A comparison of the properties of Sox-3 with Sry and two related genes, Sox-1 and Sox-2

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SUMMARY

The Sox gene family consists of a large number of embryonically expressed genes related via the possession of a 79-amino-acid DNA-binding domain known as the HMG box. Partial clones for the first three Sox genes (a1-a3) were isolated by homology to the HMG box of the testis-determining gene Sry and are now termed Sox-1, Sox-2 and Sox-3. Sox-3 is highly conserved amongst mammalian species and is located on the X chromosome. This has led to the proposal that Sox evolved from Sry. We present the cloning and sequencing of Sox-1, Sox-2 and Sox-3 from the mouse and show that Sox-3 is most closely related to Sry. We also confirm that mouse Sox-3 is located on the X chromosome between Hprt and Dmd. Analysis of the distribution of Sox-3 RNA shows that its main site of expression is in the developing central nervous system, suggesting a role for Sox-3 in neural development. Moreover, we demonstrate that Sox-3, as well as Sox-1 and Sox-2, are expressed in the urogenital ridge and that their protein products are able to bind the same DNA sequence motif as Sry in vitro, but with different affinities. These observations prompt discussion of an evolutionary link between the genes and support the model that Sry has evolved from Sox-3. However our findings imply that if this is true, then Sry has undergone concomitant changes resulting in loss of CNS expression and altered DNA-binding properties.

Key words: Sox genes, HMG Box, transcription factor, Sry, sex determination

INTRODUCTION

The mammalian testis-determining gene Sry is expressed for a brief period in the indifferent gonad and causes a switch in development that is typical of the default ovarian pathway to that of the testis (Koopman et al., 1991; Hacker et al., 1995). The gene is located on the Y chromosome and encodes a transcription factor containing a 79-amino-acid DNA-binding domain known as the HMG box (Capel and Lovell-Badge, 1993). Many genes have now been cloned on the basis of their homology to the HMG box of Sry and comprise the Sox gene family, for Sry-related HMG box-containing genes. Approximately 20 Sox genes have been found in mammals, with more being identified in other vertebrates and invertebrates such as Drosophila and C. elegans (Denny et al., 1992a; Wright et al., 1993; Laudet et al., 1993, Coriat et al., 1993; our unpublished results). The homology exhibited within the HMG box varies between members of the family but allows them to be grouped into different subfamilies. For example, the first Sox genes to be cloned, a1-a3 (now termed sox-3), are in the subfamily containing Sry, due to their high similarity (approximately 90%) (Gubbay et al., 1990; Denny et al., 1992a).

Recently, it has been proposed that Sry originated from the Sox-3 gene. This is based upon sequence information from human and marsupial Sox-3 homologues, showing it to be highly conserved in mammalian evolution and to be the Sox gene most closely related to Sry, despite the latter’s divergence (Stevanovic et al., 1993; Foster and Graves, 1994). In addition, Sox-3 has been mapped to the X chromosome in both these mammals. This is relevant because the X and the Y chromosomes are thought to have arisen from a common ancestor ‘autosome’ in the lineage that gave rise to mammals. However, given that there are at least 20 mammalian Sox genes (e.g. Wright et al., 1993) and probably many more that have not yet been identified, the location of Sox-3 on the X chromosome may be fortuitous. Sry could have originated from any other Sox gene by gene duplication and translocation or by retroposition. It would therefore be more informative to compare the properties exhibited by Sry with Sox-3 and other closely related members of the Sox gene family in order to determine how similar they are.
The expression of Sry in the mouse is tightly regulated, allowing expression in the indifferent gonad between 10.5 and 12.5 dpc to occur in order for the testis determination pathway to be initiated (Koopman et al., 1991; Hacker et al., 1995). The function of SRY protein relies critically on its ability to bind DNA in a sequence-specific manner (Berta et al., 1990; Harley et al., 1992; Pontiggia et al., 1994). When it does so, it causes the DNA to bend through a dramatic angle, which itself is thought to be crucial functionally. The ability of the protein to interact with DNA is dependent on its DNA-binding domain, the HMG box. Mutations within this domain can interfere with both DNA-binding as well as bending and result in sex reversal to give XY females (Pontiggia et al., 1994). The function of the rest of the SRY protein is unclear. It has diverged very rapidly during evolution such that the mouse and human genes show no homology outside the HMG box region (Whitefield et al., 1993; Tucker and Lundrigan, 1993). Also, no de novo mutations known to lead to sex reversal have been found outside the HMG box. These data suggest that the HMG box is the only functional part of SRY and that it works only through interaction with specific target sequences.

In short, the properties of Sry known to be required for its function are its expression within the genital ridge and the sequence-specific interaction of the protein with DNA. We have chosen to examine if the mouse Sox-3 gene and its product share these properties with Sry. We have also compared two other closely related genes, Sox-1 and Sox-2, to determine if any similarities observed are peculiar to Sry and Sox-3, or indeed, are representative of other members of the subfamily. In this report we describe some properties of Sox-1, Sox-2 and Sox-3 in the mouse and confirm that only Sox-3 is X-linked. We show that Sox-2 and SRY show similar affinities in binding to the AACAAT consensus motif but surprisingly weaker binding is effected by Sox-3 and Sox-1. The main site of expression of Sox-3 is, like Sox-1 and Sox-2, within the developing CNS, although all three genes are also expressed within the genital ridge. In addition, we show that Sox-3 is likely to be expressed in the same cell type as Sry in the indifferent gonad. Our findings do not eliminate the possibility that Sry could have evolved from any Sox gene, but Sox-3 is the best candidate due to its chromosomal position, its degree of homology to Sry and its genital ridge expression. Our results suggest that if Sox-3 is the evolutionary ancestor of Sry, then Sry must have undergone concomitant changes, resulting in loss of CNS expression and altered DNA-binding properties.

**MATERIALS AND METHODS**

**DNA analysis**

DNA manipulations were carried out according to Sambrook et al. (1989). Genomic DNA was isolated from adult spleens of male and female mice, as described by Lovell-Badge (1987). Southern blots were washed in 0.1× SSC, 0.1% SDS at 70°C for 1 hour and then exposed to X-ray film for 3 days.

Inserts were subcloned into pBluescript (Stratagene) for sequencing. Sequencing, by the dideoxy method (Sanger et al., 1977), was performed using the T7 Sequencing Kit (Pharmacia) according to the manufacturer’s instructions. Sox-3 was sequenced on both strands of subclones derived from the cDNA clone 7d and a Sox-3 genomic clone. Gaps were filled using the following primers:

- 0-30, GCCAACGCGCCCTACTCCT
- 0-31, TGGGGTACGTTGTCAGCAG
- Sox-3.3, CAGCGCTTGGAGAGCCT
- Sox-3.3, GACGCGCTTGGAGAGCCT

Sequence analysis was performed using software designed by the Genetics Computer Group at the University of Wisconsin (Devereux et al., 1984).

**Preparation of purified GST fusion proteins**

The HMG boxes of mouse SRY, Sox-1, Sox-2 and Sox-3 were subcloned into the BamHI-EcoRI sites of the bacterial expression vector pGEX3T by PCR. The fusion proteins were induced with addition of IPTG for 3 hours and purified by adsorption to glutathione agarose beads, as described by Smith and Johnson (1988). Purity was assessed by staining SDS-polyacrylamide gels with Coomassie blue.

**Gel retardation assays**

Probes were prepared by annealing the complementary oligonucleotides prior to labelling in forming a 1× agarose gel containing 7% (v/v) formaldehyde in 1× MOPS buffer and transferred onto Genescreen membrane. 32P-labelled single-stranded antisense RNA probes were produced using a 440-bp XhoI-Not fragment from the Sox-3 gene clone (200 bp from start of cDNA to position 460 on cDNA, Fig. 1) and a 460-bp EcoRI-Apel fragment from the Sox-2 cDNA (position 1-460 on cDNA, Fig. 1) and a 340-bp XhoI-XhoI fragment from the Sox-1 cDNA (position 1694-2046 on cDNA, Fig. 1). Hybridisation was performed at 65°C for 16 hours in 10% formamide, 1× SSC, 1× Denhardt’s, 20 mM sodium phosphate (pH 6.8), 10% dextran sulfate, 1% SDS, 100 μg/ml RNA and 100 μg/ml sheared denatured herring testis DNA. Filters were washed in 0.1× SSC, 0.5% SDS at 70°C for 2 hours. Background signal was eliminated by RNase treatment of the filters (0.2 μg/ml RNase A in 2× SSC for 20 minutes, followed by 2× SSC, 0.5% SDS for 30 minutes at 50°C).

**In situ hybridisation**

Two probes from the 5′ region of the Sox-3 gene were used: a 100-bp EcoRI-PstI fragment from the cDNA (position 1-108 on cDNA, Fig. 1) and a 440-bp XhoI-XhoI fragment from the genomic clone (see above). Transcription reactions were performed in vitro using T7 RNA polymerase (Promega) or T3 RNA polymerase (Pharmacia) to generate sense (control) and antisense RNA probes labelled with [32P]CTP. These were then gel-purified by electrophoresis through a 12% denaturing polyacrylamide gel. DNA-binding assays were performed essentially as described by Smith and Johnson (1988). Homoduplex DNA was incubated with 1.5 μg of sonicated salmon sperm DNA was used as non-specific competitor in the binding reactions instead of poly(dIdC). The sequence of the target oligonucleotide used is 5′ CGGAGAAACCTTCTAGAACATGGTGAAAGCACGCGCTTGGAGAGCCT 3′.

**Northern analysis**

Total RNA was isolated according to the method described by Auffray and Rougeon (1980). 10 μg of total RNA was electrophoresed in an 1× agarose gel containing 7% (v/v) formaldehyde in 1× MOPS buffer and transferred onto Genescreen membrane. 32P-labelled single-stranded antisense RNA probes were produced using a 440-bp XhoI-Not fragment from the Sox-3 gene clone (200 bp from start of cDNA to position 460 on cDNA, Fig. 1) and a 440-bp EcoRI-Apel fragment from the Sox-2 cDNA (position 1-460 on cDNA, Fig. 1) and a 340-bp XhoI-XhoI fragment from the Sox-1 cDNA (position 1694-2046 on cDNA, Fig. 1). Hybridisation was performed at 65°C for 16 hours in 10% formamide, 1× SSC, 1× Denhardt’s, 20 mM sodium phosphate (pH 6.8), 10% dextran sulfate, 1% SDS, 100 μg/ml RNA and 100 μg/ml sheared denatured herring testis DNA. Filters were washed in 0.1× SSC, 0.5% SDS at 70°C for 2 hours. Background signal was eliminated by RNase treatment of the filters (0.2 μg/ml RNase A in 2× SSC for 20 minutes, followed by 2× SSC, 0.5% SDS for 30 minutes at 50°C).

**RNAse protection**

Total RNA was prepared from adult tissue samples of Parkes inbred mice as described by Capel et al. (1993), or from embryonic tissue by homogenising in 300 μl NETS (100 mM NaCl, 50 mM Tris HCl pH 8.0, 0.5% SDS, 10% sucrose, 100 mM dithiothreitol and phenol-chloroform extraction before precipitating with 10 μg yeast tRNA. RNAse protection assays were carried out using 10 μg adult tissue RNA or RNA prepared from four pairs of genital ridge, as
Sox-3, an X-linked gene related to Sry

RESULTS

Cloning and sequencing of Sox-1, Sox-2 and Sox-3

An 8.5-dpc whole mouse embryo cDNA library (Fahner et al., 1987) was screened with a human SRY probe in order to identify genes closely related to the testis-determining gene (Gubbay et al., 1990). 12 clones were identified, seven of which correspond to Sox-2, two to Sox-1, one to Sox-3 and two weakly hybridizing clones, which were found to be Sox-4.

The full-length sequences for Sox-1, Sox-2 and Sox-3 are presented in Fig. 1. The sequence obtained for Sox-1 includes the open reading frame, but at 2.4 kb, it is shorter than the specific 4.1-kb transcript seen on northern blots (Fig. 4). No polyadenylation signal or poly(A) tail was identified at the 5’ end of the cDNA. This is missing in conjunction with 5’ untranslated sequences. The Sox-2 sequence shown is likely to correspond to the full-length transcript as its size corresponds to the specific 2.4-kb band detected in northern analyses (Fig. 4). A poly(A) tail can be seen downstream of a canonical polyadenylation signal.

Moreover, potential start and termination codons can be identified, respectively preceded or followed by several in-frame stop codons. The single cDNA obtained for Sox-3 was found to be incomplete as no translational termination codon was present. Therefore, a genomic clone was isolated from a 129/Sv mouse strain library (Gubbay et al., 1990) to enable the sequence to be completed. The transcriptional start site of Sox-3 has been confirmed by primer extension and RNase protection assays and is in an equivalent position to that of human SOX3 (data not shown; Hacker, 1995). Sequence and restriction analysis comparisons between the cDNA and genomic clones, as well as RNase protection studies (M. Parsons and R.Lovell-Badge, unpublished data), indicated that Sox-3 coding sequences are located within a single exon. This is also true for Sox-1, Sox-2 and mouse and human Sry/SRY (Clépet et al., 1993; Hacker et al., 1995).

Sequence comparisons and conservation

The three proteins obtained after conceptual translation of the Sox-1, Sox-2 and Sox-3 cDNAs show that they share sequence homology outside the HMG box region. A schematic view of this is shown in Fig. 2. The proteins start with a short (40-65 amino acids) N-terminal domain rich in hydrophobic residues, followed by the 79-amino-acid HMG box prior to a large C-terminal domain varying in length between the genes (262, 199 and 229 residues for SOX-1, SOX-2 and SOX-3 respectively).

Fig. 2B presents the sequence comparisons between the C-terminal domains of the three proteins. Four poly(alanine) stretches are present in SOX-1 and SOX-3 but not in SOX-2, two of which are at similar positions in both proteins. Furthermore, a PRD-type repeat (His-Pro (Frigerio et al., 1986) is present only in SOX-1. Thus although some similarities are evident between the three proteins, each one has a unique combination of structural motifs.

All three genes show no homology outside the HMG box with human or mouse SRY/Sry, or with sequences obtained from other Sox genes, for example Sox-4 (Gubbay et al., 1990; Sinclair et al., 1990; Farrow et al., 1993; van de Wettering et al., 1993) or Sox-5 (Denny et al., 1992b). Sox-1, -2 and -3 can therefore be grouped into a subfamily distinct from other Sox genes. Moreover, the similarity of their structure as well as the sequence of these genes suggest that they may have arisen early on by a gene duplication event from a single ancestral Sox gene of this type. From comparisons within the HMG box (Fig. 2C), Sry can be considered a member of this subfamily; as human, marsupial and mouse Sry show high degrees of homology to each of Sox-1, Sox-2 and Sox-3 (Stevanovic et al., 1993; Foster and Graves, 1994). However, comparisons between the three genes show that Sox-3 is most closely related to Sry.

Chromosomal localisation of Sox-3

Southern analysis of BglII-digested mouse genomic DNA, with both Sox-3 and Sox-1 cDNA probes, showed the 9.5-kb Sox-3 cognate band to be twice as intense in the female track compared to the male, consistent with it being X-linked (Fig. 3A). In order to confirm the linkage and to determine the position of Sox-3 on the chromosome, interspecific backcross pedigree analysis was utilized. A PstI fragment corresponding to the 5’ end of the Sox-3 cDNA was used to define a HindIII restriction fragment length variant (RFLV) between Mus musculus domesticus (allele size 5.3 kb) and Mus spretus (allele size 5.3 kb). The segregation of this RFLV was analysed through a panel of interspecific backcross animals with previously characterised breakpoints spanning the X chromosome (Kay et al., 1991). Fig. 3B shows the haplotypes of the recombinant X chromosome of 15 representative individuals out of a total of 19 selected backcross animals analysed. This analysis locates Sox-3 between the anchor loci Hprt and Dmd, at a genetic distance of 7.4 ± centiMorgans distal to Dmd. No known mutation corresponds to this position in mice, but our analysis places Sox-3 close to Fmr-1 (Laval et al., 1992). Consistent with this result, mapping data obtained for the human SOX3 gene places it in the conserved syntenic region of the X chromosome, close to fragile X syndrome (Stevanovic et al., 1993). In comparison, Sry/SRY is located on the short arm of both the mouse and human Y chromosome, whereas in contrast, the two other subfamily members, Sox-1 and Sox-2, are located on different autosomes (data not shown).

Sizing of the Sox-1, Sox-2 and Sox-3 transcripts

Northern analyses were carried out to ascertain the size of the transcripts of Sox-1, Sox-2 and Sox-3 and to determine if the cDNA clones obtained were complete. As shown in Fig. 4A, Sox-1 and Sox-2 probes detected bands at 4.0 kb and 2.4 kb, respectively, in RNA samples from embryos at 9.5 dpc to 11.5 dpc. A less abundant transcript that extends more 5’ to the Sox-
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2 transcript identified here can also be detected in the embryo (S. Sockanathan, unpublished data). The Sox-3 transcript in embryonic head RNA at 10.5 dpc and 11.5 dpc was found to be 2.3 kb in length. No expression was detected in other adult tissues examined except for testis (Fig. 4B).

In vitro DNA-binding properties of SOX-1, SOX-2 and SOX-3

It has been shown that SRY protein binds the consensus sequence AAACAT in vitro (Giese et al., 1992; Harley et al., 1994). Given the high degree of similarity between the HMG boxes of SRY, SOX-1, SOX-2 and SOX-3 and their overlapping patterns of expression (see below), it was of interest to determine if these proteins could also bind the AACAAT sequence with the same relative affinities. Identical size HMG box-GST fusion proteins were purified for all four proteins and gel-retardation assays were carried out using increasing amounts of protein (Fig. 5). SOX-3, as well as SOX-1 and SOX-2, are able to form specific complexes with the AACAAT motif. However, although SOX-3 shows the greatest sequence homology to SRY within the HMG box, it is clear that much weaker binding is exhibited by SOX-3 compared to SRY. Poor binding is also shown by SOX-1 but, in contrast, SOX-2 and SRY were found to bind the target oligonucleotide at similar affinities.

Expression of Sox-3 during development

In situ hybridisation

A detailed analysis of the expression patterns of Sox-1, Sox-2 and Sox-3 was carried out by in situ hybridisation. The data obtained for Sox-1 and Sox-2 will be presented elsewhere; however both genes are expressed in the CNS, with Sox-2 showing additional expression in the sensory placodes, the PNS and gut endoderm. The in situ hybridisation analysis for Sox-3 shown in Fig. 6 covers mouse embryonic stages between 8.5 and 13.5 dpc. Sox-3 shows overlapping domains of expression with Sox-1 and Sox-2 within the CNS and the sensory placodes throughout this period. In 8.5-dpc embryos, expression is detected throughout the neuroectoderm (Fig. 6A,B). This pattern is unchanged at 9.5 dpc, with the exception of the optic vesicles, which show a gradient of expression with the lowest level distally (Fig. 6C-E). Some expression is also evident in the olfactory placode (Fig. 6C). Transverse sections of a 10.5-dpc embryo show that Sox-3 continues to be expressed along the full length of the developing CNS, including brain and spinal cord. However, frontal sections of a similar stage embryo reveal some discontinuity in the pattern at the level of the hindbrain, with areas of weaker and stronger expression apparently contained within the boundaries of specific rhombomeres (Fig. 6F). At 11.5 dpc, Sox-3 expression is maintained throughout the fetal brain, but not in the optic cup, as seen in transverse sections through the head (Fig. 6G). However, by 13.5 dpc the expression has become restricted to the ependymal layer, where undifferentiated neural progenitor cells are still actively dividing (data not shown).

RNAse protection studies

Our results by in situ hybridisation demonstrate that the main sites of expression of Sox-3 are in the developing CNS, like Sox-1 and Sox-2. In addition to this, some overlapping sites of expression are also observed between the genes elsewhere; for example, for Sox-2 and Sox-3 in the sensory placodes and, for Sox-1 and Sox-2, in the developing lens (Collignon, 1992). In all cases, no expression was observed in the urogenital ridge where Sry is expressed. However, it has been shown that sensitive techniques such as RT-PCR or RNase protection are more reliable ways of detecting Sox-3, as well as Sox-1 and Sox-2, in the urogenital ridge, as these are quantitative assays not prone to problems of signal to noise ratio. Fig. 7 compares the expression of Sox-1, Sox-2 and Sox-3 with Sry in urogenital ridges at 11.5 dpc. It can be seen that all four of the members of the subfamily are expressed in both male and female genital ridges, with the exception of Sox-3, which is male-specific. RNA from embryonic head was used as a positive control for Sox-
Sox-2 and Sox-3 expression whereas adult liver was used as a negative control. Testis RNA was used as a positive control for Sry expression and it can be seen that both Sox-1 and Sox-3 are also expressed in this tissue, unlike Sox-2.

We have shown so far that SOX-3 has similar properties to SRY in that they are both expressed in the urogenital ridge and are able to form complexes on the AACAAT motif in the promoter of the DAZ gene (Collignon et al., 1992). SOX-3 is also expressed in the somatic cell lineages of the genital ridge (Buehr et al., 1993). The results presented in Fig. 7B show that Sox-3 is expressed by somatic cells at similar levels to those seen in wild-type genital ridges of normal embryos.

![Fig. 2. Sequence comparisons between SOX-1, SOX-2, SOX-3 and SRY.](image)

1. Sox-2 and Sox-3 expression whereas adult liver was used as a negative control. Testis RNA was used as a positive control for Sry expression and it can be seen that both Sox-1 and Sox-3 are also expressed in this tissue, unlike Sox-2.
Sox-3, an X-linked gene related to Sry

Sox-3, an X-linked gene related to Sry. This demonstrates that Sox-3 is likely to be expressed in the same cell type as Sry. Sox-3 transcripts were also found to be expressed by developing limb buds at this stage, but not in other tissues (Fig. 7 and data not shown). As the limb bud sample was much larger than the genital ridge samples, the signal is likely to represent a very low level of Sox-3 expression.

DISCUSSION

In this report, we present a comparison of the mouse Sox-1, Sox-2 and Sox-3 genes, which together make up the members of the Sox family most related to the testis-determining gene Sry. We confirm that of the three genes, Sox-3 bears the highest homology to Sry and that it is located on the X-chromosome, consistent with the proposal that Sry may have evolved from Sox-3. We have addressed this proposal further by examining sites of expression and DNA-binding properties. The main site of expression of Sox-3 is within the developing CNS, in a pattern overlapping that of Sox-1 and Sox-2, suggesting a role for all these genes in neural development. But Sox-1, Sox-2 and Sox-3 transcripts are also detected within the developing urogenital ridge. Furthermore, we show that Sox-3 is most likely to be expressed within the same cell type as Sry, suggesting that the two gene products could cooperate or compete. In gel mobility shift assays, Sox-1, Sox-2 and Sox-3 are able to bind to the same consensus motif as SRY; however Sox-3 shows much weaker affinity to the site in comparison to either SRY or Sox-2. Our findings suggest that Sry may have evolved from this subfamily of Sox genes and that of the three members, Sox-3 is the probable ancestor of Sry, because of its sequence homology, chromosomal location and expression, but there are significant differences in the properties of the proteins.

SOX-1, SOX-2 and SOX-3 can be grouped into the same subfamily, along with SRY, due to the high homology (approximately 82%) exhibited within the HMG boxes of the proteins. For SOX-1, SOX-2 and SOX-3, sequence similarity also extends outside the HMG box, although each protein has its own characteristics. Thus, Sox-2 is devoid of poly(alanine) repeats such as those found in SOX-1 and SOX-3, while Sox-1 contains a PRD repeat (His-Pro) (Frigerio et al., 1986), which is absent in both SOX-2 and SOX-3. The similarities in structure and sequence suggest that these genes are evolutionarily related and may have arisen from duplications of a single ancestral gene. This must have been a fairly ancient event as the genes map to different chromosomes, but once duplicated they seem to have acquired important individual functions as there is extremely high sequence conservation amongst Sox-2 genes and Sox-3 genes between chicken, mouse and man (Stevanovic et al, 1993, 1994; Uwanogho et al., 1995; Kamachi et al., 1995).

As shown here, the main site of Sox-3 expression is in the gnital ridge. This demonstrates that Sox-3 is likely to be expressed in the same cell type as Sry. Sox-3 transcripts were also found to be expressed by developing limb buds at this stage, but not in other tissues (Fig. 7 and data not shown). As the limb bud sample was much larger than the genital ridge samples, the signal is likely to represent a very low level of Sox-3 expression.

**Fig. 4.** Northern blot analysis of Sox-1, Sox-2 and Sox-3. (A) A 2.4-kb Sox-2-specific transcript and a 4.0-kb Sox-1 transcript were detected in RNA prepared from 9.5-dpc and 10.5-dpc embryos. The same filter was subsequently hybridised with a β-actin probe to ensure integrity of the RNA samples. (B) A 2.3-kb Sox-3-specific transcript was detected in RNA from 10.5-dpc and 11.5-dpc embryonic heads and from adult testis (top). For each sample, 10 μg of total RNA was loaded and cross-hybridisation of the probe to 28S rRNA, seen before RNase treatment (bottom), shows that similar amounts of RNA were transferred to the filter in each lane.
developing CNS from early stages, which is also true for Sox-1 and Sox-2. (see also J. Collignon et al., unpublished data; Collignon, 1992). All three of the genes show overlapping expression to some degree elsewhere in the embryo, e.g. in the genital ridge (see later); however, differences are also evident. For example, both Sox-3 and Sox-2 are expressed in the olfactory placode, but Sox-2 shows additional expression in other placodal tissue as well as the gut endoderm. Within the

Fig. 6. In situ hybridisation of Sox-3 expression between 8.5 dpc and 11.5 dpc. Sox-3 expression is detected throughout the early developing central nervous system, with stronger expression anteriorly. The signal is weak in the most dorsal part of the neural tube and is much reduced or absent in the floorplate. Sox-3 transcripts are seen in the olfactory placode, but no signal is seen in the developing eye and the otic vesicle. (A) Sagittal section of an 8.5-dpc embryo. (B) Frontal section of a 9.0-dpc embryo at eye level. (C) Sagittal section of a 9.5-dpc embryo showing olfactory placode. (D) Sagittal section of a 9.5-dpc embryo showing fore-, mid- and hindbrain and otic vesicle. (E) Frontal section of a 9.5-dpc embryo at eye level showing expression in forebrain and spinal cord. (F) Frontal section of a 10.5-dpc embryo showing CNS expression. (G) Transverse section through the region of the eye at 11.5 dpc in brightfield (left) and darkfield (right). n, neuroectoderm; s, somites; hr, heart; fg, foregut; op, optic pit; ys, yolk sac; ov, optic vesicle; ol, olfactory placode; mes, mesenchyme; f, forebrain; m, midbrain; h, hindbrain; ot, otic vesicle; sc, spinal cord; pe, lens placodal ectoderm; hg, hindgut; l, lens vesicle; nr, neural retina; oe, olfactory epithelium; d, wall of diencephalon; t, wall of rhombencephalon; rp, Rathke’s pouch; t, trigeminal ganglion.
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there are also fine distinctions between the genes where, for example, Sox-1 exhibits a sharp boundary of expression in the optic stalk and is not expressed at all in the optic vesicle; whereas Sox-3 expression decreases gradually between the forebrain and the distal part of the vesicle. These differences are also found in adult tissues where Sox-3 expression was not found in adult brain, in contrast to Sox-1 and Sox-2, but is detected in testis like Sox-1, but not Sox-2.

The pattern of expression of Sox-3 suggests that the gene functions mainly in the developing CNS. Stevanovic et al. (1993) described human patients carrying deletions of a region of the X chromosome including SOX3. These individuals show mental retardation, which is not apparent in patients deleted for similar regions of the X chromosome that do not include SOX3. Other mental retardation syndromes have also been mapped to the same region of the X chromosome, such as BORJESON-FORSSMAN-LEHMANN syndrome (Turner et al., 1989) and the X-linked centronuclear myotubular myopathy (LEICHTI-GALLATTI et al., 1991). Sox3 is therefore a candidate gene for one or more of these syndromes. The widespread expression of Sox-3 seen throughout the CNS of early mouse embryos might suggest a more severe phenotype than that observed in the human patients deleted for the gene. However, since the domain of expression of Sox-3 appears to be contained within those of both Sox-1 and Sox-2, it is possible that either of these two genes could partially compensate for the loss of Sox-3 function. Partial redundancy clearly explains the restricted phenotype of mice, with mutations in only one member of other gene families showing overlapping expression, such as with EN-1 or EN-2 (MILLEN et al., 1994; WURST et al., 1994). Also, as discussed below, it is possible that SOX-3 competes inefficiently for target sites with the other SOX proteins in some parts of its expression domain, and is therefore critically important only in a subset of this domain.

We have shown that Sox-1, Sox-2 and Sox-3 are expressed in the urogenital ridge at the point of gonadal differentiation, similar to the founder member of the subfamily, Sry. This raises the question of whether any of these genes also play a role in sex determination. Recent work has provided a precedent for this. Sox-9 falls into a distinct subfamily, less related to Sry (WRIGHT et al., 1993). The gene maps to chromosome 11 in mice and 17 in humans (FOSTER et al., 1994; WAGNER et al., 1994; WRIGHT et al., 1995) and has been shown to be expressed in the urogenital ridge throughout gonadal development (WRIGHT et al., 1995 and our own unpublished observations).

At 11.5 dpc, when Sry is thought to act, the indifferent gonad consists of primordial germ cells that are not required for testis determination, and two bipotential somatic cell lineages that give rise to supporting and steroidogenic cell types (BUERER et al., 1993). Sry acts within the supporting cell precursors that give Sertoli cells in the testis and granulosa cells in the ovary. It is therefore important to identify if Sox-1, Sox-2, Sox-3 or indeed Sox-9 are expressed in the same cell type as Sry. It is not yet possible to distinguish supporting and steroidogenic cells at 11.5 dpc (indeed there could be a common precursor cell type), but it is possible to tell whether transcripts are due to germ cells or somatic cells. We have presented evidence that...
SOX-2 is most similar in its DNA-binding activity to SRY when analysed in vitro. However, we have recently shown that SOX-2 is expressed within the germ cells of the genital ridge, thus excluding it from having a role in sex determination (S. Sockanathan, unpublished data). The cell-specific expression of SOX-1 remains unknown; however, the analysis presented here of SOX-3 expression in genital ridges of W/W homozygous mutant mice, which lack germ cells, reveals that SOX-3 is expressed in the somatic cells of the genital ridge, at a level equivalent or greater than Sry (see also Koopman et al., 1990). Also, like Sry, the expression appears to be dynamic with no transcripts detectable by 12.5 dpc (A. Hacker, unpublished data). These findings raise two questions: what is the relationship between SOX-3 and Sry, and could SOX-3 also function in sex determination?

In humans, SOX3 is not required for testis determination. Despite having small testes, patients deleted for the gene are clearly male (Stevanovic et al., 1993). However, the gene could have a role in ovarian determination. One simple hypothesis would be that the action of SOX-3 protein on its gene target(s) is a critical step in the normal genetic pathway leading to differentiation of an ovary, and that in a male, SRY protein competes for the same target site(s). We have shown here that lower concentrations of SRY are required to bind to target DNA sequences compared to SOX-3, so it is easy to imagine that the latter will be displaced by SRY. Alternatively, there may be other proteins or cofactors that interact with SOX-3 protein to modulate its sequence specificity or affinity in vivo, in which case it could act on a different set of target genes.

Such interactions could involve the HMG box itself, or other domains of the protein. In contrast to SRY, the high degree of conservation throughout the entire length of the mouse, human, marsupial and chick SOX-3 proteins, including the poly(alanine) repeat regions, suggests that the N- and C-terminal domains have important functions. It is also possible that two (or more) SOX proteins cooperate or compete at the same cis-acting binding site, giving different types of response of the target gene (see, for example, Jaynes and O’Farrell, 1988; Han et al., 1989).

Sequence comparisons between SOX-3 and Sry or their proteins show homology to be restricted to the HMG box domain. With 82% sequence identity between their HMG boxes, SOX-3 is the SOX protein most closely related to both the human and mouse SRY proteins. For the purpose of establishing evolutionary relationships with Sry, sequence homology outside the HMG box is irrelevant since these non-box regions, as well as regions outside the ORF, show little or no conservation when Sry genes from different species are compared with each other (Tucker and Lundrigan, 1993; Whitfield et al., 1993). Similar findings were presented by Foster and Graves (1994) on comparisons of marsupial and human SRY and SOX-3 sequences.

The many similarities between SOX-3 and Sry, including some aspects of their expression, and the location of SOX-3 on the X chromosome, are consistent with the notion that the two genes are evolutionarily related. Structurally distinct sex chromosomes are a common feature of genetic mechanisms of sex determination. Studies of XY pairs in various organisms led to the hypothesis that X and Y chromosomes were originally homologous, but became genetically distinct during the course of evolution because of specific constraints imparted by the sex-determining mechanism (Ohno, 1967; Charlesworth, 1991; Hodgkin, 1992). The evolution of a sex-determining locus would require the creation of a non-recombining region, which would then accumulate mutations by a process known as Muller’s Ratchet (Muller, 1964; Felsenstein, 1974). With time, this mechanism would lead to the evolution of distinct sex chromosomes. In agreement with this hypothesis, several of the Y-linked genes cloned in human or in mouse (for example ZFY, RPS4Y or Ube1-y1) have been found to have X-linked related sequences (for a review, see Graves and Schmidt, 1992). Furthermore, recent experimental evidence obtained in Drosophila now supports this model by demonstrating direct causality between the presence of a sex-determining gene and the evolution of an heterologous pair of sex chromosomes (Charlesworth, 1992; Rice, 1992, 1994).

Comparison of the relative rates of divergence of Sry and its gene homologues led Griffiths (1991) to suggest that the evolution of Sry as a sex-determining gene is a recent event that occurred subsequent to the radiation of the different Sox gene subfamilies. Our results suggest that Sry evolved from the Sox-1, Sox-2 and Sox-3 subfamilies. Sox-3 is the most obvious candidate for a gene from which Sry evolved, but how could this have happened? It is conceivable that a mutation occurred in Sox-3 such that the mutant gene product interfered with a pre-existing sex-determination mechanism, leading to a dominant male-determining mechanism. There is an experimental example of a similar situation in Drosophila, where mis-expression of the pair-rule gene hairy, which encodes an HLB protein, interferes with the process of sex-determination, despite playing no part in this process during normal development (Parkhurst et al., 1990). By taking over a sex-determining function, the mutant Sox-3 allele may have been placed under evolutionary constraints very different from those it was facing previously. These new constraints may be the reason why the HMG box is the only conserved part of SRY (although adaptive selection for change in the other domains is also feasible). However, at present, it is equally plausible that Sry originated from another HMG-box-containing gene, perhaps even Sox-9, but came to resemble Sox-3 through convergent evolution. Further examination of Sox gene sequences in lower vertebrates, and of Sox-3 and Sry in protostomia (monotremes) and metathelia (marsupials), will be necessary to establish the evolutionary origins of Sry.

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