Evidence for differential and redundant function of the Sox genes Dichaete and SoxN during CNS development in Drosophila

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SUMMARY

Group B Sox-domain proteins encompass a class of conserved DNA-binding proteins expressed from the earliest stages of metazoan CNS development. In all higher organisms studied to date, related Group B Sox proteins are co-expressed in the developing CNS; in vertebrates there are three (Sox1, Sox2 and Sox3) and in Drosophila there are two (SoxNeuro and Dichaete). It has been suggested there may be a degree of functional redundancy in Sox function during CNS development. We describe the CNS phenotype of a null mutation in the SoxNeuro/Dichaete gene and provide the first direct evidence for both redundant and differential Sox function during CNS development in Drosophila. In the lateral neuroectoderm, where SoxNeuro is uniquely expressed, SoxNeuro mutants show a loss or reduction of achaete expression as well as a loss of many correctly specified lateral neuroblasts. By contrast, in the medial neuroectoderm, where the expression of SoxNeuro and Dichaete overlaps, the phenotypes of both single mutants are mild. In accordance with an at least partially redundant function in that region, SoxNeuro/Dichaete double mutant embryos show a severe neural hypoplasia throughout the central nervous system, as well as a dramatic loss of achaete expressing proneural clusters and medially derived neuroblasts. However, the finding that Dichaete and SoxN exhibit opposite effects on achaete expression within the intermediate neuroectoderm demonstrates that each protein also has region-specific unique functions during early CNS development in the Drosophila embryo.

Key words: Drosophila, SoxNeuro, Dichaete, Sox, Neurogenesis, CNS

INTRODUCTION

Some of the earliest molecular events in neural determination have been conserved during metazoan evolution. In most higher eukaryotes, some region of the primitive ectoderm becomes competent to adopt a neural rather than an epidermal fate early in development (Arendt and Nübler-Jung, 1999). In vertebrates, competent neuroectoderm is specified by the antagonistic activity of the neural inducers Chordin and Noggin on the epidermal-promoting factor BMP4. In Drosophila, the Chordin homologue Short gastrulation (Sog) promotes neuroectoderm formation by antagonising the BMP4 homologue Decapentaplegic (Dpp) (De Robertis and Sasi, 1996). After a population of ectodermal cells becomes competent to adopt the neural fate, a specific cell within a group of equivalent cells becomes committed to the neural fate and some of the molecular mechanisms involved in this process are also conserved.

In Drosophila, the expression of proneural genes, primarily the bHLH transcription factors encoded by the Achaete Scute Complex (AS-C) (ac, sc and vsc), render a cluster of ectodermal cells competent to adopt a neural fate. The activity of the Notch-Delta (N-Dl) signalling pathway then results in the elevation of AS-C expression in a single cell within a proneural cluster and the subsequent specification of this cell as a neuroblast (Campos-Ortega, 1993). Neuroblasts (NBs) are the stem cells that give rise to the diversity of neuronal and glial cell types within the Drosophila CNS (Goodman and Doe, 1993). NBs acquire unique identity, and are thus directed down a specific pathway to produce a particular neuronal lineage, by virtue of the location of individual proneural clusters with respect to the AP and DV axes of the embryo (Udolph et al., 1995). Along the AP axis, neuroblasts acquire specific fates through the activity of segment polarity genes (Bhat, 1999). Along the DV axis, at least in the case of those neuroblasts that segregate early in development, identity is controlled by the combined action of the Epidermal growth factor receptor (Egfr), and a set of homeobox-containing transcriptional regulators encoded by the ventral nerve cord defective (vnd), intermediate neuroblasts defective (ind) and muscle segment homeobox (msh) genes (Skeath, 1999). In this way, the combined activity of an orthogonal array of gene expression along two embryonic axes divides the neuroectoderm into a Cartesian grid system that can specify a set of different neural identities (Skeath, 1999). In mammals, genes encoding bHLH transcription factors and members of the N-Dl signalling
pathway are involved in consolidating neural identity (Lewis, 1996; Lee, 1997; Chitnis et al., 1995). Similarly, the system that specifies neural identity along the DV axis in vertebrates involves homologues of the Drosophila vnd, ind and msh genes that, as with the fly, are expressed in restricted DV domains during neural specification (Davidson, 1995; D’Alessio and Frasch, 1996; Weiss et al., 1998). It is not yet clear precisely how the acquisition of neural competence and the subsequent specification of defined neural fates are molecularly linked and whether there are conserved regulatory pathways that are involved in this process. Members of the Sox family of transcription factors represent one potential set of conserved pan-neural markers, that could regulate early neural specification events.

The Sox gene encompasses a group of transcriptional regulators, related by an HMG1-type DNA-binding domain, to the mammalian testis-determining factor SRY (Gubbay et al., 1990; Pevny and Lovell-Badge, 1997). The Sox family is restricted to metazoans and within the animal kingdom; the family is large and diverse. Many members of the Sox gene family have dynamic tissue-specific expression patterns during embryogenesis, suggesting that they may play a variety of roles during development (Wenger, 1999). On the basis of sequence similarity, both in the DNA-binding domain and in other, group-specific conserved motifs, Sox proteins have been divided into at least seven subgroups (A-G) (Bowles et al., 2000). Group B Sox are most closely related to SRY, sharing over 85% sequence identity between their DNA-binding domains and recognising virtually identical DNA sequences (Harley et al., 1994; Collignon, 1996). In flies, frogs, chicks and mammals, group B Sox genes are expressed in the neuroectoderm from the earliest stages of neurogenesis (Collignon et al., 1996; Uwanogho et al., 1995; Rex et al., 1997; Russell et al., 1996; Nambu and Nambu, 1996; Wood and Episkopou, 1999; Cremazy et al., 2000). In these animals, related group B genes are co-expressed in the neuroectoderm, leading to the idea that they may function redundantly or influence each other’s activity. In mice and chicks, three group B genes (Sox1, Sox2 and Sox3) are widely co-expressed in the neuroectoderm and neural tube; in Drosophila, only two group B genes, Dichaete and SoxNeuro (SoxN), are expressed early in the CNS.

Although well characterised in terms of expression, in vivo functional studies of Sox genes in early CNS development are less well established. In the mouse, Sox1 null mutants survive until adulthood, where some role in CNS function is suggested by a spontaneous seizure phenotype. However, the fact that homozygous mutants survive without significant defects in CNS development suggests that any major role in early CNS development is dispensable (Nishiguchi et al., 1998). In mice, Sox2 mutants are reported to die prior to implantation (Collignon et al., 1996) therefore the role of Sox2 in CNS development has not been described. Sox3 mutations have not been reported. Direct evidence for the involvement of Sox genes in CNS development comes from in vitro stem cell studies, where it was shown that the Sox1 gene can induce neural fate in competent ectodermal cells (Pevny et al., 1998). Furthermore, a Sox2-βGeo insertion construct has been used to select neural precursors from stem cell populations, suggesting that Sox2 is a marker for early neural fate (Li et al., 1998). In Xenopus, the SoxD gene is first expressed in the prospective neuroectoderm and then later throughout the neural plate. Injection of SoxD mRNA into early embryos can induce ectopic neural tissue and injection of a dominant negative form of SoxD leads to loss of neural tissue, establishing a role for this Sox gene in Xenopus neuralisation (Mizuseki et al., 1998a). Additionally, the Xenopus Sox2 gene, which acts downstream of SoxD, appears to be required for establishing neural competence in neuroectodermal cells (Mizuseki et al., 1998b).

Mutations in the Drosophila gene Dichaete have specific defects in the specification or differentiation of glial lineages in the midline of the CNS, a structure in which Dichaete is a uniquely expressed Sox gene (Sanchez-Soriano and Russell, 1998; Ma et al., 2000). Outside of the midline, in the ventral neuroectoderm where Dichaete and SoxN are co-expressed (Cremazy et al., 2000), neural phenotypes are relatively weak (N. Sanchez-Soriano, PhD thesis, University of Cambridge, 1999). Recently, Zhao and Skeath (Zhao and Skeath, 2002) have shown that Dichaete is involved in the specification of cell fate in the neuroectoderm and in NB formation via interactions with the homeodomain-encoding genes vnd and ind. Mutations in the other Drosophila group B gene, SoxN, have not previously been described. We report the identification of a null mutation in SoxN and show that, as is reported for Dichaete, it is involved in early events in neural cell fate specification. By eliminating Dichaete and SoxN function simultaneously, we present the first description of the effects of eliminating all group B Sox function in the early CNS of an animal. The severe neural hypoplasia observed in the double mutants together with the reduction of ac expression suggests that both genes act on the level of the neuroectoderm. In addition, loss of specific NB lineages in SoxN mutant embryos suggests that SoxN also has a later role in NB formation. Our observations on ac regulation support the idea that group B Sox genes can act redundantly but also antagonistically in early specification events.

MATERIALS AND METHODS

Drosophila stocks

Drosophila stocks were maintained on standard yeasted cornmealagar food at 25°C; the wild-type stock used was Oregon R. Mutant nomenclature follows FlyBase conventions (FlyBase, 2002). The following stocks were used: Df(3L)225-5 (Wustmann et al., 1989), SoxN(fl6-3) (this study), balanced using Cy(wg–lacZ), TM3b–lacZ, or TM6B-AbdA-lacZ (FlyBase, 2002); GAL4 line KrGal4 (FBti0002365) (Castelli-Gair et al., 1994); UAS line UASSoxN (this study). Mutant embryos were identified by staining with anti-β-Galactosidase antibody and fluorescently conjugated secondary antibody to detect the balanced chromosomes.

Molecular biology

The coding region for SoxN (sequence Accession Number, AJ252124) was amplified by PCR from two differently balanced heterozygous stocks and sequenced on both strands using an ABI Prism kit and automatic sequencer at the Department of Genetics sequencing facility. UASSoxNeuro was generated by inserting bases 1 to 1966 of the SoxNeuro cDNA (which encompasses the entire coding region) into the EcoRI and NotI sites of pUAST (Brand and Perrimon, 1993). The construct was injected into y w embryos using standard techniques (Karess, 1985).
Antibody staining
Embryo staging was according to Campos-Ortega and Hartenstein (Campos-Ortega and Hartenstein, 1985). Antibody staining was carried out essentially as described (Patel, 1994). Primary antibodies were detected with AP-conjugated secondaries (Vector labs), biotin-conjugated secondaries (Vector labs) and the ABC elite kit (Vectorstain) or with fluorescent secondaries (Jackson Immunoresearch). The following primary antibodies were used at the indicated dilutions: rabbit anti-Dichaete 1/2000 (Sanchez-Soriano and Russell, 1998), rabbit anti-β-Galactosidase 1/2000 (Cappel), mouse anti-Achaete 1/3, mouse anti-BP102 1/100, mouse anti-Fasciclin II 1D4 1/4, mouse anti-Engrailed 4D9 1/10, mouse anti-Eve 3C10 (Developmental Studies Hybridoma Bank, Iowa), rabbit anti-Hunchback 1/1000 (gift of M. Gonzalez-Gaitan), rat anti-ems 1/1000 (U. Walldorf) and rabbit anti-Eagle 1/500 (Dittrich et al., 1997).

RESULTS
Identification of a SoxN mutation
We screened a large collection of chemically induced Drosophila mutations, isolated on the basis of abnormal CNS phenotypes (Hummel et al., 1999), for lines missing specific neuroblast lineages. One line (U6-35) was identified in which virtually all thoracic and abdominal empty spiracles (ems)-expressing neurones and glia were missing from the CNS of homozygous embryos (e.g. NB lineages 2-4, 3-3, 7-3 and 6-4 missing in over 99% of hemisegments, Fig. 1A,B; NB lineages 3-3, 3-5 and 4-4 missing in over 95% of hemisegments, Fig. 1C,D). We localised the mutation genetically by recombination and deficiency mapping and found that it was uncovered by Df(2L)N22-5, a deletion encompassing the 29F region (Lindsley and Zimm, 1992). We had previously recovered a Sox-domain containing gene in this region in the course of a molecular screen for new Drosophila Sox genes that was subsequently found to be identical to SoxNeuro (SoxN) (Cremazy et al., 2000). As SoxN is known to be expressed early in CNS development, and the related gene Dichaete had previously been shown to have specific CNS phenotypes, we considered SoxN to be a candidate for the gene mutated in the U6-35 line. We sequenced the SoxN gene from the U6-35 stock and found that it carried a C-T transition that changes a glutamine at position 133 of the protein to a stop codon. This premature stop occurs before the DNA-binding domain and is expected to eliminate the function of the gene. In support of this, we find that the phenotype of U6-35 homozygotes is identical to that observed in U6-35/Df(2L)N22-5 embryos (data not shown). Therefore, U6-35 represents a null mutation in the SoxN gene and shall be hereafter referred to as SoxNU6–35.

At a gross level, SoxNU6–35 mutant embryos show a severely disrupted CNS. When examined with the global axonal marker BP102 and the more specific marker FasII we observe a substantial reduction in the longitudinal axon tracts (Fig. 1E,H). In 60% of the mutant hemisegments scored there is a complete loss of longitudinal tracts judged by BP102 staining (n=726). In addition, the anterior and posterior commissures are also affected; in 52% of mutant segments the commissures fail to separate and are sometimes absent (2%). With FasII staining we observe a disruption of the regular axonal fasciculation pattern and many cases of axons inappropriately crossing the midline. There appears to be no difference in the phenotype along the anteroposterior axis. The PNS shows no major defects when examined with the PNS-specific 22C10 antibody (data not shown). Thus the defects in SoxNU6–35 suggest a failure in the morphogenesis or differentiation of the CNS. As expected, as SoxN expression is initiated after cellularisation (Cremazy et al., 2000), we observe no segmentation defects in SoxNU6–35 (data not shown). In addition to these phenotypes, we observe defects in spacing in 68% of SoxNU6–35 mutant embryos; within the CNS the spacing between two segments in the middle of the embryo, most often A3 and A4, is greatly increased while spacing in the neighbouring segments is reduced (Fig. 2E); in severe cases there are gaps in the neuroectoderm, however, no segments are lost. As we never observe these defects before stage 12, we believe this phenotype is a result of mechanical defects during germband retraction; in support of this, we observe a failure to complete germband retraction in a small number of mutant embryos (less than 5%).

Loss of specific Neuroblast lineages in SoxN
In order to examine the defects in the developing CNS associated with SoxNU6–35 in greater detail, we stained mutant embryos with markers for specific NBs and/or their progeny (see Materials and Methods). These data are presented in Table 1 and Figs 1, 2 and can be summarised as follows: using Hunchback (Hb) and Even skipped (Eve) (Fig. 2A,D), along with the Eg and Ems staining described above, we observe a striking asymmetry in NB loss in SoxNU6–35 mutants. The use of Hb as a marker for all NBs delaminating in SI shows that medial column NBs are less affected (between 4% (MP2) and 38% (NB5-2) missing) than those that form in the intermediate (52% of NB5-3 missing) and lateral columns (between 23% (NB7-4) and 69% (NB 5-6) missing; Fig. 2A,B). This observation is supported by using Eve as a marker for progeny of certain NBs. The CQ neurones (NB 7-1) and aCC/pCC (NB 1-1), which are progeny of NBs that delamate in the medial column during the SI wave, are relatively unaffected (less than 4% missing). By contrast, the RP2 neurone, which is a progeny of NB 4-2, an intermediate column SII NB, and the cells of the Eve lateral cluster (ELC), which are progeny of the laterally delaminating SIV NB 3-3, are strongly affected (96% and 100% missing, respectively; n=352; Fig. 2C,D). Additionally, the antibody staining against Eg and Ems show that NBs delaminating in the intermediate or lateral columns in SII-SV are often missing (e.g. 6-4, 7-3, 2-4 and 3-3, greater than 90% loss). Taken together, these data suggest that SoxN is required for the correct specification and/or formation of NBs in both the intermediate and lateral columns. It appears that there is much less of a requirement for SoxN in the medial column, at least for early delaminating NBs. As SoxN and Dichaete expression overlaps in the medial neuroectoderm and Dichaete mutants also have little effect on early medial NB lineages (Table 1) (Zhao and Skeath, 2002), it is possible that the proteins are able to functionally compensate in this part of the developing CNS. However, the fact that later-born intermediate and lateral NBs are more affected than the S1 NBs delaminating from these regions additionally suggests a stronger requirement for SoxN function in these post S1 NBs and/or their progeny.
**Table 1. Neuroblast loss in Sox mutant embryos**

<table>
<thead>
<tr>
<th>Wave</th>
<th>Lineage</th>
<th>Column</th>
<th>Marker</th>
<th>SoxN\textsuperscript{U6-35}</th>
<th>D\textsuperscript{72}</th>
<th>SoxN\textsuperscript{U6-35}; D\textsuperscript{72}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% absence (number of hemisegments)</td>
<td></td>
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<tr>
<td>S1</td>
<td>1-1 Medial</td>
<td></td>
<td>h(b)</td>
<td>12 (172)</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>eve (aCC/pCC)</td>
<td>0 (352)</td>
<td>0 (500)\textsuperscript{*}</td>
<td>15 (220)\textsuperscript{†}</td>
</tr>
<tr>
<td>MP2</td>
<td>Medial</td>
<td></td>
<td>ac</td>
<td>4 (108)</td>
<td>0 (132)\textsuperscript{‡}</td>
<td>54 (176)\textsuperscript{§}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>h(b)</td>
<td>5 (172)</td>
<td>-</td>
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<tr>
<td></td>
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<td>38 (172)</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>h(b)</td>
<td>19 (108)</td>
<td>0 (132)\textsuperscript{§}</td>
<td>54 (176)\textsuperscript{§}</td>
</tr>
<tr>
<td></td>
<td>7-1 Medial</td>
<td></td>
<td></td>
<td>4 (172)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>eve (CQ)</td>
<td>3 (352)</td>
<td>0 (500)</td>
<td>15 (220)\textsuperscript{†}</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
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<td>52 (172)</td>
<td>2 (46)</td>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>3-5 Lateral</td>
<td></td>
<td>ac</td>
<td>64 (108)</td>
<td>0 (132)\textsuperscript{§}</td>
<td>80 (176)\textsuperscript{§}</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>h(b)</td>
<td>56 (172)</td>
<td>-</td>
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</tr>
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<td></td>
<td>5-6 Lateral</td>
<td></td>
<td>h(b)</td>
<td>69 (172)</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>7-4 Lateral</td>
<td></td>
<td>ac</td>
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<td>0 (132)\textsuperscript{§}</td>
<td>80 (176)\textsuperscript{§}</td>
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<td></td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2</td>
<td>4-2 Intermediate</td>
<td></td>
<td>eve (RP2)</td>
<td>96 (352)</td>
<td>3 (500)\textsuperscript{*}</td>
<td>94 (176)</td>
</tr>
<tr>
<td>S3</td>
<td>6-4 Lateral</td>
<td></td>
<td>eg</td>
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</tr>
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<td>eg</td>
<td>100 (304)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3-3 Intermediate/lateral</td>
<td></td>
<td>eve (ELC)</td>
<td>100 (352)</td>
<td>0 (500)\textsuperscript{*}</td>
<td>99 (176)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>eg</td>
<td>100 (304)</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>4-4 Intermediate/lateral</td>
<td></td>
<td>ems</td>
<td>96 (308)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ems</td>
<td>96 (308)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S5</td>
<td>7-3 Lateral</td>
<td></td>
<td>eg</td>
<td>100 (304)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ey</td>
<td>99 (418)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*In addition to the occasional loss of RP2 in D\textsuperscript{72}, we observe a duplication of RP2 and an expansion of ELC in 8% and 1% of hemisegments, respectively, as well as a duplication of cells at the position of the aCC/pCC neurons in 16% of hemisegments.

†Owing to the severe defects found in the double mutants resulting from the SoxN\textsuperscript{U6-35} spacing defects and the D\textsuperscript{72} segmentation phenotype, we were unable to score the more severely affected abdominal segments in many embryos; hence, the figures here are rather conservative.

‡In D\textsuperscript{72} mutant embryos, we frequently observed an expansion of ac expression into the intermediate column.

§We were unable to unambiguously identify rows 3 and 7 in double mutant embryos. We have therefore only scored the presence or absence of ac in each column.

**Fig. 1.** Nervous system defects in SoxNeuro mutants. Flat preparations (A-E,G,H) or whole-mount (F) of stage 16 (A,B,E-H) and stage 11 (C,D) wild-type (A,C,E,G) and SoxNeuro U6–35 (B,D,F,H) embryos stained with anti-Eagle (blue) and anti-Engrailed (brown) (A,B), anti-Eagle (blue) and anti-Ems (brown) (C,D), monoclonal antibody mAbBP102 (E,F) and anti-Fasciclin II (G,H). (A,B) In wild-type embryos, Eagle staining is observed in progeny of the NB2-4, NB3-3, NB7-3 and thoracic NB6-4 lineages. In SoxNeuro\textsuperscript{U6-35} embryos, no Eagle staining is seen in these lineages. Eagle expression is still seen in cells in the gnathal midline. (C,D) Ems-expressing progeny of the NB3-5 and NB4-4 and NB3-3 lineages are absent in more than 96% of hemisegments in SoxNeuro\textsuperscript{U6-35} embryos. Note that in embryos in which one of these cells is observed, we are unable to unambiguously identify which of the three neuroblasts is present. Tracheal Ems expression is still present. (E,F) In SoxNeuro\textsuperscript{U6-35} embryos, longitudinal BP102 staining is absent in 60% of hemisegments (arrowheads in F); in addition commissures fail to separate correctly in 52% of hemisegments. (G,H) In SoxNeuro\textsuperscript{U6-35} embryos, the regular axonal fasciculation pattern is disrupted and many axons cross the midline inappropriately (arrow).
Sox gene function in the Drosophila CNS

Expression of SoxN in the developing CNS rescues U6-35 phenotypes

To unambiguously demonstrate that the phenotype of U6-35 mutant embryos is due to the mutation in SoxN, we tried to rescue SoxN_U6-35 phenotypes by driving UASSoxN expression in the developing CNS with Kr-Gal4 (Castelli-Gair et al., 1994). The Kr-Gal4 line expresses Gal4 at high levels in the neuroectoderm within the central domain of the embryo from stage 9 onwards (data not shown). In SoxN_U6-35/Kr-Gal4; UASSoxN embryos, we observe a substantial rescue of RP2 motorneurons and ELC cells (progeny of NB4-2 and NB3-3, respectively; Fig. 2F). Absence of the RP2 neurone is now observed in only 33% of hemisegments, while the ELC cells are absent in 67% of hemisegments compared with 96% and 100% respectively in embryos without UASSoxN. These data indicate that the CNS phenotype of U6-35 embryos results from a specific loss of SoxNeuro.

SoxN in the neuroectoderm

The differential loss of NBs and their progeny in the DV axis may result from the failure of neuroectodermal cells to be specified to a neural fate. As SoxN is expressed throughout the neuroectoderm prior to neuroblast delamination and Dichaete is reported to have effects on proneural gene expression (Zhao and Skeath, 2002), we examined proneural gene expression in SoxN_U6-35 mutants. ac is a marker for certain medial and lateral proneural clusters but is not normally expressed in the intermediate column. We observe a striking reduction in the number of lateral column proneural clusters (n=108). The loss of lateral column ac expression suggests that SoxN functions early in the neuroectoderm to specify proneural clusters correctly. In addition to this, there is an overall reduction in ac expression levels in the medial proneural clusters compared with the heterozygous sibling embryos stained in the same reaction (compare Fig. 3E with 3F). This implies that SoxN is required more generally in the neuroectoderm to establish the appropriate level of ac expression. We also examined the expression of the related proneural gene l’sc in the neuroectoderm prior to neuroblast delamination and, in contrast to the results with ac, we see no appreciable effect (data not shown). Thus it appears that SoxN is selectively required in the neuroectoderm for the regulation of some proneural gene expression. The loss of ac expression in lateral proneural clusters partly explains why we see such a dramatic loss of lateral NBs in SoxN_U6-35 mutants. However, all lateral NBs are strongly affected in SoxN_U6-35 embryos, including those which express l’sc and not ac. Hence, the normal expression of l’sc in SoxN_U6-35 mutant embryos argues against a simple linear pathway in which SoxN acts only upstream of proneural genes, and suggests a mechanism in which SoxN functions both upstream and in parallel to the proneural genes to promote neuroblast formation. This parallel function of SoxN is additionally supported by the observation that the severe hypoplasia of SoxN mutant embryos resembles the phenotype in As-C mutants, and is more severe than can be accounted for by the effect on ac expression, as loss of ac alone does not produce severe phenotypes (Jimenez and Campos-Ortega, 1987).

Zhao and Skeath (Zhao and Skeath, 2002) have reported a derepression of ac expression in the intermediate column in Dichaete mutants and we confirm those observations.
Therefore, whereas both SoxN and Dichaete mutants show loss of neuroblasts, the effect in the neuroectoderm differs: SoxN mutants display loss of ac expression but Dichaete mutants show some ac derepression.

**Evidence for functional redundancy between group B Sox proteins**

SoxN and Dichaete are both expressed early in the neuroectoderm. Dichaete is restricted to the ventral region, extending from the midline to the position of the intermediate column (Zhao and Skeath, 2002), and SoxN is excluded from the midline and extends more dorsally to encompass the entire neuroectoderm (Cremazy et al., 2000). Dichaete mutants show strong phenotypes in the midline, where it is uniquely expressed (Sanchez-Soriano and Russell, 1998), and SoxN mutants exhibit strong phenotypes in the lateral half of the CNS where it is uniquely expressed. In Dichaete mutants, SI medial NBs are not affected (Table 1) (Zhao and Skeath, 2002) but there is a loss of later delaminating SII and SIII NBs from both medial and intermediate columns. SoxN and Dichaete overlap in the medial and intermediate neuroectodermal columns and in the medial column, SoxN phenotypes are weaker than those observed in the lateral columns. These data are consistent with the idea that the genes may be able to compensate functionally in the medial column neuroectoderm. To examine the consequences of removing group B Sox function from the early CNS, we constructed a double mutant combination, using null alleles for both Dichaete and SoxN. We examined the overall structure of the CNS as well as markers for specific NBs and/or progeny in the double mutant embryos.

Staining the double mutants with BP102 reveals a severe disruption in the organisation and structure of the CNS (Fig. 4A,B). We observe a complete loss of longitudinal axons in many segments with frequent gaps in the neuropil. Commissures are often absent, and those that do form are virtually never separated. The phenotype of the double mutants is far more severe than observed with either single mutant and supports the idea that the genes can act redundantly or in related pathways. If this is the case then we expect to see an enhanced effect on medial NBs and their progeny when we remove both SoxN and Dichaete function compared with each of the single mutants, as this is the region in which they are extensively co-expressed. In line with this expectation we observe that in the SI medial lineages of NB1-1 and NB7-1, identified by eve expression, there is a rather severe reduction in the number of aCC/pCC and CQ cells in double mutants (15% loss; however, due to difficulties in reliably scoring the severely affected abdominal segments of the double mutant embryos, we believe this figure to be a conservative measure; Fig. 4C,D) compared with each of the single mutants. Note that these lineages are virtually unaffected in either of the single mutants. Additionally, in the intermediate column, the Hb expressing neuroblast 5-3 is absent at a higher frequency in double mutant embryos than in SoxN or D mutants (79% compared with 52% and 2%, respectively, Fig. 2A,B, Fig. 4H,I), indicating that Dichaete is to some extent able to compensate for a loss of SoxNeuro within this lineage. Although it is impossible to determine accurately the identity of the remaining Hb expressing SI NBs in the double mutants, we have counted the total number of cells in thoracic segments and find that, in SoxNeuro homozygotes, 30% of Hb expressing NBs are missing, in Dichaete mutants less than 1% are missing, whereas 56% are missing in the double mutants. Taken together, we conclude that in the cases of overall CNS structure as well as medial and intermediate column SI NBs, we see evidence for functional redundancy between related Group B Sox genes.

As described above, the situation in the neuroectoderm appears to be different. In Dichaete mutants the proneural gene ac is partially derepressed in intermediate column neuroectoderm, there are no major effects on the medial column (Zhao and Skeath, 2002). In SoxNeuro we see a loss of lateral column ac expression as well as an overall...
reduction in ac levels. When we examine the double mutants for ac expression, we observe a synergistic and an additive effect (Fig. 4E,F). As with SoxN, the overall level of ac expression is lower compared with heterozygous siblings and there is a marked loss of lateral column ac expression. In addition, the double mutants display the Dichaete phenotype as we see ectopic intermediate column expression in some rows (6%). However, in 21% of segments we do not detect any ac expression, suggesting that both Sox genes are principally able to positively regulate ac expression. Taken together, we conclude that in the neuroectoderm, the elimination of group B Sox expression results in an early failure in neural specification and subsequent loss of neural progenitors.

Both SoxN and Dichaete are expressed early in the neuroectoderm, SoxN expression being initiated slightly before that of Dichaete. It is therefore possible that SoxN regulates the expression of Dichaete and we examined this possibility by staining SoxNmutant embryos for Dichaete (Fig. 5). We observe a rather unexpected phenotype; in around half of the mutant embryos, Dichaete levels are apparently normal (Fig. 5A,B).

However, in the remaining half we noticed that Dichaete levels were reduced, but only in the anterior half of the neuroectoderm, the posterior appeared to be normal (Fig. 5C,D). We know that this is not due to a staining artefact because in the affected embryos Dichaete is expressed normally in the midline all along the AP axis. Thus, it appears that SoxN does have an effect on Dichaete expression, but that this effect is variable and restricted along the AP axis. In any case we cannot explain the SoxN phenotypes by a loss of Dichaete expression in the neuroectoderm because we would expect to see ectopic expression of ac in SoxNmutants (arrowheads). In I, we are unable to unambiguously identify these cells as NB 5-3.

Fig. 5. Dichaete expression is variably reduced in SoxNmutant embryos. Whole-mount ventral (A,C) and dorsal (B,D) views of stage 9 wild-type (A,B) and SoxNmutant (C,D) embryos stained with anti-Dichaete. In half of mutant embryos, Dichaete expression is reduced in the anterior region of the neuroectoderm but appears normal posteriorly. Note that expression of D in the midline and brain is unaffected.
DISCUSSION

In this paper, we provide the first report of completely removing Group B Sox gene function from the developing CNS of an animal. As we describe above, in many metazoans the developing CNS is marked by the expression of related Sox genes and the idea that the related genes may be functionally redundant has been widely discussed (see Wenger, 1999). Our results support the idea that related group B genes show a degree of functional redundancy because, in double mutants, severe neural phenotypes are observed in regions where the genes are co-expressed and much weaker phenotypes displayed by each of the single mutants.

Redundant Sox function in the CNS

We have presented a number of observations that support the view that group B Sox genes, Dichaete and SoxNeuro, are to some extent functionally redundant in the developing CNS of Drosophila. While we observe strong phenotypes in Dichaete and SoxN single mutant in regions where they are uniquely expressed, Dichaete in the midline and SoxN in the lateral CNS, we see much weaker phenotypes where the expression domains overlap, especially in the medial neuroectoderm. In double mutants, we find strong phenotypes, apparent at a gross level in the overall structure of the CNS, and also with molecular markers for the neuroectoderm or specific NBs and their progeny. Taken together, these observations support the view that when one group B Sox gene is lost the other is able to functionally substitute in a part of the region where they are co-expressed. This is not entirely unexpected as both genes share a virtually identical DNA-binding domain and would be expected to recognise the same DNA sequence. It is interesting to note that, outside of the DNA-binding domains, there is little sequence similarity between SoxN and Dichaete, suggesting that redundant function is mediated solely through DNA binding.

Differential functions of SoxN and Dichaete

Zhao and Skeath (Zhao and Skeath, 2002) found that ac expression was derepressed in the intermediate column neuroectoderm of Dichaete mutants; this is not the case with SoxN. In the double mutants, we observe the SoxN loss of ac expression in lateral and medial neuroectoderm but a low frequency of ectopic intermediate column ac expression, presumably as a consequence of the loss of Dichaete. This suggests that, although the two Sox proteins may be functionally equivalent in the medial neuroectoderm they show antagonistic functions within the intermediate neuroectodermal region. Within this area, Dichaete functions as a negative regulator of the ac gene, whereas SoxN is a positive regulator of ac, as judged by the reduction of ectopic ac expression seen in the SoxN/Dichaete double mutants. Similarly, in the case of lateral NB formation we observe differences between SoxN and Dichaete. SoxN is required for both early and late forming NBs in the intermediate and lateral columns. Dichaete, however, appears to be required for the formation of some late delaminating NBs in the medial and intermediate columns (e.g. NB6-1, NB4-1 and NB4-2) (Zhao and Skeath, 2002). In some situations where SoxN and Dichaete expression domains apparently overlap, for example, in the intermediate column, we observe a severe loss of the SI intermediate column NB 5-3 in SoxN U6–35, as judged by loss of Hb expression, a phenotype that is enhanced in SoxNU6–35, D f72. This suggests that, at least in the case of this early forming NB, Dichaete can only partially compensate for a loss of SoxNeuro in NBs derived from the intermediate column. This may be explained in part by the observation that Dichaete is rapidly downregulated in early NBs as they delaminate (Zhao and Skeath, 2002).

We presume that the differences between the two proteins may well reflect interactions between each Sox protein and a different partner mediated by protein domains outside the highly conserved DNA-binding domain. In accordance with this, Zhao and Skeath suggest that, in the neuroectoderm, Dichaete interacts with the product of the ind gene to mediate repression of ac. As ind is specifically expressed within the intermediate neuroectoderm, it is tempting to speculate that this protein might interact specifically with Dichaete to repress ac while it does not interact with SoxN in the same way if indeed at all. However, Zhao and Skeath (Zhao and Skeath, 2002) provide evidence for interactions between Dichaete and both ind and vnd in the context of NB specification. As our data suggest that SoxN and Dichaete function is at least redundant within the vnd-positive medial row, it is very likely that Vnd interacts with SoxN as well as Dichaete.

The interaction of HMG-domain proteins and homeodomain containing proteins has been recognised for some time, and appears to be a general feature of HMG1-type DNA-binding domains (Kamachi et al., 2000; Dailey and Basilico, 2001). More specific interactions between Sox-domain proteins and homeodomain genes, have been demonstrated in mouse, where Sox2 interacts with Oct4 (Yuan et al., 1995), and in flies, where Dichaete interacts with Vvl (Sanchez-Soriano and Russell, 1998; Ma et al., 2000). Therefore we consider it likely that SoxN can interact with the DV patterning protein Vnd, and also with Ind and Msh to regulate expression in the AS-C; the observation that vnd, ind and msh transcript levels are unaffected in SoxN U6–35 suggests that SoxN is likely to act in parallel with rather than upstream of these DV patterning genes (data not shown). Chu et al. (Chu et al., 1998) have shown that the loss of ac in vnd mutant embryos is insufficient to explain the loss of SI NBs as restoration of ac expression in this background does not rescue the phenotype, which itself is more severe than would be expected if the sole action of vnd was through AS-C; as in SoxNU6–35, expression of l'sc is unaffected in lineages which fail to delaminate. The authors suggest an additional proneural activity regulated by vnd – we consider it likely that the role of SoxN parallel to AS-C in the neuroectoderm is to act alongside the DV patterning genes in controlling this activity. However, given that we see an overall reduction in ac expression throughout the neuroectoderm in SoxNU6–35 it is possible that SoxN plays a more general role in regulating ac, perhaps acting as a factor for modulating chromatin structure.

Potential Sox target genes are complex

One feature that stands out in the studies of Sox activity in Drosophila is the structure of the target genes that have been identified to date. During embryonic segmentation, prior to the establishment of neuroectoderm, Dichaete is required for the correct expression of the primary pair-rule genes even skipped, hairy and runt (Nambu and Nambu, 1996; Russell et al., 1996). In the midline, slit is a direct target (Sanchez-Soriano and Russell, 1998; Ma et al., 2000), in the neuroectoderm ac is a likely target
and in the hindgut hedgehog and decapentaplegic (Sanchez-Soriano and Russell, 2000). Each of these genes is characterised by having complex structure and complex regulation. This is most apparent for the pair-rule genes, whose regulatory sequences extend over many kilobases. We notice that where Dichaete is the only Sox gene involved in the regulation of these genes (e.g. at cellular blastoderm) we observe a variable phenotype in Dichaete mutants, both at the gross morphological level and at the molecular level. We have previously suggested that this reflects an architectural role for Sox proteins in gene regulation, as Sox-domain proteins bind DNA in the minor groove and are capable of modulating chromatin structure (Russell et al., 1996). We note with interest that the regulatory sequences that control the expression of ac are also extremely complex (Campuzano et al., 1985) and the ac expression phenotype we observe in SoxN-Dichaete mutant embryos is also variable. This suggests that at least one of the functions of Sox proteins may be modulating chromatin structure at complex regulatory regions, allowing the integration of many different regulatory inputs. In this view, the loss of Sox function would destabilise gene expression but would not be expected to completely eliminate it.

**Conservation of Sox function**

As we describe in the introduction, many of the molecular mechanisms that control early events in CNS development have been conserved during evolution. We also describe how the expression of group B Sox genes has similarly been conserved in the early neuroectoderm. Is it possible that Sox genes perform similar roles in neural specification in mammals and flies? The expression of Sox1 in the mouse suggests that it is expressed in the neuroectoderm as an early response to neural inducing signals and may function to direct cells toward a neural fate (Pevny et al., 1998). This is analogous to the situation we observe in Drosophila, where SoxN is reported to be regulated by the DV signalling system (Cremazy et al., 1999) and regulates ac, a neural fate determining gene. We have previously shown that the role of Sox proteins in early CNS development may indeed be conserved, and it will be of considerable interest to ascertain whether or not mouse group B Sox genes can regulate proneural targets such as the mouse AS-C homologues.

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