of the endolymphatic duct (Fig. 6C), incubation for longer time periods revealed no subsequent morphogenetic events. Instead, the transplants remained as undifferentiated vesicles, eventually lost \( cNkx5-1 \) expression, and later regressed (Fig. 6G,H and not shown). The endogenous control (Fig. 6G) illustrated that anlagen of individual organs as basilar papilla or semicircular canals developed normally as described for E6 chick embryos (Bissonnette and Fekete, 1996), whereas the ectopic vesicles remained arrested and lost the \( cNkx5-1 \) signal (Fig. 6H).

**cNkx5-1 expression and otic morphogenesis are not maintained in the wing buds**

The otic placode transplants into the wing buds of older hosts behaved differently from those transplanted within the head mesenchyme. In contrast to transplantations to rostral locations, we did not observe formation of ectopic vesicles from placodes younger than stage 10 (Table 1). Transplantation experiments were controlled by parallel operations using quail donors and QCPN antibody staining, which indicated the presence of the transplanted tissue (not shown). Only a small fraction (3 out of 9, Table 1) of stage 10 to 12 placodes formed vesicles in wing buds, whereas all the placodes of stage 10-12 formed otic vesicles when transplanted to the head mesenchyme (Table 1). Transplants from this age group never showed \( cNkx5-1 \) expression in the wing buds (Table 1). Only transplanted vesicles of stage 18-19 embryos maintained their morphology and the expression of the \( cNkx5-1 \) gene. However, the intensity of the \( cNkx5-1 \) hybridisation signals in vesicles ectopically placed in wing buds was always weaker than that of the endogenous vesicles (data not shown). In contrast, the

---

**Table 1. Summary of otic placode transplantations hybridized with Nkx5-1**

<table>
<thead>
<tr>
<th>H.H. stage of the donor embryo for the otic placode isolation</th>
<th>H.H. stage of the host embryo</th>
<th>Location of the transplanted otic placode</th>
<th>Ectopic otic vesicle formation</th>
<th>cNkx5-1 hybridisation signal</th>
<th>Number of experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>8+ to 10−</td>
<td>9 to 10</td>
<td>head mesenchyme at the level of rhombomeres 1 and 2 or the midbrain</td>
<td>8</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>10 to 12</td>
<td>10 to 12</td>
<td>head mesenchyme at the level of rhombomeres 1 and 2 or the midbrain</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>8 to 9+</td>
<td>18 to 21</td>
<td>wing buds</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>10 to 12</td>
<td>18 to 21</td>
<td>wing buds</td>
<td>3</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>18 to 19</td>
<td>18 to 21</td>
<td>wing buds</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

---

**Fig. 2. cNkx5-1 expression in E2 and E3 chick embryos.** (A) Stage 10 embryo; (B,C) stage 12+ embryos; the embryo in C is stained more intensely than the one in B. (D-F) Stage 17 embryo shown from lateral (D,F) and dorsal (E) side. (E,F) Higher magnifications of D. Abbreviations: V, the fifth rhombomere; 1, the first somite; md, mandibular arch.
signals of ectopic otic vesicles in the head mesenchyme always matched the intensity of the corresponding endogenous controls (Fig. 6A-F).

**Early expression of Pax2 gene in the chick inner ear**
The reconstitution of endogenous cNkx5-1 expression pattern in ectopically formed otocysts suggested that at least some aspects of molecular patterning can be preserved independently of the original environment. However, as pointed out above, placodes or vesicles never gave rise to normal inner ear morphogenesis after transplantation. We were interested to investigate whether other genes expressed in defined regions of the otocyst behaved similarly to cNkx5-1 in an ectopic location. We chose Pax2 as a gene that shows an almost complementary transcript distribution to Nkx5-1 in the mouse otocyst and inner ear with a clear restriction to the prospective cochlear region (Rinkwitz-Brandt et al., 1995, 1996).

---

**Fig. 3.** Vibratome sections of cNkx5-1 hybridised embryos. (A-C) Anterior-to-posterior 30 µm sections at the otic placode region of the stage 10 embryo showed as a whole mount in Fig. 2A. (D-F) Anterior-to-posterior 30 µm sections from the otic pit region of the stage 12+ embryo showed as a whole mount in Fig. 2B. (G-I) Anterior-to-posterior sections (30 µm) at the level of the open otic vesicle of a stage 14 embryo. (J-L) Anterior-to-posterior sections (30 µm) from the closed otic vesicle region of the stage 17 embryo showed as a whole mount in Fig. 2D-F. (M,N) The planes of sections shown in A-C and J-L, respectively. Abbreviations: hb, hindbrain; nc, notochord.

**Fig. 4.** A scheme illustrating the transplantation experiments.
(A) Transverse body sections were made of donor embryos of stages 8-12 and 18-19 at the level of the 5th and 6th rhombomeres.
(B) Placodes were released from neighbouring tissues in dispase solution and (C) inserted either into the more anterior locations of the age matched hosts or (D) into the wing buds of hosts at stage 18-21. (E) The host embryos were screened for ectopic otic vesicles and cNkx5-1 expression after 2 days of further development.

Abbreviations: fb, forebrain; mb, midbrain; 1-7, rhombomeres 1-7.
cPax2 is activated early during otic development and its transcripts can be detected by in situ hybridisation already during placodal stages (Fig. 7A). In contrast to cNkx5-1, cPax2 expression in the otic placode does not show any rostrocaudal restriction but is present along the entire length of the placode (not shown). Laterally the cPax2 expression domain appears wider than that of cNkx5-1 and extends into the surface ectoderm beyond the placode itself (compare cPax2 expression in the 12-somite-stage placode shown in Fig. 7A to cNkx5-1 expression at 10-somite-stage placode in Fig. 3A). During vesicle formation, cPax2 expression undergoes regionalization and concentrates to the dorsomedial wall (Fig. 7C). This is different from the Pax2 expression pattern described in the mouse where the Pax2 domain is placed in the ventromedial wall of the otocyst (Nornes et al., 1990; Rinkwitz-Brandt et al., 1995, 1996). Beside this slight spatial difference Pax2 expression domains are generally conserved between mouse and chick (Fig. 7D and not shown).

Ectopic otocysts do not restore normal regionalization of cPax2 transcripts

In order to analyze the dependence of cPax2 transcript distribution on local cues, a total of 20 transplantations of otic placodes at stage 10-12 to the rostral locations were analyzed for cPax2 expression (Table 2). As already described, such placodes always gave rise to ectopic vesicle formation after healing of the transplanted tissue. However, cPax2 expression in those vesicles differed significantly in its response to transplantation from that observed for cNkx5-1 transcripts. According to the intensity of cPax2 expression in ectopic vesicles, two groups of results were obtained. In slightly more than one half of vesicles (11 out of 20, Table 2), the level of cPax2 expression was comparable to or only slightly lower than that observed in the endogenous otocysts of the same embryo. Examples of such ectopic vesicles are shown in Fig. 8C and F-H. The other half (9 out of 20, Table 2) showed significantly weaker or no cPax2 expression, whereas expression level in the endogenous control remained normal (Fig. 8E,I). These results indicate that the regulation of cPax2 mRNA levels is much more sensitive to signals from the local environment than that of cNkx5-1.

Another striking difference between cNkx5-1 and cPax2 transplants concerned the specific regionalized distribution of transcripts. Whereas ectopic otic vesicles reconstituted quite faithfully the endogenous cNkx5-1 expression pattern, this was not the case for cPax2 transcripts. Ectopic otocysts exhibited a very variable regional cPax2 expression and often switched on cPax2 in the lateral wall instead of the medial wall which is the normal region of cPax2 expression and often switched on cPax2 in the lateral wall instead of the medial wall which is the normal region of cPax2 expression (compare Fig. 7C and 8B,D for endogenous and Fig. 8C and E-I for ectopic cPax2 expression). As already mentioned above, the orientation of transplanted placodes was random. Therefore, changes...
observed in cPax2 expression cannot be explained by preservation or rotation of the original orientation. Moreover, several vesicles were found that showed cPax2 expression throughout the otic vesicle and not confined to only one side (see Fig. 8F). To summarize, our results demonstrate that two regulatory genes behave differently after transplantation of otic placodes to more rostral locations. While the distribution and accumulation of cNkx5-1 transcripts was readily maintained in ectopic otocysts for extended periods of time (up to two days), the correct spatial distribution as well as the level of cPax2 transcripts appeared much more susceptible to local influences.

**DISCUSSION**

In this study, we have analysed the development of otic placodes in ectopic locations in the chick and correlated it with expression of two otic-specific regulatory genes, cNkx5-1 and cPax2. Our experiments confirm some of the previously published data on amphibia that ear placodes become determined to some extend already by the early neurula stage (Jacobsen, 1963). In addition, we demonstrate that such determination may include the vestibular but not the cochlear pattern as exemplified by cNkx5-1 and cPax2 expression, respectively.

Otic placodes younger than stage 10 (5-9 somites) can undergo the initial steps of morphogenesis in permissive environment

In contrast to previous observations in the chick (Waddington,
Despite the variety of experimental data on the inner ear induction and specification, we still understand very little about it in molecular terms. Therefore, we monitored expression of cNkx5-1, a gene uniquely expressed in the ear placode beginning at the 10-somite stage. Our results have demonstrated that, beginning at stage 9 or even slightly earlier, chick otocysts could not only be formed ectopically but were also able to generate a specific pattern of cNkx5-1 expression. This was an unexpected observation since in vitro experiments on explanted mouse otocysts suggested that a hindbrain influence is required for patterning and differentiation until relatively late stages (Van De Water, 1983). Together with the fact that cNkx5-1 expression was not maintained in the wing environment, these experiments strongly suggest that specific supporting signals are present in rostral locations. It is still not clear whether the onset of cNkx5-1 transcription requires external signals, i.e. those from the hindbrain, or whether intrinsic placode signals, which are activated once the ‘placode forming program’ has been initiated, are responsible for cNkx5-1 activation. It is also possible that different signals may be required for the first gene activation and for the subsequent regionalization of cNkx5-1 transcripts.

Specific expression pattern of regulatory genes are established independently during early stages of the otic development and seem to require different signals as documented by differences obtained by cNkx5-1 and cPax2 pattern reconstitution in ectopic locations

Most interestingly, another regulatory gene, cPax2, behaves very differently than cNkx5-1 and appears to be more dependent on local signals. Whereas all ectopic vesicles older than stage 10 were cNkx5-1 positive and restored their original regionalized expression pattern, only approximately a half of vesicles obtained in identical transplantation experiments retained the endogenous level of cPax2 transcriptional activity. cPax2 signals in the remaining vesicles were always weaker than the corresponding endogenous control and the specific, regionalized cPax2 transcript distribution was never restored. It remains to be elucidated which mechanisms are responsible for the observed differences in the ability to reconstitute patterning in ectopic otic vesicles. It might be significant that the two genes analyzed here are involved in the control of morphogenesis of different parts of the inner ear. In the mouse, Pax2 is responsible for the outgrowth of the cochlea (Torres et al., 1996) whereas Nkx5-1 is required for the formation of the semicircular canals, as has been recently demonstrated by our group (Hadrys et al., 1998). It might well be that vestibular and cochlear parts of the inner ear respond to different signals and develop largely independently as already suggested by others (Fekete, 1996). Our experiments suggest either that unknown signals influencing cNkx5-1 expression in the ectopic plaeocytes are present in anterior locations or that vesicles of stages 10-12 are already able to maintain some of the intrinsic patterning features. However, the random orientation of the transplants in our experiments suggests that, in the rostral locations, either lateral supportive, or medial inhibitory, or both, signals exist that influence the cNkx5-1 expression. Such signals are obviously not sufficient for the regulation of cPax2 transcription. Interestingly, some signalling molecules such as wnt3a and wnt4 (Moon, 1993), FGF3 (McKay et al., 1996) or BMP4, BMP5 and BMP7 (Oh et al., 1996; Wu and Oh, 1996)

Otic placodes are determined for activation and regionalization of cNkx5-1 expression around stage 10 but need permissive environment for their maintenance

Despite the variety of experimental data on the inner ear
have been already reported to be unequally distributed in the otic vesicle. Further experiments are necessary for the identification of the functional significance of these signals. The influence from the hindbrain is a good candidate for an external regulatory signal because hindbrain signals are important not only for the primary induction but also for the further steps of the otic determination and/or differentiation (Li et al., 1978; Van de Water, 1983).

We are grateful to Peter Gruss for providing the mouse Pax2 cDNA. We would like to thank Thomas Braun and Astrid Buchberger for stimulating discussions and critical reading of the manuscript. This work was supported by Deutsche Forschungsgemeinschaft, grant No. SFB 271 (E. B.) and Boehringer Ingelheim Fonds (S. R.-B.). E. B. is grateful to the EMBO for the short-term fellowship.

REFERENCES


