Subfunctionalization of Duplicated Zebrafish pax6 Genes by cis-Regulatory Divergence

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Gene duplication is a major driver of evolutionary divergence. In most vertebrates a single PAX6 gene encodes a transcription factor required for eye, brain, olfactory system, and pancreas development. In zebrafish, following a postulated whole-genome duplication event in an ancestral teleost, duplicates pax6a and pax6b jointly fulfill these roles. Mapping of the homozygously viable eye mutant sunrise identified a homeodomain missense change in pax6b, leading to loss of target binding. The mild phenotype emphasizes role-sharing between the co-orthologues. Meticulous postulated whole-genome duplication event in an ancestral teleost, duplicates in zebrafish (Danio rerio), and pufferfish (Fugu rubripes) identified a homeodomain missense change in pax6a, and Wnt11 targeted exons have been lost in zebrafish. Reporter transgenic studies in both mouse and zebrafish, combined with analysis of vertebrate sequence conservation, reveal loss and retention of specific cis-regulatory elements, correlating strongly with the diverged expression of co-orthologues, and providing clear evidence for evolution by subfunctionalization.

Introduction

Complex spatiotemporal control is required to regulate the expression of major tissue-specific transcription factors and signaling molecules which fulfill multiple roles in developmental patterning [1,2]. Accumulating evidence suggests that evolutionarily conserved non-coding elements orchestrate this process [3–5]. In addition to transgenic reporter studies in multiple species [6–12], human disease-associated genomic rearrangements (reviewed in refs [2,13]) and mutations [8,14], as well as natural and targeted deletions in mice [15–17], have contributed to our current understanding of how these regulatory elements control gene expression. Alteration of cis-regulatory function has been proposed as an important mechanism for evolutionary divergence [18]. Gene duplication provides an opportunity for such diversification without major penalties for loss of function [19]. About 350 million years ago, whole genome duplication occurred in an ancestor of teleost fishes, followed by variable loss of duplicated segments, and this process has been suggested to account for extensive speciation [20–23], that half of all vertebrate species are teleost fish. Mechanisms of retention of duplicated copies remain controversial. Gain of new functions (neofunctionalization) has been widely proposed, but recently subfunctionalization, a more neutral partitioning of ancestral functions between duplicates, has been suggested [20,24]. A number of key transcription factors represented only once in mammalian genomes, are present as duplicates in zebrafish (Danio rerio). Often different loci are duplicated in other teleosts, such as medaka (Oryzias latipes) and pufferfish (Fugu rubripes). Where duplicate (or triplicate) genes have been examined, they reveal functional divergence, although the mechanisms have generally not been explored [25].

Our interest in developmental eye anomalies in humans and model systems, led us to map the homozygous viable and fertile zebrafish microphthalmia mutation sunrise (sri) [26]. The original mutant was isolated in the Tubingen ENU mutagenesis screen [27]. We identified a deleterious missense mutation in the homeodomain of the pax6b gene. To assess gene function in the context of observed phenotype, this
finding triggered a comparison of expression patterns and regulatory control elements for the duplicated \textit{pax6a} and \textit{pax6b} genes, with each other and with other vertebrates where generally only a single orthologue is found.

PAX6 is a highly conserved protein, with paired- and homeodomain DNA-binding regions; it functions as a transcription factor with a major role in eye and brain development from Drosophila to humans [28,29]. Homozygous loss-of-function mutations lead to absence of the eye and lethal brain anomalies in mice, humans, and flies [30–33]. Heterozygous null mutations (haploinsufficiency) are associated with human aniridia and microphthalmia (Small eye); missense changes lead to related, sometimes more severe, eye defects [29]. Associated brain anomalies have also been described in both human and mouse heterozygotes [34,35]. Its expression pattern suggested, and whole animal functional studies have shown, that Pax6 also plays an essential role in the development and adult maintenance of pancreatic endocrine cells [36]. When the conditionally targeted \textit{Pax6} gene is homozygously inactivated in the mouse pancreas at E9.5, the pups die of severe diabetes between postnatal days 3 and 6.

The complex spatiotemporal expression of Pax6 is controlled by an extensive downstream regulatory region [6] whose existence was heralded by haploinsufficient aniridia-associated chromosomal disruptions positioned more than 150 kb downstream of \textit{PAX6} [37]. DNaseI hypersensitivity analysis and strong, consistently patterned enhancer function in reporter transgenic animals confirmed and elaborated the predicted regulatory element organization [6,7,38]. In many cases regulatory element function can be predicted by non-coding region genomic sequence conservation in mammals or, more broadly, in vertebrates [7,10,12,38–40].

It was against this background that we examined the \textit{sri} mutant and the regulation of the two \textit{pax6b} co-orthologues, to gain insight into the evolutionary conservation and divergence of these duplicate genes.

**Results/Discussion**

**Mapping and Identification of \textit{pax6b} as the \textit{sri} Gene; Functional Analysis of Wild Type and Mutant Proteins and Definition of the Phenotype**

Detailed analysis of eyes in \textit{sri} mutant zebrafish [27], revealed a variable, but fully penetrant recessive phenotype, with abnormal lens and corneal structure leading to reduced eye size (Figure 1A). Affected homozygotes are viable and fertile, and this allowed outcrossing to the wild-type line WIK for mapping [41,42]. The uniformly heterozygous F1 siblings from this cross were interbred and the recessive phenotype was recovered, permitting the collection of phenotypically classified individuals for mapping. Standard techniques [41,42] were used to map the \textit{sri} locus to a region, between 29.7 and 33.2 cm from the top of linkage group 7 (LG7) (Figure S1A). \textit{pax6b} [43] was identified as a strong candidate gene. Sequencing of \textit{sri} homozygotes and heterozygotes identified a leucine to proline missense mutation in a highly conserved residue of the \textit{pax6b} homeodomain (Figures 1B, S1B, and S1C). The L244P alteration, in the first helix of the homeobox, is predicted to affect protein structure and function significantly [44]. A luciferase reporter assay was used to assess the regulatory capabilities of the full length Pax6 and Pax6b wild type proteins, and that of the L244P Pax6b mutant. Activation by the two wild type co-orthologues through the P3 homeodomain target [45] (Figure 1D), or the CD19 paired domain target [46] (Figure 1E), was not significantly different, in contrast to the original observations by Nornes et al [43]. However, the mutation abolished activation through the P3 homeodomain target and severely compromised CD19 paired domain function (Figure 1D and 1E) [47,48]. Binding of mutant protein to both high-affinity homeodomain target sequences P2 and P3, with different spacing between the twin sites [45], is also reduced in an electrophoretic mobility shift assay (Figure 1F). Following the identification of the mutation, the frequencies of the three expected genotypes were assessed after crossing obligate heterozygotes and found not to deviate from the expected 1:2:1 Mendelian ratios at 5 dpf, confirming the full fitness of the homozygotes at this stage (Figures 1C and S2). Survival into adulthood is good; \textit{sri} fish are maintained as homozygotes. The viability, fertility and relatively mild eye phenotype of the homozygous \textit{pax6b} mutant fish, led us to investigate further the role of this gene, and its co-orthologue \textit{pax6a}, which maps to LG25 (http://zfin.org/cgi-bin/mapper_select.cgi) and Supporting Information.

**Comparison of the \textit{pax6a} and \textit{pax6b} Expression Patterns and Analysis of the \textit{sri} Mutant**

Overlapping divergent expression patterns have been reported for \textit{pax6a} and \textit{pax6b} (previously named \textit{pax6.1} and \textit{pax6.2} respectively) [43,49]. \textit{pax6b} is the “minor” co-orthologue, expressed in the developing eye (retina and early lens placode), and also in thin strips of dorsal diencephalon, at the midbrain-hindbrain boundary (MHB), and in the pancreas. \textit{pax6a} is expressed in the lens and retina, as well as more...
widely in the developing telencephalon, diencephalon, hind brain, and spinal cord, although not in developing pancreas [49]. The expression pattern of the co-orthologues was confirmed by RNA in situ analysis at 24 and 32 hpf (Figure 2A–2J). There is significant overlap between the territories of the co-orthologues, clearly illustrated in the sections showing pax6a and pax6b expression (Figure 2I and 2J).

We set out to verify that the L244P mutation is causative for the sunrise phenotype. First, pax6b morpholino injections, using two different morpholinos, resulted in reduced eye size, a phenotype overlapping the sri phenotype, but somewhat more severe, as total eye size reduction (Figure 3A and 3B) rather than just small lens size [27] (Figure 1A) was observed. Morpholino injection was found to reduce protein expression proportionately to dosage (Western blot data not shown), ultimately leading to a null phenotype, while the homeo-domain missense mutation may possess some residual function, even if DNA-binding capacity was strongly diminished by the mutation. This differential effect of missense and null mutations is also illustrated by the distinct phenotypes observed when patients with heterozygous missense mutations in the paired domain are compared with haploinsufficient cases ([29,50,51] and van Heyningen et al unpublished). In addition to the reduced eye phenotype, developmental
delay is observed if the fish are followed for 48 hpf (Figure 3B), although expression of pax6a mRNA continues (Figure 3C and 3D). Simultaneous injection of pax6a and pax6b morpholinos disrupts eye development leading to microphthalmia and general developmental delay (data not shown). Rescue of the sri phenotype was attempted, using capped mRNA injection into 1–2 cell stage embryos [52,53], but this led to severe developmental delay at a later stage, with reduced eye size, at mRNA levels normally used for such studies (Figure 3E). We postulate that this is because the requirement for functional Pax6 protein is both tissue-specific and highly dosage sensitive, and neither of these aspects can be controlled during mRNA-rescue by injection. Protein carrying a single altered amino-acid is usually expressed normally, probably with some intact functional domains. It is likely to be present at regular or even at elevated levels, as protein with reduced function may not be capable of driving the negative autoregulation that has been observed for Pax6 in mice [54,55]. Titration of mRNAs in wild type one- or two-cell embryos was repeated three times and the data combined (Table 1). This revealed that abnormal phenotypes begin to be elicited even with 10 pg injections of wild type pax6b, and increasing the amount of mRNA increases the severity score (Table 1). However the mutant L244P Pax6b-encoding mRNA consistently produces less severe phenotypes than the wild type at equivalent levels (Figure 3E; Table 1). Thus, although we were unable to rescue the effect of the missense mutation using capped mRNA injection into 1–2 cell stage mutant embryos, we show that increased dosage of wild type pax6b leads to a deleterious phenotype, and that the over-expression phenotype is less severe with an equal amount of mRNA encoding the L244P mutant protein, thus providing additional indirect evidence that this partial loss-of-function mutation is the underlying cause of the sri phenotype.

In the mouse Pax6 expression is observed in fetal and adult...
reveal that the paired domain [62]. Although the luciferase reporter studies produce significantly milder phenotypes than nonsense mutations in humans, that rare homeodomain missense mutations in unpublished data die immediately postnatally, if allowed to heterozygotes in humans [31], and van Heyningen et al, in mice [56–58], as well as most reported compound somatostatin are all regulated by the this theory. Another possibility is that the paired domain, and of homeodomain target DNA-binding, seen when the L244P mutations or paired-domain missense changes known homozygous null and most missense mutations of compound heterozygosity for two different recently identified (van Heyningen et al, unpublished) between the paired- and homeo-domains. Interestingly, we protein-DNA binding interaction requires collaboration homeodomain binding [47,48], suggesting that the Pax6 pancreatic insulin and glucagon in the single-islet zebrafish pancreas of sri/sri fish, while eyes from the same individuals express both pax6a and pax6b (Figure S3). We also showed that pax6a expression is not induced in the pancreas of the sunrise mutant. However, if only pax6b is expressed in the zebrafish pancreas, then the continuing normal expression of insulin and glucagon in the single-islet zebrafish pancreas of sri homozygotes (Figure 1C), is surprising. All known homozygous null and most missense mutations of Pax6 in mice [56–58], as well as most reported compound heterozygotes in humans [31], and van Heyningen et al, unpublished data) die immediately postnatally, if allowed to come to term. However, there is evidence, in both mouse and humans, that rare homeodomain missense mutations in Pax6 produce significantly milder phenotypes than nonsense mutations or paired-domain missense changes [29,51,56,59,60]. The significant but not complete abolition of homeodomain target DNA-binding, seen when the L244P mutation is assessed using EMSA (Figure 1F), is in line with this theory. Another possibility is that the paired domain, and not the homeodomain, fulfills the critical role in driving gene expression in the pancreas [61], where insulin, glucagon and somatostatin are all regulated by the 5a form of the Pax6 paired domain [62]. Although the luciferase reporter studies reveal that the sri homeodomain mutation severely limits paired domain binding as well (Figure 1E), this may be a cell-line-specific effect [63]. However, the converse has also been reported, namely that paired domain mutations disrupt homeodomain binding [47,48], suggesting that the Pax6 protein-DNA binding interaction requires collaboration between the paired- and homeo-domains. Interestingly, we recently identified (van Heyningen et al, unpublished) compound heterozygosity for two different Pax6 mutations (a premature truncation and a missense change at a completely conserved arginine just N-terminal to the homeodomain) in a child who is developing normally apart from anophthalmia, suggesting that missense changes in the homeodomain region may be viable. The missense mutation carrying mother of this child has a severe eye phenotype. A similar surviving compound heterozygote case has also been reported [64].

Table 1. Injection of Capped mRNA into Wild Type (Tupfel Long Fin) Fish

| Wild Type Recipients | Eye Defects, Normal Body Size | Eye Defects, Dwarf Body |
|----------------------|-----------------------------|------------------------|
|                      | Eye Defects (Reduced) | One Eye | No Eyes | Percentage Eye Defect | Two Eyes | One Eye | No Eyes | Percentage Eye Defect |
|----------------------|-----------------|-------|--------|-----------------------|---------|-------|--------|-----------------------|
| Wild type (400)      | 0               | 0     | 0      | 0%                    | 0       | 1     | 1      | 6%                    |
| L244P (400)          | 24 (69%)        | 11    | 9 (25%)| 0%                    | 1       | 1     | 1      | 6%                    |
| Wild type (25)       | 7 (28%)         | 1     | 6 (24%)| 27%                   | 0       | 1     | 2      | 9%                    |
| L244P (25)           | 12 (30%)        | 28    | 15     | 50%                   | 1       | 1     | 2      | 9%                    |
| Wild type (10)       | 7 (13%)         | 47    | 13     | 38%                   | 1       | 2     | 1      | 7%                    |
| L244P (10)           | 6 (11%)         | 51    | 3      | 9%                    | 0       | 0     | 0      | 0%                    |

Evolution of Synteny Relationships around pax6a and pax6b

To gain further insight into the evolution of the duplicated zebrafish pax6a and pax6b genes, we assessed their conservation and divergence through extensive sequence comparison over coding and non-coding domains, including many functionally defined cis-regulatory elements [6,7,9,65], and through regional synteny studies. Human reticulocalbin (RCN1) was mapped between PAX6 and WT1 (Wilms tumour predisposition gene), using somatic cell hybrids [66]. Synteny conservation with mouse was noted [66], and later extended to Fugu [67]. Subsequently, the transcriptional elongation protein 4 (ELP4), a component of the elongating RNA polymerase II complex, was identified as the neighbour gene downstream of PAX6 [68]. In addition to well-defined regulatory elements upstream of promoters P0 and P1 [39, 65,69], and within introns [9,65,70,71], a number of conserved elements required for correct spatiotemporal expression of PAX6 were found to map downstream of PAX6 within introns of ELP4, thus creating a requirement for obligate synteny conservation between the two genes [67,68]. Several of the conserved elements have been shown to function as transgenic enhancers capable of driving lacZ reporter expression, in spatiotemporal patterns corresponding to subsets of the complete Pax6 expression pattern [6,7,38].

The suggestion that the two copies of zebrafish pax6 arose through whole genome duplication [72] led us to explore the current synteny relationship of each co-orthologue, with the expectation that we would find two genomic copies of the known closely linked human markers, WT1, RCN1 and ELP4 (Figure 4A). However, only one copy has been identified for each of these three closely linked genes in zebrafish at one or other of the expected syntenic sites [73] on either LG7 or LG25 (Figure 4A). Genomic localisation was confirmed for all three genes by mapping on the T51 radiation hybrid map [41,42], using specific primers designed from available zebrafish sequence data in public genome annotations. Assignments were confirmed on multiple BAC clones we had isolated for each pax6 orthologue, including DKEYP-46C10 and DKEY-157G7 containing pax6a and pax6b respectively (Figures S4 and S5). These BACs were part of the zebrafish genomic sequence assembly, and are integrated into regional maps for LG7 and LG25, verifying the syntenic relationships on these linkage groups.

Zebrafish wt1a was linked to z4229 as the nearest marker, upstream of pax6a on LG25 (Figures 4A and S4), showing well-

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conserved exon structure and sequence, in agreement with recently reported data [74]. A related wt1 sequence was also found on LG18, close to marker zc50f22, but with no neighbouring pax6 sequence (data not shown), although this region of LG18 is known to harbour a human chromosome 11 synteny region [73]. Sequences corresponding to the coding exons of rcn1 and elp4 were only found flanking pax6b on LG7 (Figures 4A and S5). This pattern of partial synteny conservation is best illustrated with a PIP plot [75] using the compact Fugu sequence as the baseline (Figure S6), which reveals the exonic sequence conservations very clearly: showing that wtla is linked to pax6a; and rcn1 and elp4 to pax6b [67]. A similar PIP plot with the chick sequence as the baseline (Figure S7) shows unequivocally that the conserved elements associated with the downstream region of human and mouse PAX6, mapping within a number of the ELP4 introns, are still present downstream of zebrafish pax6a, despite the loss of elp4 exonic conservation. In contrast, most downstream elements have been lost from the pax6b locus where elp4 has been maintained. This suggests that the whole syntenic region was ancestrally duplicated, but, in the absence of strong selective constraints, the elp4 duplicate copy associated with pax6a was lost, presumably through multiple mutations (non-functionalisation), while the proposed pax6 regulatory elements, formerly residing in its introns, have been selectively maintained. These finding clearly imply that these conserved elements are not involved in elp4 RNA processing, a possible role suggested for intronic conserved sequences [76].

**Evolutionary Divergence of Regulatory Elements Associated with the Co-orthologues—Bioinformatic and Transgenic Reporter Analysis in Mouse and Zebrafish**

Focusing on the evolving role of the duplicated zebrafish pax6 genes, we observed multiple examples of subfunction-
alization, or job-sharing, between pax6a and pax6b. The differential expression patterns of these co-orthologues are reflected by loss and retention of relevant conserved regulatory elements (Figure 4B).

In the PAX6 downstream region, in the large intron 9 of ELP4, we identified a new regulatory element, E60, showing 94% nucleotide sequence identity between human and mouse over 1400 bp, through sequence comparisons by PIP plot (Figures 4B and S7). Two distinct subcomponents, E60A and E60B, can be distinguished, as shown (Figures 4B and 5A). E60B contains one of the largest ultra-conserved elements: 601bp of complete human-mouse identity [77]. Detailed VISTA analysis [78] revealed clear conservation of E60B in Xenopus and to some extent in both zebrafish pax6a and pax6b (Figure 5A). For E60A only pax6a showed discernible conservation (Figures 5A and S8A), while pax6b (Figure S8B) has no homologous conserved sequence. There have been recent suggestions that enhancer activity may be maintained even where no sequence conservation can be observed between mammals and teleosts [79]. We therefore set out to assess the function of the E60A region in parallel studies in both mice and zebrafish. A set of transient and permanent mouse transgenic reporter lines was produced, with the human E60A region (Figure S8A) as the enhancer, using previously described methods [6,7,9] (Figure 5B–5E). The transgenic mice show lacZ expression consistently in the early retina, in the telencephalon, and in the future ventral thalamic region of the diencephalon (Figure 5B), with minor ectopic expression seen only occasionally, for example, in the limb (Figure 5D and 5E). It is not clear whether the neural tube staining is due to the Hsp70 minimal promoter used.

The zebrafish E60A region (Figure S8A and S8B) from pax6a or pax6b (located using the conservation at the linked E60B element as an anchor point) was inserted, using Gateway cloning, into a Tol2 transposon based vector containing a cFos minimal promoter-GFP reporter cassette (Figure 5A) for co-injection with Tol2 mRNA, as described [53] (Figure S8C). The E60A region from pax6a gives rise to transgenic fish expressing GFP in the optic vesicle and the telencephalon (24/38 surviving transgenic embryos showed this expression pattern at 32 hpf in a typical experiment) (Figure 5G and 5I). No consistent or significant expression was seen in any of 23 surviving transgenic embryos similarly injected with the homologous pax6b construct (Figure S8C and S8D). In this instance, therefore, maintenance or loss of sequence conservation correlates strongly with the presence or absence of tissue-specific enhancer function across multiple species.

Next, using zebrafish reporter transgenics, we assessed the roles of the compound element, P/EE, situated upstream of the two PAX6 promoters, P1 and P0 in the mouse, and previously shown to include an ectodermal enhancer (EE) involved in regulation of Pax6 expression in lens, cornea and lachrymal gland development, and a pancreatic enhancer P (Figures 4B and S9) [36,65,80,81]. Conditional knockouts had confirmed the role of P/EE in both lens and pancreas development [36,80,81]. PIP plots [75] illustrate the conservation of the pancreas component of the 5′ pancreas component [65] in the upstream region of pax6b and its absence in pax6a (Figures 2, 4B, and S7), which is not expressed in pancreas (Figure S3) [43,49]. In contrast EE and an additional neighbouring element appear to be conserved in association with both pax6a and pax6b. The P/EE element from pax6a and pax6b failed to elicit GFP expression when either was inserted into the same c-fos minimal promoter containing vector as the two zebrafish E60A elements (Figure 5A). We therefore engineered a new Tol2 based vector system containing a two-way Gateway destination cassette which can accommodate a reporter
The patterns of expression observed for the P/EE(A)-P0(A) (AA) and the P/EE(B)-P0(B) (BB) constructs are illustrated in Figure 6C. At 28 hpf, the alkaline phosphatase-labelled YFP in situ results reveal expression patterns that recapitulate part of the endogenous pax6a and pax6b expression patterns in accordance with their divergent expression in pancreas and MHB. Frequencies of observed expression sites for the four combinations are shown in Figure 6D. All constructs show a high frequency of expression in the telencephalon, including the constructs with a random sequence linked to the P0 promoters, suggesting that telencephalon enhancer activity resides in the P0 promoter regions from both loci. Interestingly, the telencephalic expression frequency appears lower in the presence of P/EE from the pax6a locus. In contrast, expression at the MHB and at lower frequency in the pancreas are clearly dependent on the presence of P/EE(B).
Figure 6. Transgenic Analysis of the Zebrafish P/EE Enhancers from the pax6a and pax6b Loci in Combination with the pax6 P0 Promoters
(A) PIP plot showing the conservation levels in the Pax6 upstream regions of mouse, Xenopus tropicalis, and the two zebrafish co-orthologues using the human gene as base sequence. The position of the pancreas/ectodermal (P/EE) and the P0 promoter regions used in the construction of the reporter transgenes are shown.

(B) Schematic representation of the Tol2-2way system to create combinatorial constructs for Tol2 mediated zebrafish transgenesis.

(C) Expression analysis of pax6a and pax6b shown by RNA in situ analysis with alkaline phosphatase staining at 28 hpf (top). YFP expression in P/EE(A)-P0(A)-YFPpA (left) and P/EE(B)-P0(B)-YFPpA (right) transgenic fish at 28 hpf shown, using in situ analysis for YFP mRNA. 56 hpf fluorescence images of YFP expression in transgenic lines for the same two constructs are shown on the bottom row.

(D) Frequency of expression in different sites in transient transgenic zebrafish with the four combinations of P/EE enhancer and P0 promoter from the two pax6 loci. T, telencephalon; MHB, midbrain hindbrain boundary; HB, hindbrain; P, pancreas; NT, neural tube.

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Constructs with the P/EE(A) element or a random sequence in combination with either promoter show reporter expression only in the telencephalon. Occasionally expression was found in a few isolated cells in the retina with the P/EE containing constructs. More detailed analysis of these expression patterns will be possible in transgene transmitting G1 and subsequent generations, when any transgene mosaic will have been eliminated.

Concluding Remarks

Gene duplication presents multiple discrete opportunities for differential alteration of gene function in closely related individuals. Divergence at just a few essential loci may lead to reproductive isolation and speciation, as in teleost fish [19–23]. Zebrafish pax6a and pax6b probably arose through large scale genome duplication, rather than regional duplication and translocation. Their position on different linkage groups, both showing vestiges of conserved synteny with ancestral neighbouring genes, is good evidence for this. Surprisingly, the pax6 genes, which are strongly dosage sensitive in mammals [30,82–84], have survived duplication, while the ubiquitously expressed flanking genes renl and elp4, which do not give rise to a dosage (haploinsufficiency) phenotype in humans [85] or mice [68], have lost their co-orthologues. It is interesting to speculate whether the coordinated loss of tissue-specific regulatory elements in duplicate pax6 loci is selected for because gene dosage needs to be maintained at the correct level. Further studies in other teleost species may help to resolve this question.

The diverged functions of the pax6 co-orthologues are unlikely to be due to coding region changes [43], although there are ~20 amino acid differences between them, and also between each zebrafish gene and their single human orthologue. In contrast, the L244P mutation found in the sri mutant is deleterious; it shows reduced binding in vitro to a canonical paired-type homeodomain target site and its ability to activate both the canonical homeodomain target P3 and the paired domain target CD19 is abolished or severely reduced. In keeping with the expression spectrum of pax6b, the mutation gives rise predominantly to a microphthalmic phenotype with variable reduction in lens size and, in extreme cases, disorganisation of the retina (Figure 1A), that may be secondary to extreme lens reduction (cf Ashery-Padan et al, 2000 [80]). The absence of a severe pancreas phenotype is intriguing; our discussions raise various possible explanations, but further analysis is needed for better insight.

Our findings provide strong experimental evidence for the concept of evolutionary divergence by subfunctionalization through differential loss and retention of cis-regulatory elements at ancestrally duplicated tissue-specific loci [86]. This has also been termed the “duplication, divergence and complementation” model [87]. For the retention of a full set of functions, the loss of elements needs to proceed in an orderly manner. Interdependent cis-elements can only be lost from the same copy of the duplicated gene, otherwise gene activity in certain tissues may be totally lost. This may be the situation where several brain-specific elements, with spatiotemporal overlap in expression pattern, have been lost from pax6b. The persistence of pax6a-associated regulatory elements, when the exons of the elp4 gene have disappeared, may be one mechanism for the evolution of gene deserts containing only conserved non-coding sequences [12,88].

Methods

Embryo collection. General maintenance, collection, and staging of zebrafish was carried out according to the Zebrafish Book [89]. The approximate stages are given in hours post fertilization (hpf) at 28 °C and were determined according to morphology (data not shown).

Genetic mapping of the sri locus. The zebrafish mutant sunrise (allele: sri<sup>23</sup>), produced as part of an ENU mutagenesis screen [27], was provided by the Tübingen zebrafish stockcentre. Homozygous sri fish, showing the variable recessive phenotype, were found to be fully viable and fertile. Fish carrying the sri mutation on the Tübingen background were crossed to the wildtype strain WIK (provided by Peter Currie). The F1 was raised, and 5 dpf F2 larvae showing the mutant phenotype, and their WT siblings, were collected and fixed in 100% methanol prior to mapping. The sri mutation was mapped by linkage analysis with SSLP (sequence length polymorphism) markers between embryos showing the homozygous mutant phenotype and their unaffected siblings.

Radiation hybrid mapping. Radiation hybrid (RH) mapping was carried out using the Goodfellow T51 RH panel. To obtain the positions of the tested markers the Children’s Hospital Zebrafish Genome Initiative webpage (http://izrhrmaps.tch.harvard.edu/ ZonRHmapper/instanceMapping.html) was used. Intronic primers flanking exons 1 and 6 of pax6b were used to map this strong candidate gene onto the T51 RH map that was also used as a reference for the markers used in the genetic mapping. The map position of pax6b was closest to the marker f370g8, which is now known to be part of the pax6b coding region in NM_131641 at http://www.ncbi.nlm.nih.gov/ entrez/viewer.fcgi?db=nucleotide&val=18855920.

Mutation analysis using RT-PCR and sequencing. pax6b cDNA was determined by RT-PCR from sri and WT embryos using a primer set (Gibco). Sequencing revealed four changes identified in the sri coding sequence compared to the published pax6b cDNA [43] (Genbank NM_131641). Three of the four nucleotide changes were synonymous (429 A>C, 989 G>A, 1304 A>C), and also found to be present in the wildtype sequence of the T51 strain, in which the sri mutation was generated [55], as well as in the public genomic sequence in BAC DKEY-157G7. The fourth, a T to C transition at position 991 in the cDNA is present only in sri DNA and gives rise to a leucine to proline missense mutation in the homeodomain. The 991 T>C mutation creates a Ddel digestion site that was used for further genetic analysis.

Functional studies of the sri mutant protein. Luciferase assays were carried out as follows. Mammalian expression vectors, pCMV-ZIPax6.1 (pax6a), pCMV-ZIPax6.2 (pax6b) and pCMV-ZIPax6.2_sri (pax6b_sri), respectively containing the two wild type or L244P mutant full-length cDNA clone, were used in co-transfections into HeLa cells with the luciferase reporter plasmids 3XP3-Luc and 3XCD19-Luc, containing respectively three P3 homeodomain binding sites [45] or three CD19 paired domain binding sites [46] linked 5’ to the basal promoter-luciferase cassette. HeLa cells were cultured in DMEM medium with 10% calf serum (Gibco, Milan-Italy) and transfected using calcium phosphate co-precipitation [91]. Cells were plated at 6 × 10<sup>5</sup> cells/100 mm culture dish 24 h prior to transfection. The plasmids used were: pCMV-ZIPaxb6 and pCMV-ZI Paxb6s: 1 μg; 3XP5-Cat: 9 μg; RSV-CAT: 2 μg. RSV-CAT contains the RSV promoter 5’ to the chloramphenicol-acetyl-transferase (CAT) gene, used to normalize transfection efficiency. Cells were harvested 42–44 h after transfection, and extracts prepared by freeze-thawing. CAT activity was measured by ELISA (Amersham). Luciferase activity by chemiluminescence. The data presented are mean values plus/minus standard deviations of a representative experiment performed in triplicate (three independent transfections).

Electrophoretic mobility shift assays (EMSA) were conducted as follows. cDNA sequences encoding either wild-type ZF paxb6 or mutant L244P homedomain (from aminoacid 228 to amino acid 291 [42]) were expressed in BL21 cells, and partially purified. 32P end-labeled double-stranded oligonucleotides P2 and P3 containing high-affinity HD-binding sequences 5’-TCTGAGGGGATCAGGATGCTAATTGATTAGCATCC-GATCCG-3’; P3: 5’-TCTGAGGGGATCAGGATGCTAATTGATTAGCATCC-GATCCG-3’ were used in gel-retardation assays [47,92]. HD-containing protein at a concentration of 50, 100 and 300 ng/sample was incubated for 30 minutes at room temperature with probe DNA (3 μg) in a buffer containing 20 m M Tris-HCl pH 7.6, 75 mM KCl, 0.25 mg/ml bovine serum albumin (BSA), 5 mM dithiothreitol (DTT), 12.5 μg/ml calf thymus DNA, 10% glycerol). Protein-bound and free oligos were
separated on native 7.5 % polyacrylamide gel, run in 0.5 X TBE for 1.5 hours at 4 °C. Gels were fixed and autoradiographed. Electrophoretic mobility shift assays were carried out for wild type and mutant homeodomain protein fragments on the P2 and P3 homeodomain binding sites.

For transgenic analyses, wild type and mutant aged siblings were fixed in 4% paraformaldehyde in PBS, dehydrated in a standard ethanol series, embedded in Technovit (Heraeus Kulzer, Germany), sectioned and stained with 0.5% toluidine blue in 1% borax buffer.

Comparative sequence analysis was carried out by through PIP plots, which were generated using the programme PIPmaker (http://bio.cse.psu.edu/pipmaker/). Evolutionary sequence comparison of element E60+ was prepared using the VISTA program [78] with a window size of 50 bp and a minimal sequence identity of 70% using sequences derived from Z83001 (human), AL512589 (mouse), and AL929172, BX001478 (zebrafish). Xenopus sequence was obtained from Xenopus tropicalis genome assembly 3.0 from the JGI.

Expression studies of pax6a, pax6b, and YFP by RNA in situ analysis shows that the probe used in the initial screen is in the ribosomal 5′ region of pax6a (Figure S1). The wild-type and homozygous mutant sunrise fish with Trizol 2008). Made from carefully dissected adult (age 6 months) pancreas from Z. The E60A-þ vector was constructed by cloning a 2.3 kb fragment containing the E60 arv::5′-GGGGACAACTTTGTACAAGAAAGCTGGGTG-3′ and 5′-AGGGGACTGCTTTTTTGTACAAACTTGA-3′ into the SalI site of the p610 vector to generate E60A–Z microinjection construct. E60A–Z microinjection fragment was generated from this construct using the Asp718I restriction site localised between the two subregions of the full-length E60+ fragment. All the expression patterns were photographed on a Leica MZ FLIII Microscope fitted with a Hamamatsu Orca-ER digital camera.

Supporting Information

Figure S1. Identification and Validation of the sri Mutation

(A) Mapping of the sri mutation to the pax6b region on LG7. Markers used in the region are shown for a Radiation Hybrid (RH) map and by linkage.

(B) Alignment of the amino acid sequences for the Pax6 homeodomain with Pax6 proteins from multiple other species and with other human homeodomains from multiple genes with paired-type homeoboxes. The alignment shows (arrowed) that the L244P change in the human protein is conserved in both fish and mammals.

(C) Documentation of the nucleotide differences (red boxes) between the published genomic and DNA sequences for pax6b and showing the position of the proposed ENU-induced CCT to CCT nucleotide change leading to the missense mutation. All the other nucleotide variants (strain differences) do not lead to protein residue changes.
RT-PCR Analysis Shows That Only
Figure S3.
Restriction Analysis Reveals the Expected Numbers of Each Genotype
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Nature 424: 147–151.

Figure S6. Sequence Comparison around pax6 by PIP Plot, with Fugu as the Base Sequence, Showing That elp4 Exons Are Present Downstream of Zebrafish pax6b, but Absent from pax6a

Found at doi:10.1371/journal.pgen.0040029.sg001 (323 KB PPT).

Accession Numbers
The RefSeq (National Center for Biotechnology Information [NCBI]) (http://www.ncbi.nlm.nih.gov/RefSeq) accession numbers for the genes discussed in this paper are for human: PAX6 (NM_000280, NP_0001595); ELPlf (NM_019040); RCNI (NM_002901); WT1 (NM_021472); mouse: Pax6 (NM_013627); Elplf (NM_023876); Wt1 (NM_0141783); Zebrafish: pax6 (NM_131304); pax6b (NM_131314); elplf (NM_001101638); rcll (predicted) (NM_080640); wt1a (NM_131046); wt1b (NM_00109634).

Diseases, etc.: human aniridia (MIM 106210); mouse small eye (MGI:1856153); zebrafish sunrise (ZDB-GENE-070117–2413).

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Author contributions. DAK, RMB, VvH, and PC conceived and designed the experiments and analyzed the data with significant input by PLY. RMB carried out the mating and phenotype selection and confirmations for the mapping. DAK and PC developed the transgenic strategies and constructs and made and analyzed mouse and fish transgenics with help from AS. PC carried out mRNA rescue and morpholino experiments. PG and PC provided bioinformatics contributions. RD supplied the sunrise mutant and worked with HBS on the fish mapping. RD and PLY analyzed the fish eye phenotype. AMH analyzed the pancreas. GD conceived and carried out the mutant protein functional analyses. VvH wrote the paper.

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Competing interests. The authors have declared that no competing interests exist.

Found at doi:10.1371/journal.pgen.0040029.sg009 (63 KB PPT).

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Nature 424: 147–151.

Figure S4. BAC Assembly of the LG25 pax6a Region, Showing the Synteny Conservation with wtla

The other two immediate pax6 flanking genes normally seen in vertebrates, elp4 and rcll, are however absent from this contig.

Found at doi:10.1371/journal.pgen.0040029.sg003 (199 KB PPT).

Figure S5. BAC Assembly of the LG7 pax6b Region, Showing the Presence of elp4 and rcll

Found at doi:10.1371/journal.pgen.0040029.sg005 (56 KB PPT).

Figure S8. Details of the E60 Elements in Mouse and Zebrafish Transgenic Studies

(A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region. (B) E60A sequence from the (A) Mouse human and zebrafish comparisons for the E60A region.

Figure S2. Genotyping the Offspring of Two Heterozygous Parents by Restriction Analysis Reveals the Expected Numbers of Each Genotype

Found at doi:10.1371/journal.pgen.0040029.sg002 (197 KB PPT).

Figure S3. RT-PCR Analysis Shows That Only pax6b Is Expressed in the Pancreas of Both Wild Type and sri/sri Homozygous Adult Fish. In Contrast, Both pax6a and pax6b Are Expressed in Adult Eye

Found at doi:10.1371/journal.pgen.0040029.sg003 (199 KB PPT).

Figure S7. Sequence Comparison around pax6 by PIP Plot, with Chick as the Base Sequence Comparing to Human, Mouse, Fugu and pax6a and pax6b from Zebrafish

The enhancer elements discussed in this paper are highlighted with red boxes (P/E, E60, and CE2). A blue box draws attention to the greater conservation of regulatory elements downstream of pax6a than pax6b, which is noteworthy since pax6a has lost the elp4 exons, while pax6b has retained them.

Found at doi:10.1371/journal.pgen.0040029.sg007 (315 KB PPT).

Figure S9. Summary of Conserved Elements within and Flanking the PAX6 Gene, Most with Proven Tissues-Specific, Pax6 Compatible Enhancer Function in the Mouse.

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