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**goosecoid** and **HNF-3β** genetically interact to regulate neural tube patterning during mouse embryogenesis

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SUMMARY

The homeobox gene **goosecoid** (**gsc**) and the winged-helix gene **Hepatic Nuclear Factor-3β** (**HNF-3β**) are co-expressed in all three germ layers in the anterior primitive streak and at the rostral end of mouse embryos during gastrulation. In this paper, we have tested the possibility of functional synergism or redundancy between these two genes during embryogenesis by generating double-mutant mice for **gsc** and **HNF-3β**. Double-mutant embryos of genotype **gsc**/−;**HNF-3β**/− show a new phenotype as early as embryonic days 8.75. Loss of **Sonic hedgehog** (**Shh**) and **HNF-3β** expression was observed in the notochord and ventral neural tube of these embryos. These results indicate that **gsc** and **HNF-3β** interact to regulate **Shh** expression and consequently dorsal-ventral patterning in the neural tube. In the forebrain of the mutant embryos, severe growth defects and absence of optic vesicles could involve loss of expression of **fibroblast growth factor-8**, in addition to **Shh**. Our results also suggest that interaction between **gsc** and **HNF-3β** regulates other signalling molecules required for proper development of the foregut, branchial arches and heart.

Key words: **Sonic hedgehog**, Fgf-8, neural tube, patterning, forebrain, foregut, **HNF-3β**, **goosecoid**

INTRODUCTION

Early regionalization of the neural tube is characterized by the anterior-posterior (A-P) division of the neural tube into transverse domains, namely forebrain, midbrain, hindbrain and spinal cord and the further subdivision of these regions into dorsal-ventral (D-V) longitudinal domains. Along the A-P axis, this process is revealed in the cephalic neural plate of mouse embryos as early as embryonic day 7.75 (E7.75), by the expression of regulatory genes in distinct domains. For example, the transcription factors Otx2 (Simeone et al., 1993; Ang et al., 1994a), Six3 (Oliver et al., 1995), Fkh2 (Kaestner et al., 1995) and Pax2 (Rowitch et al., 1995) are expressed at the early headfold stage in subdivisions of the presumptive forebrain and midbrain regions. Within the forebrain, further regionalization along the A-P and D-V axes becomes apparent at early somitic stage, with the expression of later markers such as BF-1 (Tao and Lai., 1992) and Emx2 (Simeone et al., 1992) which are restricted to the anterior and dorsal part of the forebrain, respectively. Later on, other genes are activated in smaller territories within the telencephalon and diencephalon, further subdividing the forebrain into more transverse and longitudinal domains (reviewed in Rubenstein et al., 1994; Shimamura et al., 1995).

Classical embryological experiments have demonstrated that regionalization of the neural tube along the A-P and D-V axes is regulated by a specialized group of cells called the organizer (reviewed in Kelly and Melton, 1995). Organizer cells have been identified in many vertebrate species, and correspond to the dorsal blastopore lip in *Xenopus*, the Hensen’s node in chick, the embryonic shield in zebrafish and the node in mouse. Recent studies have focused on understanding the properties of the organizer at the molecular level. Two classes of genes have been cloned and are implicated in patterning of the A-P axis of the neural tube in *Xenopus* and mouse (reviewed in De Robertis, 1994). One class, encoding nuclear transcription factors, includes the homeobox genes gsc and Otx2, the winged-helix gene **HNF-3β** and the LIM homeobox gene **Lim1**. The other class encodes signalling molecules such as chordin, follistatin and noggin that can mimic properties of the organizer when administered ectopically to *Xenopus* embryos.

D-V patterning of the neural tube occurs later than A-P patterning and is regulated by axial mesoderm derivatives of the organizer, which form the prechordal mesoderm and notochord. Gene targeting experiments in mice have demonstrated that mutations in **HNF-3β** and the signalling molecule **Sonic hedgehog** (**Shh**), which are both expressed in the prechordal mesoderm and notochord, severely affect D-V patterning of the neural tube (Ang and Rossant, 1994b; Weinstein et al., 1994; Chiang et al., 1996). Moreover, the presence of a single fused optic vesicle in **Shh** mutant mouse embryos (Chiang et al., 1996) and the ectopic expression of **Pax-2** and...
suppression of Pax-6 expression by injections of Shh RNA into zebrafish embryos demonstrate an additional role for Shh in eye development (Macdonald et al., 1995). Shh has also been shown to induce ventral cell fates of different A-P character in early neural plate or intermediate neural tube explants (reviewed by Placzek, 1995; Tanabe and Jessell, 1996). Transgenic experiments in mice resulting in ectopic expression of Shh and HNF-3β at the mid-hindbrain junction have shown that HNF-3β and Shh regulate each other’s expression (Echelard et al., 1993; Sasaki and Hogan, 1994; Hynes et al., 1995). Thus, HNF-3β and Shh represent key components of the ventralising signal emanating from axial mesoderm derivatives.

The in vivo functions of other transcription factors expressed in the organizer have also been investigated in gene targeting experiments. The mutations of Otx2 and Lim1 result in a very similar phenotype involving loss of forebrain, midbrain and anterior hindbrain (Shawlot and Behringer, 1995; Acampora et al., 1995; Matsuoka et al., 1995; Ang et al., 1996). Although homozygous HNF-3β mutants show severe defects in D-V patterning due to the loss of an organised node and of axial mesoderm cells (Ang et al., 1994b; Weinstein et al., 1994), patterning of the neural tube along the A-P axis occurs in mutant embryos from the midbrain to the posterior end of the spinal cord. One possible explanation for this residual A-P patterning activity is that cells with organizer activity remain in the primitive streak of HNF-3β mutant embryos. This hypothesis is supported by the observation that gsc, which is normally expressed in cells that have the ability to induce an organizer (Blum et al., 1992; Izpisua-Belmonte et al., 1993), is still expressed in HNF-3β mutant embryos (Ang et al., 1994b). Null mutations of gsc in mice do not affect A-P patterning of the neural tube, but result in craniofacial abnormalities (Rivera-Perez et al., 1995; Yamada et al., 1995), consistent with the later domains of expression of gsc (Gaunt et al., 1993). Possible redundant functions of HNF-3β and of HNF-3β have been evoked to explain the lack of phenotype affecting regionalization of the neural tube in gsc mutant embryos.

A thorough comparison of the expression patterns of gsc and HNF-3β has not been reported, although the expression of both gsc and HNF3β in the anterior primitive streak raised the possibility of genetic interactions between these genes at early stages of gastrulation (Blum et al., 1992; Ang et al., 1993). In this paper, we set out to compare the expression patterns of the two genes to determine the extent of their overlap in E6.5-E9.5 mouse embryos. We found that gsc and HNF3β are co-expressed not only in cells in the anterior primitive streak of E6.5-E7.5 embryos but also at the anterior end of embryos at E7.75. To determine if the two genes function redundantly or synergistically, we have generated double mutant embryos for gsc and HNF-3β. Double homozygous mutant embryos are not more severely affected than single HNF-3β homozygous mutant embryos in early A-P regionalization of the neural tube, indicating that these genes do not have a redundant function in this process. However, gsc−/−:HNF-3β−/− embryos present a new phenotype as early as E8.75. Analysis of the double-mutant phenotype shows that gsc and HNF-3β function synergistically in the mouse organizer, forebrain and/or foregut to regulate Shh expression and proper development of the neural tube. Our results have thus revealed an earlier role than previously described for gsc in growth and patterning of the neural tube as well as in optic vesicle, forebrain, branchial arch, and heart development.

**RESULTS**

**Comparison of gsc and HNF-3β expression in mouse embryos from E6.5-E9.5**

Earlier studies by different groups have demonstrated that the expression of gsc and HNF-3β are localised in the anterior

**MATERIALS AND METHODS**

**Generation and genotyping of wild-type and mutant mice**

gsc heterozygous mice of 129/Sv × C57BL/6 background (Rivera-Perez et al., 1995) were crossed with HNF-3β heterozygous mice of 129/Sv × CD1 background (Ang and Rossant, 1994b) to generate double heterozygous animals. For genotyping of pups, DNA was extracted from tail tips as described in Laird et al. (1991), and Southern blot analysis was performed as described in Rivera-Perez et al. (1995) for gsc and Ang and Rossant (1994b) for HNF-3β. PCR analysis was used to genotype embryos. Yolk sac DNA extraction and PCR for wild-type and mutant HNF3β alleles were performed as described in Ang and Rossant (1994b), except that the following primers 5′-GCCCATAGCTTGTTGGT-3′ and 5′-GCACGGCATCAGCTTCTATC-3′ were used to detect the mutant allele. The presence of a mutated gsc allele was detected using the following primers 5′-ATCCATCTTGGTTCAATGGCCAATC-3′, 5′-TTACACGTAGCTCCTCGTGTC-3′, to amplify a fragment of 696 bp. For the wild-type gsc allele, the following primers were used 5′-GAGCTGACGTGCTCAACCACGCTGACTG-3′, and 5′-TGACATCGACTGCTGTGCAAATCGTC-3′ to amplify a fragment of 743 bp. The DNA was amplified for 35 cycles (94°C/1 minute, 55°C/30 seconds, 72°C/1 minute) in 25 μl volume containing 67 mM Tris HCl, pH 8.8, 6.7 mM MgCl2, 170 μg/ml BSA, 16.6 mM (NH4)2SO4, 1.5 mM dNTPs, 10% DMSO and 0.2 μg of each oligonucleotide.

**RNA in situ hybridization, immunohistochemistry and histology**

Whole-mount in situ hybridization was performed as described previously (Conlon and Hermann, 1993). For section in situ hybridization, embryos were fixed 1 hour in 4% paraformaldehyde in PBS, equilibrated in 20% sucrose in PBS and embedded in 7.5% gelatin and 14 μm cryosections were cut. In situ hybridization of sections was performed as described in Gradwohl et al. (1996).

The following probes were used: Pax-2 (Nornes et al., 1990), Pax-6 (Walter and Gruss, 1991), a kb gsc cDNA probe containing the entire coding region, Shh (Echelard et al., 1993), Otx2 (Ang et al., 1994a), En1x2 (Simeone et al., 1992), Mox-1 (Candia et al., 1992), Bf-1 (Tao and Lai, 1992), En-2 (Davis and Juynier, 1988), Hoxb-1 (Wilkinson et al., 1989), Fgf-8 (Crossley and Martin, 1995), Dlx-2 (Price et al., 1991) and netrin-1 (Serafini et al., 1994).

Whole-mount immunocytochemistry was performed according to published procedures (Davis et al., 1991) using a rabbit polyclonal anti-NKx2.1 (Lazzaro et al., 1991) and anti-HNF-3β antibodies at a dilution of 1:500. After immunocytochemistry or whole-mount in situ hybridization, embryos were postfixed and sectioned in gelatin as described (Gradwohl et al., 1996). Some of the gelatin sections were counterstained for 1 second with hematoxylin.

For histological analysis, embryos at E9.5 were fixed by immersion in 2.5% glutaraldehyde in phosphate-buffered saline (PBS) for 16 hours at 4°C. Embryos were then rinsed in PBS and dehydrated with graded alcohols series and embedded in Epon. 4 μm sections were cut and stained with toluidine blue.
expression of gsc and HNF-3β in front view. Mox-1 expression, also analysed in this embryo, is detected in the somites (staining in the lower part of the panel). (D) A transverse section at the level of the forebrain of embryo depicted in C showing co-expression of gsc (purple) and HNF-3β (brown) in the ventral forebrain (arrowhead) and foregut (arrow). (E-H) E8.75 embryos. (E) gsc is expressed in the ventral diencephalon. (F) HNF-3β is also expressed in the ventral diencephalon and, in addition, in the Rathke’s pouch, notochord (arrow) and floor plate. (G) gsc is expressed in the oral epithelium (arrow). (H) HNF-3β is also expressed in the oral epithelium (arrow) and in the pharyngeal endoderm, ventral diencephalon and floor plate. Anterior is to the top, except for A where anterior is to the left. Abbreviations: l, left; r, right; di, diencephalon; rp, Rathke’s pouch; fp, floor plate and ph, pharynx. Scale bar: 100 μm.

primitive streak during early stages of gastrulation (Blum et al., 1992, Ang et al., 1993; Monaghan et al., 1993). We have compared the expression patterns of the two genes by double-labelling experiments to determine the extent of their overlap. We first analysed expression at E6.0-E6.5, by whole-mount RNA in situ hybridization with a gsc cDNA probe followed by whole-mount antibody staining with a HNF-3β specific antiserum. At the early to mid-streak stage, we found co-expression of gsc and HNF-3β in many cells in all three germ layers at the anterior end of the primitive streak and in visceral endoderm cells (Fig. 1A,B). Although the domains of expression of the two genes overlap to a large extent, there were also cells expressing uniquely HNF-3β in the ectoderm germ layer, in particular in the distal-most region of the primitive streak (arrowhead in Fig. 1A,B). Thus, gsc expression is encompassed within the domain of expression of HNF-3β in the anterior primitive streak.

At headfold (E7.75) and early somite (E8.25) stages, we found a domain of gsc expression at the anterior end of the embryo (Fig. 1C,D) that has not been previously reported. As at earlier stages, this domain was contained within the HNF-3β expression domain. Sections through embryos doubly stained for HNF-3β and gsc revealed expression of both genes in all three germ layers, i.e. in ventral neuroepithelium of the forebrain, prechordal mesoderm and foregut endoderm (Fig. 1D and data not shown). Analysis of gsc expression at later stages was performed by radioactive in situ hybridization on tissue sections. In E8.75 embryos, gsc expression was observed in the ventral diencephalon (Fig. 1E) and in the oral epithelium (Fig. 1G). Both tissues also expressed HNF-3β (Fig. 1F,H). At E9.5, the expression of the two genes persisted in the oral epithelium but expression in the diencephalon was no longer detected (data not shown). At E10.5, the patterns of the two genes become distinct, and gsc and HNF-3β show complementary expression in the mesenchyme and endoderm of the first branchial arch, respectively (Gaunt et al., 1992; Monaghan et al., 1993). We have thus identified domains of gsc expression at the rostral end of the embryo from E7.75 to E9.5. In addition, double-labelling studies allow us to conclude that gsc and HNF-3β are co-expressed in many cells in the anterior primitive streak and in the forebrain, prechordal mesoderm and foregut endoderm.

**Morphological analysis of gsc and HNF-3β double mutant embryos**

The expression of gsc and HNF-3β in the same cells raised the possibility that these genes interact during early mouse embryonic development. To study genetic interactions between gsc and HNF-3β, we have generated double heterozygous animals. These animals appeared normal and, when intercrossed, gave rise to embryos with 9 different genotypes at roughly the expected Mendelian frequencies at E9.5 (Table 1). Embryos with the genotypes gsc+/+;HNF-3β+/−, gsc+/−;HNF-3β+/−, gsc+/−;HNF-3β+/−, and gsc+/−;HNF-3β−/− were morphologically normal at this stage. Embryos with four different genotypes were morphologically abnormal and fell into two different classes. One class of embryos, which includes the genotypes gsc+/+;HNF-3β−/−, gsc+/−;HNF-3β−/− and gsc−/−;HNF-3β−/−, resembled the phenotype of single HNF-3β homozygous mutant embryos. These mutant embryos looked
very abnormal, were small and thin with a bulkier end that corresponded to the anterior end of the embryo, as confirmed by the expression of anterior neural markers such as *Emx2* and *Six3* (Fig. 2A,B and data not shown). Importantly, all these embryos, including *gsc<sup>−/−</sup>*;*HNF-3β<sup>−/−</sup>* embryos, showed development of an A-P axis and did not appear more severely affected embryos. Anterior is to the top. Abbreviations: fb, forebrain; ha, branchial arches; mb, midbrain; hb, hindbrain; ht, heart; ov, optic vesicles; so, somites. Scale bar: 100 μm.

Table 1. Offspring of *Gsc* and *HNF-3β* mutant mice at E9.5

<table>
<thead>
<tr>
<th>Genotype</th>
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<td>Predicted (%)</td>
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<td><em>gsc</em>&lt;sup&gt;+&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;+&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;−/−&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;+&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;+&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;−/−&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;+&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;+/−&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;−/−&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;+/−&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;−/−&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;+/+&lt;/sup&gt;</td>
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<td><em>gsc</em>&lt;sup&gt;−/−&lt;/sup&gt;&lt;br&gt;<em>HNF-3β</em>&lt;sup&gt;−/−&lt;/sup&gt;</td>
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<sup>†</sup>The fit to mendelian expectations was tested with a chi-square goodness-of-fit test: χ²=11.57, df=8, P=0.20.

Histological analyses of the *gsc/3β* phenotype

To further characterise these mutant defects, semi-thin plastic sections of *gsc/3β* embryos and normal littermates at E9.5 were
made and processed for histological analysis (Fig. 3). Transverse sections of less severely affected gsc/β muts at the level of the forebrain clearly showed a thinner neuroepithelium and smaller optic vesicles (Fig. 3A, D). The neuroepithelium of the hindbrain and spinal cord were also thinner compared to normal embryos, but the reduction in size was always more severe and observed earlier in the forebrain region (Fig. 3A-F). In contrast, notochord cells, which fail to develop in single homozygous HNF-3β mutant embryos, were clearly observed in transverse sections of gsc/β embryos at different levels along the A-P axis (open arrowheads in Figs. 3D-F). Thus, the neural tube was affected, but axial mesoderm cells were present along the A-P axis in less severely affected gsc/β embryos. In severely affected gsc/β embryos, however, axial mesoderm cells expressing HNF-3β were initially present, but this expression was not maintained and notochord cells subsequently disappeared from the rostral half of these embryos (see below).

Mutant defects were also observed outside of the neural tube. Transverse sections showed the presence of pyknotic cells in the mesenchyme of the first and second branchial arches (Fig. 3B,E). The first branchial arch arteries were either not visible or not well formed and pharyngeal endoderm cells formed a smaller and abnormal pharynx. Furthermore, the epithelium of the first branchial arch did not fuse ventrally with the pharyngeal endoderm to form the buccopharyngeal membrane (Fig. 3B,E). Thus, development of the first and second branchial arches and of the pharynx were severely affected in the gsc/β mutants.

The heart of gsc/β embryos developed as a straight or S-shaped tube in the midline, but failed to loop further (Fig. 2D,F). Transverse sections of gsc/β at the level of the heart showed that the heart was directly connected to the gut, due to the lack of formation of the dorsal mesocardium from splanchnopleuric mesoderm (Fig. 3C,F). The absence of separation between heart and gut could be responsible for the looping defects in the heart. Histological sections also clearly showed an abnormal vasculature. The dorsal aorta was elongated, enlarged or disorganised (Fig. 3C,F and data not shown). These defects could be caused by increased blood pressure resulting from the abnormal heart looping. In contrast, the presence of myogenic and endocardial cells in the heart of gsc/β mutants indicated that development of these two cell types does occur in these embryos (Fig. 3C,F). Thus, the heart problems most likely result secondarily from defects in gut endoderm and dorsal mesocardium development.

**Patterning defects in the neural tube**

In Xenopus and chick embryos, the ability of ectopic gsc to induce a secondary neural axis has suggested a role for gsc in induction and patterning of the neural tube (Blum et al., 1992; Izpisua-Belmonte et al., 1993). Furthermore, our finding of gsc expression in the anterior axial mesoderm and forebrain of mouse embryos at E7.75 suggested to us that gsc may have a role in forebrain development. To determine if A-P patterning of the neural tube was affected in gsc/β embryos, the expression of regional markers specific for distinct domains along the A-P axis was examined. We used the markers Otx2, Emx2 and BF-1, for the forebrain region. At E9.5, both Otx2 and Emx2 were expressed at the correct A-P level of gsc/β embryos but in a smaller domain, consistent with a reduced size of the forebrain in these embryos (Fig. 4A-D). BF-1 was...
also correctly expressed in the telencephalon of gsc/3β embryos at the same stage but its expression domain was markedly reduced dorsally (Fig. 4E,F). This loss of dorsal BF-1 expression was already detected in E8.75 embryos (Fig. 4G,H). In contrast, expression of BF-1 in the nasal placode was observed in mutant and normal embryos. To analyse A-P patterning of more posterior regions, En-2 and Hoxb1 expression were also examined in gsc/3β mutants. Both genes were similarly expressed in gsc/3β and wild-type embryos (Fig. 4I-L). Together, these results indicate that A-P patterning of the neural tube occurs normally in gsc/3β embryos. In contrast, D-V patterning of the forebrain appears specifically affected.

To further study D-V patterning of the neural tube, we analysed expression of Pax-6 (Walther and Gruss, 1991) in the alar and basal plates of the neural tube of gsc/3β embryos at E9.5. Pax-6 expression was expanded ventrally in the forebrain, hindbrain and spinal cord in less severely affected gsc/3β mutants, when compared to normal littermates (Fig. 5A-D). In the diencephalic region of some severely affected gsc/3β embryos, no optic vesicles could be identified morphologically and loss of Pax-2, which is expressed in the optic vesicles of normal littermates (Fig. 5E), confirms a loss of these structures (Fig. 5F). Loss of optic vesicles in severely affected gsc/3β embryos is not due to a lack of formation but rather to a lack of maintenance of this structure, since optic vesicles are present earlier in these embryos at E8.75 (data not shown). We also studied expression of two homeobox genes that show restricted expression along the D-V axis of the diencephalon, Dlx-2 (Price et al., 1991) and Nkx2.1 (Lazzaro et al., 1991). Both genes were expressed in the ventral diencephalon of normal E9.5 littermates but were missing in gsc/3β embryos (Fig. 5G,H and IJ respectively). We next examined whether floor plate cells, in the ventral midline of the neural tube, were present in gsc/3β mutants, using netrin-1 (Serafini et al., 1994) as a marker for these cells. netrin-1 was not expressed in floor plate cells at the anterior end of severely affected gsc/3β embryos, whereas expression in the heart and somites was normal (Fig. 5K,L). Thus, analysis of additional D-V molecular markers demonstrated that dorsal cell fates are expanded ventrally, while ventral cell fates, including optic vesicles, are lost.
vesicles in the diencephalon and floor plate cells in the midbrain and hindbrain, are missing in severely affected gsc/3β embryos.

Expression of Shh, HNF-3β and Fgf-8 are severely affected in gsc/3β embryos

One possible explanation for the loss of ventral markers in the neural tube is the absence of a ventralizing signal such as Shh, normally provided by the floor plate or the notochord (reviewed in Placzek, 1995; Tanabe and Jessell, 1996). We thus analysed gsc/3β mutants at E8.75 for expression of Shh, and found it severely reduced or missing at the anterior end, and present to variable levels along the rest of the A-P axis of mutant embryos (Fig. 6C,D and data not shown). Sections through the less severely affected gsc/3β embryos at E9.5 showed expression of Shh which was weaker than normal in the notochord and barely detectable or absent in the neural tube, except in the diencephalon where Shh expression was still present, although at much reduced levels (Fig. 6E-H). Shh expression was also missing in the pharyngeal endoderm and in the ventral foregut region (Fig. 6C,D,G,H). Absence or reduction of Shh expression was first observed at E8.75 (Fig. 6C,D), whereas its expression was found in the prechordal mesoderm, notochord and foregut at E8.5 (Fig. 6A,B). These results demonstrate that Shh expression is initiated in the axial mesoderm and foregut of gsc/3β embryos but is not maintained in these tissues anteriorly. Shh expression is also severely reduced in the diencephalon and ventral neural tube at E9.5.

Altered expression of Shh in gsc/3β embryos raised the possibility that HNF-3β expression was affected in these embryos, since HNF-3β has previously been shown to regulate expression of Shh in the neural tube in transgenic mice (Echelard et al., 1993; Hynes et al., 1995). We therefore examined expression of HNF-3β in gsc/3β embryos between E7.75 and E9.5. HNF-3β was normally expressed in the ventral neural tube, prechordal mesoderm, notochord and gut of gsc/3β embryos at E7.75-E8.5 (Fig. 7D-F and data not shown), compared to gsc+/−;HNF-3β+/− littermates (Fig. 7A-C). At E8.75, however, HNF-3β expressing cells and a notochord structure were no longer observed between the neural tube and gut of gsc/3β embryos from the heart level to the rostral end (Fig. 7K-M). HNF-3β expression was also lost in the ventral neural tube at rostral levels (Fig. 7L,M) and in the oral epithelium (Fig. 7L). In more caudal regions, HNF-3β expression was still present in the notochord and floor plate (Fig. 7N). In contrast, HNF-3β expression in gsc+/−;HNF-3β+/− littermates at E8.75 was observed in floor plate, axial mesoderm and gut all along the A-P axis (Fig. 7G-J). HNF-3β expression also remained in the gut of gsc/3β embryos at E8.75, although the size, shape and position of the gut were very abnormal (Fig. 7L,M). Thus, expression of HNF-3β was initiated normally in the

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**Fig. 5** Whole-mount RNA in situ hybridization and antibody staining of dorso-ventral CNS markers. Wild-type (A,C,E,G,K) and gsc/3β (B,D,F,H,I,L) embryos at E9.0 to E9.5. (A) Wild-type Pax-6 expression. (B) Pax-6 expression domain is expanded ventrally in the forebrain and hindbrain of less severely affected gsc/3β mutants (arrows in B). Ventral regions in the neural tube of wild-type embryos that do not express Pax-6 (A) (demarcated by brackets) are missing in gsc/3β embryos (B). (C) Transverse sections showing wild-type Pax-6 expression in the spinal cord. (D) Expansion of Pax-6 expression to the ventralmost region of the spinal cord in gsc/3β embryos. (E) Wild-type Pax-2 expression. (F) The expression of Pax-2 in the optic vesicle is missing in a gsc/3β embryo, whereas its expression at the mid-hindbrain junction (arrowhead), otic vesicles and lateral mesoderm is detected. (G) Wild-type Dlx-2 expression (arrowhead, expression in the ventral diencephalon). (H) In gsc/3β embryos, Dlx-2 expression in the ventral diencephalon is not detected and expression in the branchial arches is severely reduced. In the forebrain region, Dlx-2 expression was detected in mesenchymal cells. (I) Wild-type Nkx2.1 expression (arrowhead, expression in the ventral diencephalon). (J) Nkx2.1 expression in the ventral diencephalon is missing in a gsc/3β mutant. (K) Wild-type netrin-1 expression. (L) In a gsc/3β embryo, expression of netrin-1 is not observed in the anterior neural tube but is present in the somites and heart. Arrowheads in L: normal expression of netrin-1 in the anterior floorplate. Scale bar: 100 μm.
ventral neural tube and axial mesoderm at E8.5, but was not maintained in these tissues subsequently in the rostral half of severely affected gsc/3β embryos.

Fibroblast growth factor-8 (FGF-8), another signalling molecule that is expressed in the midbrain and forebrain regions, has been shown to play a key role in regulating growth and polarity in the midbrain (Crossley and Martin, 1995; Crossley et al., 1996; Lee et al., 1997). We have analysed gsc/3β mutants for Fgf-8 expression and found that it was severely affected in the commissural plate of the forebrain. At E8.75, this domain of Fgf-8 expression appeared reduced in gsc/3β mutants compared to wild-type embryos (Fig. 8A,B) and it was no longer detected at E9.5 in severely affected embryos (Fig. 8C,D). In contrast, Fgf-8 expression in the midhindbrain junction, the branchial arches and the tail bud appeared normal. These results demonstrate that, as for Shh and HNF-3β, gsc/3β embryos initiated but did not maintain Fgf-8 expression in the forebrain.

Defects in first and second branchial arch development

The first and second branchial arches appeared small and morphologically abnormal in the gsc/3β mutants at E9.5 (Fig. 2F,G). To determine if mesodermal or neural crest cells were affected in the mutant branchial arches, Dlx-2 and Mox-1 were used as markers of these two cell populations, respectively. Expression of Dlx-2 was severely reduced in the first and second mutant branchial arches (Figs 5G,H). Expression of Mox1 in the second branchial arch was also severely reduced (arrowheads in Fig. 4B,F), but its expression in the third and fourth branchial arches of mutant embryos appeared relatively normal. Thus, both mesodermal and neural crest cells appear affected in the first and second branchial arches of gsc/3β embryos.

DISCUSSION

Overlapping expression domains of gsc and HNF-3β in early mouse embryos

In this paper, we have investigated the possibility of genetic interactions between gsc and HNF-3β during mouse embryogenesis by identifying tissues that co-express the two genes and analysing the phenotype of gsc and HNF-3β double-mutant embryos. Double-labelling studies for gsc and HNF-3β expression by whole-mount in situ hybridization and whole-mount antibody staining, indicate that their expression patterns overlap between E6.5 and E8.25. At E6.5, cells in the three germ layers of anterior primitive streak and in the visceral endoderm co-express gsc and HNF-3β. We also found cells expressing uniquely HNF-3β localized more distally in the embryo. These results demonstrate that cells in the anterior part of the primitive streak are heterogenous in their expression of transcription regulators. It will be important to determine whether this molecular heterogeneity correlates with functional or cell fate differences within the mouse organizer.

We have identified another domain of gsc expression at the anterior end of mouse embryos from E7.75 to E8.25, which is very similar to the anterior domain of gsc expression in chick and zebrafish embryos (Izpisua-Belmonte et al., 1993; Thissie et al., 1994). In this domain, gsc is found in the three germ layers, i.e. in ventral cells of the anterior neural plate, in prechordal mesoderm and in foregut, where it is co-expressed with HNF-3β. Previous fate-map studies in the chick have demon-
strated that a region similar to the gsc domain in the ventral neural plate is fated to form the diencephalon (Coulby and le Douarin, 1988). Thus, later gsc expression observed in the ventral diencephalon at E8.75 could result from the maintenance of gsc expression in the neural plate. gsc and HNF-3β are also both expressed in the oral epithelium at this stage and at E9.5. In summary, these studies demonstrate that gsc and HNF-3β are co-expressed in the anterior primitive streak, prechordal mesoderm, forebrain, foregut and oral epithelium from E6.5 to E9.5, raising the possibility of functional interactions between the two genes in these different tissues.

Dosage-dependent genetic interactions between gsc and HNF-3β in forebrain and foregut development

Interactions between gsc and HNF-3β were analysed in gsc and HNF-3β double-mutant embryos. We did not observe a more severe phenotype in gsc<sup>−/−</sup>;HNF3β<sup>−/−</sup> and gsc<sup>+/−</sup>;HNF-3β<sup>−/−</sup> embryos compared to single homozygous HNF-3β mutant
embryos with respect to A-P patterning of the neural tube. Lack of an enhanced phenotype in early A-P axis development indicates that the two genes do not have redundant functions in this process.

Interestingly, however, we observed a new phenotype in embryos with the genotype gsc\textsuperscript{−/−};HNF-3\textsuperscript{β}\textsuperscript{+/−}. The earliest morphological defects in these gsc/3β embryos were observed at E8.75 in the forebrain, the first branchial arch and the heart. The phenotype in the forebrain of gsc/3β embryos is most likely related to the co-expression of gsc and HNF-3β in this tissue. In the first branchial arches, only the pharyngeal endoderm and the oral epithelium co-express these genes. We thus hypothesize that the branchial arch defects could arise from a primary problem in these two tissues. A foregut defect could also lead to the lack of formation of dorsal mesocardium, and thus secondarily result in heart looping and vasculature defects. gsc/3β embryos are growth arrested at 20- to 25-somite stage and die around E11.5. The reasons for the growth retardation and death in the double mutants have not been investigated but could be related to the incomplete heart looping and the vasculature defects.

The new mutant phenotype was only observed in gsc\textsuperscript{−/−};HNF-3β\textsuperscript{+/−} embryos, and not in gsc\textsuperscript{−/−} or HNF-3β\textsuperscript{+/−} single mutant embryos. This result and the co-expression of the two genes in the forebrain, foregut and oral epithelium favor the hypothesis of synergistic interactions of gsc and HNF-3β within the same cells. A normal level of HNF-3β, in the absence of gsc, is sufficient for proper development. However, if only half the normal amount of HNF-3β is present, gsc becomes essential for proper growth and development of these tissues. Haploinsufficiency of HNF-3β has previously been demonstrated in HNF-3β\textsuperscript{−/−} animals. In our previous single-mutant study, 20% of HNF-3β heterozygous adults had a runted appearance and died within two months of age (Ang et al., 1994b). Furthermore, loss of one dose of HNF-3β leads to changes in the expression of nodal, a member of the transforming growth factor-β superfamily of secreted growth factors, and affects the left-right asymmetry of heart looping (Collignon et al., 1996).

Surprisingly, loss of HNF-3β expression was observed in the notochord and floor plate of severely affected gsc/3β embryos. Thus, a gsc null background can lead to loss of HNF-3β expression in the presence of a single copy of the HNF-3β gene. No qualitative change in HNF-3β expression levels was observed by whole-mount RNA in situ hybridization and whole-mount antibody staining in gsc\textsuperscript{−/−} embryos when two copies of HNF-3β were present (data not shown). However, more sensitive methods, such as RNase protection studies will be necessary to determine whether there are quantitative changes in HNF-3β expression in these embryos. Nevertheless, the fact that HNF-3β expression is not maintained in gsc/3β embryos demonstrates that gsc behaves as a positive regulator of HNF-3β expression, when the dosage of HNF-3β is lowered. Given that Shh and HNF-3β expression have been shown to be interdependent (Echelard et al., 1993; Sasaki and Hogan, 1994; Hynes et al., 1995; Chiang et al., 1996), HNF-3β expression could be regulated either by direct binding of gsc to the HNF-3β promoter, or indirectly through regulation of Shh by gsc (see below).

gsc and HNF-3β interact to regulate Shh expression in the notochord, forebrain and floor plate of the neural tube

Our phenotypic analyses has revealed that A-P patterning in the neural tube of gsc/3β embryos appears normal, whereas D-V patterning present clear defects. In the neural tube, dorsal fates appear to spread ventrally as shown by the expansion of Pax-6 expression domains. Dorsalization of the forebrain was also confirmed by the loss of expression of the ventral cell fate markers Dlx-2 and Nkx2.1. Loss of floor plate development was demonstrated by loss of expression of HNF-3β, netrin-1 and Shh in the brain of severely affected gsc/3β embryos. Loss of ventral forebrain markers and D-V patterning defects in the neural tube could be due to the loss of or reduction in Shh expression observed in gsc/3β embryos. This hypothesis is supported by similarities in the forebrain and D-V phenotypes of gsc/3β mutants and of the Shh homozygous mutants that have been recently been reported (Chiang et al., 1996).

Alterations of Shh expression in the foregut and diencephalon of gsc/3β embryos strongly suggest that interaction between gsc and HNF-3β in these tissues is involved in Shh regulation. Loss of Shh expression is however also observed in the notochord and floor plate, two tissues that express HNF-3β but not gsc. Lineage studies in mouse have demonstrated that
the precursors of the node and notochord are found exclusively in cells at the anterior primitive streak of E6.5 mouse embryos (Lawson and Pedersen, 1992). This observation indicates that cells in the anterior primitive streak correspond to the early mouse organizer. Thus, one possible explanation for the loss of Shh expression in the notochord is that both gsc and HNF-3β regulate Shh in organizer cells at the anterior end of the primitive streak and that loss of gsc and of one copy of HNF-3β in these organizer cells leads intrinsically to reduced Shh expression in their derivatives. Since Shh expression in the notochord has been shown to be necessary for induction of floor plate cells in the neural tube (reviewed by Placzek, 1995; Tanabe and Jessell, 1996), loss of Shh expression in the notochord is most likely responsible for the loss of Shh expression in the neural tube of gsc/3β embryos. We have also observed, however, that, in less severely affected gsc/3β embryos, Shh was expressed in the notochord but not in the neural tube (Fig. 6H). In these cases, loss of Shh expression in the neural tube could be explained by reduced Shh signalling due to lower levels of Shh expression in the notochord and/or to an increased distance between the abnormally positioned notochord and the neural tube (Fig. 6H).

gsc/3β embryos show reduced growth of the telencephalon, diencephalon and optic vesicles. The winged-helix transcription factor BF-1 has been shown to regulate proliferation of the telencephalic vesicles in mice (Xuan et al., 1994) and loss of its dorsal expression suggest that growth of the dorsal telencephalon may be particularly affected. FGF-8, a molecule with growth-promoting activity in the limb, is also expressed in the forebrain. We have found that the expression of Fgf-8 in the commissural plate is initiated in gsc/3β mutants at E8.75, but is not maintained at E9.5. Shh may also have a function in growth of brain tissues since Shh+/− mutant embryos have a reduced brain size (Chiang et al., 1996). Thus, growth defect in the forebrain and lack or abnormal development of the optic vesicles in gsc/3β embryos could be caused by the loss of Fgf-8 and Shh. We will test the role of Shh and Fgf-8 in forebrain development by adding recombinant SHH and FGF8 proteins to neural plate explants of gsc/3β embryos and assay for the rescue of the forebrain defects.

CONCLUSIONS

gsc and HNF-3β genetically interact to regulate development of the neural tube, branchial arches, heart and foregut as early as E8.75, demonstrating an earlier role for gsc during embryonic development than determined from single-mutant studies. All gsc-expressing cells also express HNF-3β at this early stage, indicating that this interaction results from both genes functioning in the same cells. Furthermore, the loss of Shh expression in gsc/3β embryos strongly suggests that the activities of both genes in organizer, foregut and forebrain cells converge on the regulation of Shh expression. Further studies will be necessary to examine the possibility that the two genes interact directly by binding to the Shh promoter. An alternate possibility is that gsc regulates HNF-3β expression by directly binding to the HNF-3β promoter. In this model, we propose that loss of gsc expression in gsc/3β embryos that contain only one copy of the HNF-3β gene, would lead to reduced levels of HNF-3β expression beyond a threshold level necessary to activate an autoregulatory loop. Thus, HNF-3β expression is not maintained and consequently leads to a loss of Shh expression in these embryos. A third possibility is that gsc and HNF-3β regulate different target genes in distinct pathways that are both involved in Shh expression.

Our analysis of the gsc/3β mutant phenotype also suggests that Shh is not the only target gene regulated by gsc and HNF-3β. For example, severe growth defects in the forebrain and loss of optic vesicles in gsc/3β embryos could be caused by loss of expression of both Fgf-8 and Shh, since an abnormal optic vesicle remains in Shh mutant embryos (Chiang et al., 1996). In addition, loss of Shh expression alone cannot explain the defects seen in the heart and branchial arches, since Shh mutant embryos do not show any defects in these tissues at E8.75. It will thus be interesting to investigate in future experiments whether gsc and HNF-3β interact in the foregut and/or oral epithelium to regulate other signalling molecules that are involved in morphogenesis of the branchial arches and the heart.

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