Functional equivalence of the transcription factors Pax2 and Pax5 in mouse development

Maxime Bouchard, Peter Pfeffer and Meinrad Busslinger*

Research Institute of Molecular Pathology, Dr Bohr-Gasse 7, A-1030 Vienna, Austria
*Author for correspondence (e-mail: busslinger@nt.imp.univie.ac.at)

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SUMMARY

Pax2 and Pax5 arose by gene duplication at the onset of vertebrate evolution and have since diverged in their developmental expression patterns. They are expressed in different organs of the mouse embryo except for their coexpression at the midbrain-hindbrain boundary (MHB), which functions as an organizing center to control midbrain and cerebellum development. During MHB development, Pax2 expression is initiated prior to Pax5 transcription, and Pax2<sup>−/−</sup> embryos fail to generate the posterior midbrain and cerebellum, whereas Pax5<sup>−/−</sup> mice exhibit only minor patterning defects in the same brain regions. To investigate whether these contrasting phenotypes are caused by differences in the temporal expression or biochemical activity of these two transcription factors, we have generated a knock-in (ki) mouse, which expresses a Pax5 minigene under the control of the Pax2 locus. Midbrain and cerebellum development was entirely rescued in Pax2<sup>5ki/5ki</sup> embryos. Pax5 could furthermore completely substitute for the Pax2 function during morphogenesis of the inner ear and genital tracts, despite the fact that the Pax5 transcript of the Pax2<sup>5ki</sup> allele was expressed only at a fivefold lower level than the wild-type Pax2 mRNAs. As a consequence, the Pax2<sup>5ki</sup> allele was able to rescue most but not all Pax2 mutant defects in the developing eye and kidney, both of which are known to be highly sensitive to Pax2 protein dosage. Together these data demonstrate that the transcription factors Pax2 and Pax5 have maintained equivalent biochemical functions since their divergence early in vertebrate evolution.

Key words: Pax2/5, Gene substitution, Midbrain, Eye, Ear, Kidney development, Mouse

INTRODUCTION

The duplication of developmental control genes has been a driving force in evolution to increase the diversity and complexity of higher eukaryotes. One of these multigene families codes for the Pax transcription factors, which can be divided into four distinct subclasses based on their sequence similarities (Noll, 1993; Mansouri et al., 1996). The vertebrate Pax2, Pax5 and Pax8 genes constitute one such subclass, which has been even further diversified during zebrafish evolution by a recent Pax2 gene duplication (Pfeffer et al., 1998). The genome of most invertebrates, however, contains only a single Pax2/5/8 gene (Czerny et al., 1997; Fu and Noll, 1997; Wada et al., 1998; Kozmik et al., 1999), indicating that the complexity of this Pax subfamily has arisen by gene duplications at the onset of vertebrate evolution.

Structure-function analyses revealed that the mammalian Pax2, Pax5 and Pax8 proteins possess similar biochemical activities. For instance, the DNA-binding specificity of these proteins is highly similar due to extreme sequence conservation of the N-terminal paired domain (Adams et al., 1992; Kozmik et al., 1993; Czerny et al., 1997). All three proteins, furthermore, contain a conserved transactivation domain at the C terminus (Dörrfler and Busslinger, 1996; Lechner and Dressler, 1996) as well as a partial homeodomain, which constitutes an interaction surface for the retinoblastoma (Rb) and TATA-binding (TBP) proteins (Eberhard and Busslinger, 1999). The three Pax proteins are also able to negatively regulate gene transcription by utilizing a conserved octapeptide motif for recruitment of Groucho corepressor proteins (Eberhard et al., 2000).

The Pax2, Pax5 and Pax8 genes are expressed in a spatially and temporally overlapping manner at the midbrain-hindbrain boundary (MHB) and in the spinal cord of the mouse embryo (Nornes et al., 1990; Plachov et al., 1990; Adams et al., 1992; Asano and Gruss, 1992). Outside the CNS, Pax2 and Pax8 are coexpressed only in the mesenchymal aggregates and derived tubular structures of the developing kidney (Dressler et al., 1990; Plachov et al., 1990). The Pax2 gene is uniquely expressed in most tissues of the developing urogenital system as well as during eye and inner ear development (Dressler et al., 1990; Nornes et al., 1990), Pax5 during B-lymphopoiesis (Adams et al., 1992) and Pax8 in the developing thyroid gland (Plachov et al., 1990). Consistent with these expression patterns, targeted gene inactivation resulted in severe phenotypes, primarily in the unique expression domains of these Pax genes. The loss of Pax2 results in pathfinding defects of the optic nerve, extension of the pigmented retina into the optic stalk and lack of optic fissure closure during eye development, in the absence of kidney, ureter and genital tracts...
in the urogenital system and in agenesis of the cochlea in the developing inner ear (Torres et al., 1995, 1996; Favor et al., 1996). Mice lacking Pax5 fail to develop B-lymphocytes (Urbáné et al., 1994), which reflects the inability of hematopoietic progenitor cells to undergo B-lineage commitment in the absence of Pax5 (Nutt et al., 1999). Conversely, the thyroid gland of Pax8-deficient mice is devoid of follicular cells (Mansouri et al., 1998).

Individual Pax gene mutations, however, show only variable (Pax2\(^{-/-}\)), mild (Pax5\(^{-/-}\)) or no (Pax8\(^{-/-}\)) effects in development of the midbrain and cerebellum, both of which are derived from a common expression domain of these Pax genes at the midbrain-hindbrain boundary (MHB) of the embryo (Urbáné et al., 1994; Torres et al., 1996; Mansouri et al., 1998). Interestingly, the severity of the phenotype correlates with the temporal onset of Pax gene expression in this brain region. Pax2 transcription is already initiated in the prospective MHB region during late gastrulation (at day 7.5) (Rowitch and McMahon, 1995), followed by Pax5 expression at the 3- to 5-somite stage (day 8.25) (Urbáné et al., 1994) and Pax8 expression at approx. 9 somites (day 8.5) (Pfeffer et al., 1998). Surprisingly, the Pax2 mutant phenotype is strongly influenced by the genetic background of the mouse strain analyzed, as it can range from complete deletion of the posterior midbrain and cerebellum in the C3H/He strain (Favor et al., 1996) to almost normal development of these brain structures on the C57BL/6 background (Schwarz et al., 1997). In contrast, the posterior midbrain and cerebellum were consistently deleted in Pax2, Pax5 double-mutant embryos regardless of their genetic background (Schwarz et al., 1997). Moreover, progressive inactivation of Pax2 and Pax5 alleles resulted in increasing loss of the midbrain and cerebellum, indicating that these two transcription factors cooperatively regulate MHB development in a dosage-dependent manner (Urbáné et al., 1997).

The analysis of double-mutant mice thus suggested that Pax2 and Pax5 fulfill similar functions during midbrain and cerebellum development. In apparent contradiction to this hypothesis, we have recently demonstrated a hierarchical relationship between these two transcription factors. Pax2 was shown to directly bind to and thereby activate the MHB-specific enhancer of the Pax5 gene (Pfeffer et al., 2000). Furthermore, both Pax genes are expressed in a contrasting spatiotemporal expression or biochemical functions since their divergence at the onset of vertebrate evolution.

**MATERIALS AND METHODS**

**Generation of Pax2\(^{5ki}\) mutant mice**

The targeting vector was assembled in pSP64 containing a polynucleotide with appropriate loxP and restriction sites. A 6.5-kb SpeI-BspEI fragment containing Pax2 exon 1 and a 1.7-kb NcoI fragment from intron 2 were inserted as homology arms, and mouse Pax5 cDNA was fused at a common NcoI site to Pax2 exon 2. A floxed cassette containing the HSV-\(\beta\)-galactosidase and TdR-neo (positive selection) genes and a 3.7-kb BamHI fragment containing the lacZ gene of pGNA-Pax5 (Urbáné et al., 1994) were inserted downstream of the Pax5 minigene. Ascl1-linearized DNA (15 \(\mu\)g) of the targeting vector was electroporated into E14.1 ES cells (1\(\times\)10\(^7\)), followed by selection with 350 \(\mu\)g/ml G418. Individual clones were screened for homologous recombination by nested PCR, using primers in the lacZ gene and Pax2 intron 2, followed by Southern blot analysis of BsmI-digested DNA with the NcoI-BsmI probe ‘a’. Cells (1\(\times\)10\(^7\)) of one correctly targeted clone were electroporated with pMC-Cre (3 \(\mu\)g) followed by selection with 2 \(\mu\)g/ml gancyclovir. Deletion of the selection cassette was monitored by nested PCR, using primers in Pax2 intron 1 and the lacZ gene, and was confirmed by Southern blot analysis of SacI-digested DNA with the SacI-BspEI probe ‘b’. This clone was injected into C57BL/6 blastocysts, and chimeric males were mated with C3H/He females followed by back-crossing of the Pax2\(^{5ki}\) allele into the C3H/He background for five generations.

**Histological and immunohistochemical analyses**

Embryos or dissected organs were fixed in 4% paraformaldehyde/PBS, and Hematoxylin, Eosin or Nissl staining was performed on 16 \(\mu\)m paraffin-embedded sections. Cryosectioning and immunohistochemical analyses (Matise and Joyner, 1997) were performed with rabbit anti-N-CAM (1:100 dilution), goat anti-E-cadherin (Santa Cruz; 1:100) and rabbit anti-phosphoH3 antibodies (Upstate Biotechnology, 1:200). These antibodies were detected with FITC-labeled donkey anti-rabbit IgG (Santa Cruz; dilution 1:200), biotinylated donkey anti-goat IgG (Santa Cruz; 1:100) detected with Texas Red-coupled avidin (Vector Labs, 1:200) and biotinylated goat anti-rabbit IgG detected by DAB staining with the Vectastain ABC kit (Vector Labs), respectively.

**\(\beta\)-galactosidase and TUNEL staining**

Embryos were stained for \(\beta\)-galactosidase activity as described (Pfeffer et al., 2000). TUNEL assays were performed on paraffin-embedded sections using the fluorescein in situ cell death detection kit (Roche).

**Western blot analysis**

Whole cell extracts of 18.5-day-old kidneys were prepared by homogenization in buffer A and analyzed by SDS-PAGE and western blotting as described (Eberhard et al., 1999).

**RNase protection assay**

RNase protection analysis (Urbáné et al., 1994) was performed with riboprobes, which were derived from Pax2\(^{5ki}\) kidney by RT-PCR cloning of cDNA using the following primers: lacZ: 5'-GGAGGATCCCTTAGCTCGTGGTGCTGTTG-3'; Pax5: 5'-GAGGATCTCGTGGTGCTGTTG-3'; 5'-CCCGAAGGTTAGGCAGAAGCTAGCTGCT-3';
RESULTS

Insertion of a Pax5 minigene into the Pax2 locus

The Pax5 protein is collinear with Pax2b, the major isoform encoded by the Pax2 gene (Adams et al., 1992; Dressler and Douglass, 1992). Moreover, the equivalent exons 2 of Pax2 and Pax5 code for identical paired domain sequences and share a common NcoI site. We therefore fused the mouse Pax5 cDNA at this NcoI site to Pax2 to generate a Pax5 minigene, which is expressed under the control of the Pax2 locus (Fig. 1A). The expected fusion protein differs from the endogenous Pax5 protein only at five amino acid positions within its N-terminal sequence, which lacks any function and is encoded by Pax2 exon 1 (see legend to Fig. 1A). The targeting vector additionally had the following features. The Pax5 cDNA and the selection cassette consisting of the tk and neo genes were flanked by loxP sites, which facilitated subsequent deletion of these sequences by Cre recombinase (Fig. 1A). To be able to monitor deletion in vivo, we inserted a lacZ gene with its own 3' splice site downstream of the tk and neo genes. Upon Cre-mediated deletion, these lacZ sequences should be brought into the position of the deleted Pax5 cDNA and thus be spliced at the mRNA level onto exon 1 sequences (Fig. 1A). The Pax2lacZ allele should furthermore correspond to a null allele, as it is unable to code for a functional Pax2 protein (Fig. 1A).

Correctly targeted ES cells lacking the tk and neo selection cassette were injected into blastocysts to generate heterozygous Pax2skil/+ mice (Fig. 1B). These mice were crossed with a nestin-cre transgenic line (Betz et al., 1996) to obtain Pax2skil/+ mice by Cre-mediated deletion of the Pax5 minigene in the germline. The Pax2ski and Pax2lacZ alleles were subsequently back-crossed for five generations into the C3H/He strain background.

Expression of the Pax2lacZ and Pax2ski alleles

The expression of the Pax2lacZ gene was analyzed by β-galactosidase staining of Pax2skil/+ embryos at days 8.5-11.5 (Fig. 2A-C). β-galactosidase activity was detected in all the previously described Pax2 expression domains, i.e. in the optic stalk, otic vesicle, spinal cord, developing kidney and at the MHB (Dressler et al., 1990; Nornes et al., 1990; Püschel et al., 1992). Hence, we conclude that the targeted Pax2lacZ allele is expressed like the endogenous Pax2 gene in heterozygous embryos.

We next investigated expression of the Pax2ski allele by RNase protection analysis of kidney RNA, which was isolated from Pax2ski/+ and Pax2ski/ski embryos at day 18.5. Riboprobes detecting the Pax2, Pax5 and lacZ transcripts were used individually or in combination for the RNase protection experiment shown in Fig. 3A. Surprisingly, the Pax2ski/+ kidney expressed the Pax5 transcript of the Pax2ski/+ allele at a lower level than the Pax2 mRNA of the wild-type allele. Moreover, even the lacZ transcript could be detected, indicating that exon skipping of the primary Pax2ski transcript can occur by directly splicing Pax2 exon 1 to the downstream lacZ sequences (Fig. 3A). Quantitation and normalization of
the RNase-protected signals to the control mRNA of the ribosomal \( S16 \) gene indicated that the \( \text{Pax5} \) transcript of the \( \text{Pax2}^{5\text{ki}} \) allele was approx. fivefold less abundant than the \( \text{Pax2} \) mRNA of the wild-type allele in heterozygous kidneys (Fig. 3B). The \( \text{Pax2}^{5\text{ki}} \) allele furthermore gave rise to approx. threefold higher levels of the \( \text{lacZ} \) transcript compared to the \( \text{Pax5} \) mRNA. Western blot analysis revealed a similar situation at the protein level, as less \( \text{Pax5} \) protein was detected in the \( \text{Pax2}^{5\text{ki}/5\text{ki}} \) kidney compared to the \( \text{Pax2} \) protein in the wild-type kidney (Fig. 3C). As predicted by the RNase protection results, \( \text{Pax2}^{5\text{ki}/5\text{ki}} \) embryos expressed \( \beta \)-galactosidase activity in all \( \text{Pax2} \) expression domains (Fig. 3D). Hence, the observed exon skipping is not restricted to the kidney but instead is a general property of the \( \text{Pax2}^{5\text{ki}} \) allele.

**Normal midbrain and cerebellum development in \( \text{Pax2}^{5\text{ki}} \) mutant embryos**

At day 8 of mouse embryogenesis, an organizing center is established at the midbrain-hindbrain boundary (MHB) that specifies patterning of the posterior midbrain and cerebellum (reviewed by Wassef and Joyner, 1997). \( \text{Pax2} \) transcription is already initiated at day 7.5 in this embryonic brain region, whereas \( \text{Pax5} \) expression is activated only later at the 3- to 5-somite stage (Urbánek et al., 1994; Rowitch and McMahon, 1995). Hence, \( \text{Pax2} \) is the only member of the \( \text{Pax2/5/8} \) family that is expressed in the prospective MHB region between day 7.5 and 8.25. This short period is, however, critical for establishing the MHB organizer, since the midbrain and cerebellum fail to develop in \( \text{Pax2}^{-/-} \) embryos on the C3H/He background (Fig. 4C,F,I; Favor et al., 1996) in contrast to the minor patterning defects observed in \( \text{Pax5}^{-/-} \) mice (Urbánek et al., 1994).

To assess whether \( \text{Pax5} \) can substitute for \( \text{Pax2} \) during this critical time window, we analyzed the morphology of the developing midbrain and cerebellum in \( \text{Pax2}^{5\text{ki}/5\text{ki}} \) embryos at days 12.5 (Fig. 4B) and 18.5 (Fig. 4E,H). Inspection of the whole brain as well as examination of histological sections failed to reveal any morphological abnormality compared to wild-type embryos (Fig. 4A,D,G). The isthmic constriction was normally formed at the MHB of \( \text{Pax2}^{5\text{ki}/5\text{ki}} \) embryos and...
was separated by a normal midbrain tectum from the posterior commissure, which consists of an array of transverse axon bundles demarcating the forebrain-midbrain boundary (Fig. 4B). The cerebellum also developed normally in Pax2\(^{5ki/5ki}\) embryos (Fig. 4E,H). In contrast, the isthmic constriction and midbrain tectum was missing in Pax2\(^{+/-}\) embryos, resulting in a caudal extension of the posterior commissure (Fig. 4C) (Schwarz et al., 1999) and loss of the posterior midbrain and cerebellum (Fig. 4F,I; Favor et al., 1996). These data unequivocally demonstrate that Pax5 can completely substitute for the critical Pax2 function at the onset of MHB development.

### Normal morphogenesis of the inner ear in Pax2\(^{5ki}\) mutant embryos

We next investigated whether Pax5 can also replace Pax2 function during development of those organs (ear, eye and kidney) that never express the endogenous Pax5 gene. The vertebrate inner ear develops from an epithelial thickening, the otic placode, which is located in proximity to the posterior hindbrain (Fig. 2A). Invagination of this placode gives rise to the otic vesicle, and later the otocyst, which differentiates into the ventral cochlea and dorsal vestibular apparatus of the inner ear (reviewed by Torres and Giráldez, 1998). Pax2 expression is initiated in the otic placode and then becomes restricted to the ventral region of the otic vesicle, which is known to generate the saccule, cochlea and spiral ganglia of the auditory nerve (Fig. 2; Nornes et al., 1990; Püschel et al., 1992). Consistent with this expression pattern, all three structures fail to form in the Pax2\(^{+/-}\) embryo, which instead contains an enlarged chamber at the ventral side of the inner ear. Development of the dorsal vestibular region encompassing the semicircular canals is, however, largely normal (Fig. 5D; Torres et al., 1996; Favor et al., 1996).

Histological examination at embryonic day 18.5 did not reveal any morphological abnormalities in the inner ear of Pax2\(^{5ki/5ki}\) embryos compared to wild-type embryos (Fig. 5A,B). The spiral ganglia, cochlea and its sensory organ of Corti consisting of inner and outer hair cells developed normally in Pax2\(^{5ki/5ki}\) embryos (Fig. 5A,B,E,F; data not shown). Moreover, both the saccule and utricle were properly formed in their usual size and location (Fig. 5A,B). These data therefore demonstrate that Pax5 can fully substitute for the Pax2 function in ear development.

Interestingly, a twofold reduction of Pax5 expression in Pax2\(^{5ki/-}\) embryos resulted in enlargement and fusion of the utricle and saccule compartments at the expense of the cochlea (Fig. 5C). The cochlear canal was wider and markedly reduced in length (Fig. 5C), although the organ of Corti still developed normally (Fig. 5G). The ear phenotype of Pax2\(^{5ki/-}\) embryos is thus intermediate between the normal morphology of wild-type or Pax2\(^{5ki/5ki}\) embryos (Fig. 5A,B) and the severe Pax2\(^{+/-}\) phenotype, which is characterized by complete fusion of the utricle and saccule as well as by the absence of the cochlea (Fig. 5D). Hence, the analysis of Pax2\(^{5ki/-}\) embryos has uncovered a dependency of inner ear development on Pax protein dosage.

### Rescue of eye development by the Pax2\(^{5ki}\) allele

The vertebrate eye develops via multiple inductive and morphogenetic processes from two principal components, the neuroectoderm and the overlying surface ectoderm which, upon induction, forms the lens. The initial out-pocketing of the neuroectoderm from the diencephalon generates the optic vesicle, which subsequently invaginates to generate a bilayered optic cup, giving rise to the neural and pigmented retina, and the optic stalk, later being transformed into the optic nerve (reviewed by Jean et al., 1998). The invagination of the retina leaves on the ventral side of the optic cup a transient cleft, the optic fissure, which further extends as a groove along the optic stalk. Vascularization of the retina occurs through this optic fissure, which later closes to form a uniform retina.
At embryonic day 9, Pax2 expression is initiated in the optic vesicle, specifically within the region that later invaginates to form the optic cup. Subsequently, it is found in the ventral part of the optic cup on both sides of the optic fissure and along the entire optic stalk up to the diencephalon (Fig. 2; Nornes et al., 1990; Püschel et al., 1992; Otteson et al., 1998). Pax2 expression is then excluded from all pigmented and neuroepithelial cells of the retina, thus forming a sharp boundary at the optic disc where the ganglion cell axons leave the retina and enter the optic nerve (Torres et al., 1996; Otteson et al., 1998). Consistent with this expression pattern, Pax2 mutant embryos fail to close the optic fissure, exhibit severe abnormalities of optic disc and nerve formation and are unable to prevent pigmented retina cells from migrating into the optic stalk (Fig. 6D,H; Torres et al., 1996; Favor et al., 1996; Otteson et al., 1998). We conclude therefore that the Pax2 mutant eye phenotype.

To investigate the potential of Pax5 to rescue this mutant eye phenotype, we compared dissected eyes and optic nerves of wild-type, Pax2<sup>-/-</sup> embryos at day 18.5. As shown in Fig. 6B, the optic fissure was closed in the eyes of all Pax2<sup>-/-</sup> embryos analyzed, in marked contrast to Pax2<sup>5ki/-</sup> embryos (Fig. 6D), indicating that Pax5 can fully replace this Pax2 function in eye morphogenesis. Closure of the optic fissure was even observed in Pax2<sup>5ki/-</sup> embryos (Fig. 6C), indicating that this process requires only a minimal amount of Pax activity. Moreover, the extension of pigmented retina cells into the optic stalk was almost completely abolished in Pax2<sup>5ki/-</sup> eyes compared to Pax2<sup>-/-</sup> embryos (Fig. 6F,H). A few pigmented cells were, however, present in the nerve close to the optic disc (Fig. 6F). Cells of the pigmented retina extended further into the optic nerve in Pax2<sup>5ki/-</sup> eyes, although they were drastically reduced in number compared to Pax2<sup>-/-</sup> eyes (Fig. 6G,H). Abnormalities (‘scars’) in the ventral region of the pigmented retina constitute yet another feature of the Pax2<sup>-/-</sup> phenotype (Fig. 6D), which was never fully corrected in Pax2<sup>5ki/-</sup> or Pax2<sup>5ki/5ki</sup> eyes (Fig. 6B,C). We conclude therefore that the Pax2<sup>5ki</sup> allele can rescue most but not all aspects of the Pax2 mutant eye phenotype.

**Development of normal genital tracts, but hypoplastic kidneys, in Pax2<sup>5ki</sup> mutant embryos**

Both the genital tracts and kidneys are derived by epithelial transformations from the intermediate mesoderm of the early embryo, which results in sequential development of the pronephros, mesonephros and metanephros. Whereas the pronephros is only a transient embryonic structure, the Wolffian duct of the mesonephros gives rise to the male genital tract consisting of the epididymis, vas deferens and seminal vesicle. In contrast, the Müllerian duct, another mesoderm-derived structure formed in parallel to the Wolffian duct, develops into the oviduct, uterus and part of the vagina of the female genital tract. Evagination of the ureteric bud from the posterior Wolffian duct is the first sign of metanephros development. Its invasion of the surrounding mesenchyme initiates an intensive phase of reciprocal inductive signaling, which results in formation of the glomeruli, tubules and collecting ducts of the adult kidney (reviewed by Saxén, 1987). The Pax2 gene is expressed throughout development in mesenchymal and epithelial cells of the urogenital system. Pax2 expression was thus observed in the Wolffian and Müllerian ducts as well as in the ureter, condensing mesenchyme, collecting ducts and differentiating nephrons of...
Fig. 6. Eye development in Pax25ki mutant embryos. The eyes together with the optic nerve (on) were dissected at day 18.5 from Pax2+/+ (A,E), Pax25ki/5ki (B,F), Pax25ki/− (C,G) and Pax2−/− (D,H) embryos and photographed in ventral (A-D) and lateral (E-H) views. The optic fissure (of) failed to close in Pax2−/− embryos (D), where cells of the pigmented retina expanded into the optic nerve (limit of migration denoted by arrowhead). Note the presence of malformations (scars, indicated by white arrows) in the ventral retina of Pax25ki/5ki, Pax25ki/− and Pax2−/− embryos (B-D).

the metanephros (Fig. 2; Dressler et al., 1990; Torres et al., 1995). Embryos lacking Pax2 initially form both the Wolffian and Müllerian ducts in the anterior region of the genital ridge (Torres et al., 1995); however, both ducts subsequently degenerate, resulting in the complete absence of genital tracts and kidneys, which is responsible for the perinatal lethality of Pax2−/− mice (Fig. 7D,H; Torres et al., 1995; Favor et al., 1996).

To assess whether Pax5 can substitute for Pax2 during development of the urogenital systems, we dissected the kidneys and genital tracts of wild-type, Pax25ki/5ki and Pax2−/− embryos at day 18.5. The metanephros was dramatically reduced in Pax25ki/5ki embryos of both sexes, ranging from 10% to 30% of the size of a wild-type kidney (Fig. 7A,B,E,F). The ureter was, however, normally formed in these embryos (Fig. 7B,F). In addition, the epididymis, vas deferens and seminal vesicle developed normally in male embryos (Fig. 7B; data not shown), as did the oviduct, uterus and vagina in female embryos (Fig. 7F; data not shown). The presence of all structures of the genital tract thus indicates that the Wolffian and Müllerian ducts are normally formed along their entire axis up to the cloaca in Pax25ki/5ki embryos, in marked contrast to Pax2−/− embryos (Fig. 7D,H; Torres et al., 1995). We conclude, therefore, that Pax5 can fully replace the function of Pax2 in development of the genital tracts. The Pax25ki allele behaved, however, like a hypomorphic Pax2 mutation in metanephros development, as it allowed formation of only small hypoplastic kidneys, which resulted in perinatal death of all Pax25ki/5ki mice due to renal failure.

Kidney development was more severely affected in Pax25ki/− embryos compared to Pax25ki/5ki embryos. The kidney was either formed only as a small remnant or was often totally absent together with the ureter (Fig. 7C,G). The male and female genital tracts, however, developed normally in these embryos (Fig. 7C,G), further indicating that distinct structures of the urogenital system require different Pax protein levels for their development.

Histological and immunohistochemical analyses at day 18.5 revealed that the Pax25ki/5ki embryos were able to form all components of the metanephric kidney (Fig. 7I-L). The condensing mesenchyme around the ureteric tip, the comma- and S-shaped bodies, glomeruli, nephric tubules and collecting ducts were all present, although reduced in total number (Fig. 7J,L). This hypoplastic phenotype could be explained by a reduction in either cell proliferation or survival during Pax25ki/5ki kidney development. By analyzing the expression of phosphorylated histone H3 as a proliferation marker, we failed to observe any change in the proliferative index of Pax25ki/5ki kidneys relative to wild-type embryos at day 14.5 (Fig. 7M,N). In contrast, a significant increase of apoptotic cells was detected by TUNEL assay in Pax25ki/5ki kidneys compared to wild-type embryos (Fig. 7O,P). These data therefore suggest that increased apoptosis is responsible for the small size of Pax25ki/5ki kidneys, thus implicating Pax2 in the control of cell survival during metanephros development.

DISCUSSION

Functional equivalence of the Pax2 and Pax5 proteins in mouse development

The protein-coding sequences of Pax2 and Pax5 have been well conserved since their divergence from a common ancestral gene at the onset of vertebrate evolution (Pfeffer et al., 1998). In contrast, both genes have acquired radically different expression patterns, as they are to date coexpressed only in the developing CNS of the mouse embryo (Adams et al., 1992; Nornes et al., 1990). Consistent with this divergent regulation, gene targeting revealed an essential role of Pax2 in the development of the midbrain, cerebellum, eye, ear, kidney and genital tracts (Torres et al., 1995, 1996; Favor et al., 1996), whereas Pax5 fulfills an important function in B-lymphopoiesis (Urbáněk et al., 1994; Nutt et al., 1999). By generating a mouse containing a Pax5 minigene insertion in the Pax2 locus, we have now demonstrated that the Pax25ki knock-in allele can rescue almost all aspects of the Pax2 mutant phenotype. The midbrain, cerebellum, ear and genital tracts are normally formed in Pax25ki/5ki embryos, and even development of the
kidney and eye is largely restored by the Pax2\(^{5ki}\) allele. These data therefore indicate that the transcription factors Pax2 and Pax5 are able to regulate the same sets of target genes during mouse embryogenesis. This conclusion is further supported by structure-function analyses demonstrating that both proteins possess similar, if not identical, DNA-binding, transactivation and repression functions (Kozmik et al., 1993; Dörfler and Busslinger, 1996; Lechner and Dressler, 1996; Czerny et al., 1997; Eberhard et al., 2000). This functional conservation is also reflected at the amino acid sequence level, as the Pax2b and Pax5 proteins share 98%, 53% and 77% sequence identity in the N-terminal paired domain, central sequences and C-

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**Fig. 7.** Development of the urogenital system in Pax2\(^{5ki}\) mutant embryos. (A-H) The urogenital system of male (A-D) and female (E-H) 18.5-day embryos of the indicated genotypes was dissected and photographed. (I,J) Histological sections revealed the presence of all the characteristic structures of the wild-type kidney also in the hypoplastic Pax2\(^{5ki}\) kidney. (K, L) Normal condensation of the mesenchyme around the ureteric tip in the Pax2\(^{5ki}\) kidney as revealed by E-cadherin immunostaining (red) of the ureter and N-CAM staining (green) of the condensing mesenchyme. (M,N) Staining with anti-phosphoH3 antibodies (black dots indicated by arrows) revealed similar proliferation indices in Pax2\(^{+/+}\) and Pax2\(^{5ki/5ki}\) kidneys at day 14.5. The sections were counterstained with Eosin. (O,P) Increased cell death in the Pax2\(^{5ki/5ki}\) kidney at day 14.5. Cells undergoing apoptosis (green and yellow dots indicated by arrows) were identified by TUNEL assay on DAPI-counterstained sections. The blue color of DAPI was artificially adjusted to red. a, adrenal gland; b, bladder; c, calyx; cm, condensing mesenchyme; da, dorsal aorta; g, glomerulus; k, kidney; o, ovary; s, S-shaped body; st, stroma; t, testis; tu, tubule; u, ureter; ur, uterus; v, vas deferens.
Dosage-dependent effects of the Pax2^5ki allele

Heterozygous mutation of the human PAX2 gene is the underlying cause of the renal-coloboma syndrome, which is characterized by optic nerve abnormalities and renal insufficiency due to small hypoplastic kidneys (Sanyanusin et al., 1995; Cunliffe et al., 1998). A similar haploinsufficient phenotype was observed in heterozygous Pax2 mutant mice, indicating that the development of the optic nerve and metanephros is critically dependent on the Pax2 expression level (Keller et al., 1994; Torres et al., 1995; Favor et al., 1996; Otteson et al., 1998). Optic nerve abnormalities and hypoplastic kidneys are also the two phenotypic traits, which could not be fully rescued in Pax2^5ki/5ki mouse. These two phenotypes can, however, be explained by our finding that the Pax5 minigene of the Pax2^5ki allele is expressed at a fivefold lower level than the wild-type Pax2 gene during mouse embryogenesis. This reduction of the Pax5 mRNA level is caused by efficient skipping of the Pax5-coding sequences, due to alternative splicing of the primary transcript to the downstream lacZ gene in the Pax2^5ki locus. Consequently, the Pax5 mRNA is expressed at a lower level (approx. 20%) in homozygous Pax2^5ki/5ki embryos than in the wild-type Pax2 embryos (50%) in heterozygous Pax2^+/ki embryos. This expression difference is also reflected by the more severe hypoplasia of Pax2^5ki/5ki kidneys (Fig. 7) compared to Pax2^+/ki kidneys (Keller et al., 1994; Torres et al., 1995; Porteous et al., 2000). Hence, the correlation between gene expression and phenotype strongly suggests that the lower expression level rather than a different biochemical property of Pax5 is responsible for the optic nerve and kidney abnormalities seen in Pax2^5ki/5ki embryos.

The Pax2 gene is known to give rise, by alternative splicing, to distinct protein isoforms (Dressler and Douglass, 1992; Ward et al., 1994; Heller and Brändli, 1997). The Pax5 protein encoded by the Pax2^5ki allele is colinear with Pax2b, the most abundant of these splice variants (Dressler and Douglass, 1992), and therefore Pax2^5ki/5ki embryos express only the equivalent of this major isoform. Nevertheless, the Pax2^5ki allele is able to rescue most aspects of the Pax2 mutant phenotype, which argues against a functional significance of the minor Pax2 splice variants.

Pax2-dependent control of cell survival during metanephros development

Due to the reduced expression of the inserted Pax5 minigene, the Pax2^5ki allele behaves like a hypomorphic Pax2 mutation in kidney development. Morphogenesis of the mesonephros appears to be normal in Pax2^5ki/5ki embryos, as indicated by the normal formation of male genital tracts. Metanephros development is, however, severely affected, as these embryos are able to form only a small number of all the epithelial structures characteristic of the adult kidney. The small size of Pax2^5ki/5ki kidneys is, however, not the consequence of reduced cell proliferation, but rather reflects an increase in apoptosis during metanephros development. Heterozygous Pax2^+/ki mice have recently been shown to exhibit a similar, though less severe, kidney phenotype (Ostrom et al., 2000; Porteous et al., 2000). It appears therefore that a moderate reduction in Pax2 protein level enhances programmed cell death, which is known to occur even during normal kidney morphogenesis (Koseki et al., 1992; Coles et al., 1993). Hence, the transcription factor Pax2 is likely to control the expression of cell survival factors or anti-apoptotic regulators in the developing kidney. Other members of the Pax gene family have previously been implicated in the regulation of cell survival, which may reflect a common function of Pax transcription factors (Bernasconi et al., 1996; Nutt et al., 1998; Borycki et al., 1999). The related Pax5 protein was shown to indirectly upregulate the expression of the antiapoptotic bcl-xL gene during B-lymphopoiesis (Nutt et al., 1998). Likewise, quantitative RT-PCR analysis revealed a significant reduction of bcl-2 mRNA in the Pax2^5ki/5ki kidney (M. Bouchard, unpublished data). Interestingly, the kidney-specific expression of bcl-2 is under the control of the transcription factor WT1 (Mayo et al., 1999), which itself is considered to be a target of Pax2 (Dehbi et al., 1996). Hence, Pax2 appears to indirectly regulate the bcl-2 gene during kidney morphogenesis.

Pax gene function in midbrain and cerebellum development

Pax2 and Pax5 are coexpressed at the MHB of the mouse embryo, although with different spatiotemporal patterns. Transcription of the Pax2 gene is already initiated in this embryonic brain region during gastrulation (at day 7.5), whereas Pax5 expression is first observed at the 3- to 5-somite stage (at day 8.25) (Urbánek et al., 1994; Rowitch and McMahon, 1995). This difference in timing defines a period of 0.75 day, during which only Pax2 is expressed in the prospective MHB region. This time period is important for the development of the midbrain and cerebellum, as both brain structures fail to develop in Pax2^-/- embryos on the C3H/He background (Favor et al., 1996) (this study) and yet exhibit only minor patterning defects in Pax5^-/- mice (Urbánek et al., 1994). During this time window, Pax2 is critically involved in the activation of the Fgf8 gene (Schwarz et al., 1999; M. Bouchard, unpublished data), which codes for an essential component of the signaling center at the MHB (Meyers et al., 1998). Pax2 furthermore controls the initiation of Pax5 transcription by directly binding to the MHB-specific enhancer of Pax5 (Pfeffer et al., 2000). Our finding, that development of the midbrain and cerebellum is completely rescued in Pax2^5ki/5ki embryos, unequivocally demonstrates that the transcription factors Pax2 and Pax5 can fulfill identical functions during MHB development. The functional difference between the two genes is therefore entirely determined by their distinct onset of expression at the MHB. A similar situation has previously been described for the differentially expressed En1 and En2 genes, which were also shown by gene replacement to code for functionally equivalent transcription factors involved in midbrain and cerebellum development (Hanks et al., 1995). Functional equivalence was furthermore demonstrated for the transcription factors Otx1 and Otx2 (Suda et al., 1999) as well as for paralogous Hox proteins (Greer et al., 2000).
Surprisingly, the loss of Pax2 is compatible with normal development of the midbrain and cerebellum in C57BL/6 mice (Schwarz et al., 1997), yet Pax2, Pax5 double-mutant embryos on the same genetic background fail to develop a posterior midbrain and cerebellum, which identifies Pax5 as the gene compensating for the lack of Pax2 (Schwarz et al., 1997). Our demonstration, that Pax2 and Pax5 are functionally equivalent transcription factors, suggests that differences in either the level and/or timing of Pax5 expression are responsible for the background-dependent phenotype of the Pax2 mutation. The dependency of Pax5 expression on Pax2 (Pfeffer et al., 2000) may be less stringent in the C57BL/6 embryo compared to the C3H/He strain, which would result in Pax5 expression even in Pax2 mutant embryos. The initiation of Pax5 expression could additionally be shifted to an earlier time point in C57BL/6 embryo, thus shortening the critical window between the onset of Pax2 and Pax5 expression at the MHB.

Unique functions of the vertebrate Pax2/5/8 genes by evolutionary divergence of cis-acting regulatory elements

The functional conservation of the Pax2 and Pax5 proteins entails that the vertebrate Pax2, Pax5 and Pax8 genes have diverged in function by the acquisition of different regulatory patterns. Interestingly, the single Pax2 gene of invertebrate chordates is expressed in embryonic structures that appear to be homologous to the expression domains of the vertebrate Pax2, Pax5 and Pax8 genes (Wada et al., 1998; Kozmik et al., 1999). Hence, the primordial Pax5 genes, which arose by gene duplications at the onset of vertebrate evolution, may initially have shared an identical expression pattern. Selective deletion of individual tissue-specific enhancers could subsequently have established a unique expression pattern for each of the three Pax2/5/8 genes during vertebrate evolution. This hypothesis is supported by the fact that Pax5 is still expressed during ear development of two lower vertebrates, the zebrafish (Pfeffer et al., 1998) and frog (Heller and Brändli, 1999), in marked contrast to the mouse (Urbánék et al., 1994). Hence, the Pax5 gene seems to have lost its ear-specific regulatory element only in the mammalian lineage. Moreover, Pax8 is still coexpressed together with Pax2 during eye development of the zebrafish in contrast to the frog and mouse (Pfeffer et al., 1998). Pax8 is known to be a key regulator of thyroid development in the mouse (Mansouri et al., 1998). Surprisingly, however, Pax2 instead of Pax8 is expressed in the developing thyroid gland of the frog (Heller and Brändli, 1999), thus further supporting the notion that all three members of the vertebrate Pax2/5/8 family are functionally equivalent transcription factors.

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