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The morphogenetic role of midline mesendoderm and ectoderm in the
development of the forebrain and the midbrain of the mouse embryo

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SUMMARY

The anterior midline tissue (AML) of the late gastrula mouse embryo comprises the axial mesendoderm and the ventral neuroectoderm of the prospective forebrain, midbrain and rostral hindbrain. In this study, we have investigated the morphogenetic role of defined segments of the AML by testing their inductive and patterning activity and by assessing the impact of their ablation on the patterning of the neural tube at the early-somite-stage. Both rostral and caudal segments of the AML were found to induce neural gene activity in the host tissue; however, the de novo gene activity did not show any regional characteristic that might be correlated with the segmental origin of the AML. Removal of the rostral AML that contains the prechordal plate resulted in a truncation of the head accompanied by the loss of several forebrain markers. However, the remaining tissues reconstituted Gsc and Shh activity and expressed the ventral forebrain marker Nkx2.1. Furthermore, analysis of Gsc-deficient embryos reveals that the morphogenetic function of the rostral AML requires Gsc activity. Removal of the caudal AML led to a complete loss of midline molecular markers anterior to the 4th somite. In addition, Nkx2.1 expression was not detected in the ventral neural tube. The maintenance and function of the rostral AML therefore require inductive signals emanating from the caudal AML. Our results point to a role for AML in the refinement of the anteroposterior patterning and morphogenesis of the brain.

Key words: Prechordal plate, Ventral diencephalon, Neurulation, Patterning activity, Regionalisation, Mouse

INTRODUCTION

Regionalisation of the neural plate in Xenopus and chick embryos has been shown to be regulated by both planar and vertical signals emanating from the gastrula organizer and its mesendodermal derivatives (Sharpe and Gurdon, 1990; Storey et al., 1992; Ruiz i Altaba, 1993; Storey et al., 1995; Lumsden and Krumlauf, 1996). In the mouse, recent findings suggest that the anterior identity of the neural axis may be specified independently of the organizer’s derivatives and mediated by the activity of the visceral endoderm of the early embryo (Thomas and Beddington, 1996; Bouwmeester and Leyns, 1997; Varlet et al., 1997; Beddington and Robertson, 1998, 1999; Ding et al., 1998; Knöttgen et al., 1999; Sun et al., 1999). Mutations of the Lim1 and Otx2 genes encoding putative transcription factors, which are expressed in the visceral endoderm and also in the anterior mesendoderm, result in the loss of anterior neural structures (Acapomara et al., 1995; Matsuo et al., 1995; Shawlot and Behringer, 1995; Ang et al., 1996). Embryological studies on ES cell→embryo chimeras have provided a means to dissect genetically the relative role of the visceral endoderm and primitive-streak-derived anterior mesendoderm during anterior neural patterning (Rossant and Spence, 1998). Interestingly, the anterior deficiency of the Otx2 and Lim1 in mutant embryos cannot be fully rescued in chimeras suggesting a requirement for wild-type primitive-streak-derived mesendoderm (Rhinn et al., 1998; Shawlot et al., 1999). In addition, recent analysis of the Wnt3 null-mutation has demonstrated that, although anterior visceral endoderm markers are expressed and correctly positioned in the mutant embryo, the ectoderm lacks anteroposterior (AP) neural patterning (Liu et al., 1999). Collectively, these findings suggest that, following the initial specification of anterior identity by the extraembryonic tissues, subsequent morphogenetic interactions provided by the anterior mesendoderm are required for the complete development and patterning of the anterior neural structures.

Fate-mapping studies have shown that cells of the posterior epiblast of the early primitive streak mouse embryo contribute to the prechordal plate and the most anterior part of the ventral neural tube of the early-somite-stage embryo (Lawson et al., 1991; Tam et al., 1997). Cells of the head process that lie rostral to the node of the late gastrula embryo also contribute to the anterior midline mesendoderm and ventral tissues of the brain (Tam et al., 1982; Beddington, 1994; Sulik et al., 1994). In contrast to the avian embryo where the prechordal plate and the head process are distinct in their anatomy and tissue fate (Selleck and Stern, 1991; Seifert et al., 1993; Dale et al., 1999),
these structures in the mouse are contiguous, with no clear anatomical distinction and their developmental fate is not well characterised (for review, Tam and Behringer, 1997). However, at the early-neural-plate stage of the mouse embryo, the expression pattern of several genes seems to reveal a fine subdivision within the anterior axial mesendoderm. In the most rostral segment, underlying the prospective forebrain, Gsc, Shh and Hnf3β are expressed (Chiang et al., 1996; Filosa et al., 1997). By contrast, genes such as Lim1, Otx2, Hnf3β, Shh and Bmp7 are expressed in the rest of the anterior axial mesendoderm, which underlies the prospective midbrain and hindbrain (Acampora et al., 1995; Lyons et al., 1995; Matsuo et al., 1995; Ang et al., 1996; Chiang et al., 1996; Filosa et al., 1997; Belo et al., 1998; Perea-Gomez et al., 1999). At a more posterior level, the notochord that is derived from the node of the late gastrula expresses Brachyury (T), Hnf3β, Shh and Noggin (Wilkinson et al., 1990; Chiang et al., 1996; Filosa et al., 1997; McMahon et al., 1998).

It has been postulated that, in vertebrate embryos, the mesendoderm is instrumental in specifying different AP segments of the neural axis. Studies supporting this concept have demonstrated that transplantation of different segments of the axial mesendoderm can induce neural tissues displaying the morphological and molecular properties consistent with the segmental origin of the graft (Sharpe and Gurdon, 1990; Ruiz i Altaba, 1994; Foley et al., 1997). In the chick, there is inconsistency regarding the extent to which derivatives of the organizer, such as the head process or the prechordal mesoderm, possess neural-inducing or regionalising activity (Darnell et al., 1992; Dale et al., 1997; Foley et al., 1997; Pera and Kessel, 1997; Rowan et al., 1999). Transplantation experiments demonstrated that the prechordal plate possesses neuralising properties and produces signals that ventralise the prospective forebrain (Pera and Kessel, 1997). However, another study showed that prechordal tissues do not have neural-inducing ability but can confer more anterior character to posterior neuroectoderm (Foley et al., 1997). Investigations of the properties of defined regions of the head process showed that this tissue refines the rostrocaudal character rather than specifies regional differences within the neural plate (Rowan et al., 1999). Remarkably, AP polarity can be specified in zebrafish mutants, such as floating head and no tail, which exhibit defects in axial mesendoderm and in embryos following the ablation of the presumptive prechordal tissue (Halpern et al., 1993; Talbot et al., 1995; Grinblat et al., 1998). Similarly, homozygous Hnf3β mutant mouse embryos that lack the node and axial mesendoderm show appropriate AP patterning of the neural tube from the forebrain to the posterior end of the spinal cord (Ang and Rossant, 1994; Weinstein et al., 1994; Klingensmith et al., 1999). In the mouse, germ layer recombination experiments have shown that the mesendoderm from head-fold embryos (which includes some axial, paraxial and lateral tissues) can regulate the expression of two region-specific neural genes, Otx2 and En1, within the epiblast tissue (Ang and Rossant, 1993; Ang et al., 1994). Despite these findings, the role of the mouse axial midline tissues during anterior neural development remains unresolved.

In the present study, we have undertaken an embryological approach to study the morphogenetic role of the axial tissues by analyzing the effects of removing defined segments of the anterior midline tissues (AML) on the development of specific brain regions. We have found that removal of the rostral region of the AML severely affects the patterning of the forebrain, although some degree of AP patterning is observed in other regions of the brain. Interestingly, ablated embryos can reform tissue that resembles the prechordal plate and specifies ventral forebrain tissue. Furthermore, our results have shown that the caudal AML is required for the maintenance and the specification of the AML comprising the prechordal plate and presumptive ventral diencephalon. Analysis of gene expression of Gsc-deficient embryos demonstrated that Gsc activity is involved in the patterning of the ventral neural tube. In addition, transplantation of AML fragments to ectopic sites in recipient embryos has provided evidence of the neural inductive activity of the AML. Collectively, results of these experiments point to a role for AML in the maintenance and refinement of AP patterning in the neurulating mouse embryo.

MATERIALS AND METHODS

Micromanipulation of mouse embryos

Mouse embryos were explanted from pregnant ARCs and Gsc mutant mice (Rivera-Perez et al., 1995; M. W. and R. R. B., unpublished) at 7.5 days postcoitum (dpc). Embryos from no allantoic bud to late bud stage (Downs and Davies, 1993), which display early signs of neural plate formation but no thickening of the anterior ectoderm, were selected for experiments. The AML that consists of the mesendoderm and the overlying ectoderm between the anterior edge of the neural plate and the node of the embryo was microsurgically ablated using finely drawn glass needles or electrolytically polished alloy needles. Three types of ablation were performed (Fig. 1A) to remove (i) the rostral segment of the AML associated with the prospective forebrain and rostral midbrain (A1 segment), (ii) the caudal segment of the AML associated with the caudal midbrain and the hindbrain (A2 segment) or (iii) the entire AML (A1+A2). The A1 or A2 fragments were approximately 175 μm long (about half the length of the anterior side of the cylindrical embryo) and about 70 μm wide, which is equivalent to one-tenth of the girth of the embryo. At this stage of development, the mesendoderm is about 10 cells in width and the cephalic neural plate spans about 200 μm on either sides of the anterior midline of the embryo. Two other midline regions of the embryo were ablated in parallel experiments: the node with the adjacent germ layer tissues (Davidson et al., 1999) and the anterior one-third segment of the primitive streak (PS). Ablated embryos were harvested either immediately or after a period of development in vitro (4-7 or 24-30 hours) in Dulbecco’s modified Eagle medium containing 75% rat serum (Tam, 1998). Embryos were fixed in 4% paraformaldehyde and examined for morphogenesis of anterior neural structures, axis morphology and somite number.

Tracking the displacement of anterior midline tissues

Early-neural-plate stage embryos were labelled by microinjection of a diluted DiI solution (1:10 dilution in 0.2 M sucrose of a 2 mg/ml ethanolic stock solution, Molecular Probes) into the anterior midline tissues within the A1 or A2 segment. In A1-labelled embryos, midline tissues were ablated from the A2 region and, conversely, in A2-labelled embryos, A1 tissues were ablated. Some A1- and A2-labelled embryos were cultured as intact control. In addition, some embryos were labelled in both the A1 and A2 segments for an assessment of the relative movement of the tissues in the midline. All embryos were cultured for 6-7 hours in vitro and then fixed in 4% paraformaldehyde. They were examined under a Leica MZFL11 fluorescence dissecting microscope with a Rhodamine filter set (absorption at 574 nm). Bright-field and fluorescent images were captured using a SPOT2 digital camera (Scitech) and the digital images are electronically
superimposed to show the location of the DiI-labelled cells in the anterior region of the embryo.

**Tissue transplantation to test for inductive activity**

Midline tissue fragments (A1 and A2) were tested for their ability to induce de novo neural gene expression by transplantation to ectopic sites. The donor tissues were isolated from no-allantoic-bud to late-bud stage embryos that express an X-linked 

**Gsc and Gsc\textsuperscript{lacZ} mutant embryos**

Embryos were collected at 7.5 dpc from mice of Gsc\textsuperscript{+/-} x Gsc\textsuperscript{+/-} matings (Rivera-Perez et al., 1995). After 24-30 hours of in vitro development, yolk sacs of AML-ablated and control embryos were collected and digested for 3-4 hours in 50 µl of buffered enzyme solution (50 mM Tris-HCl pH 8.0, 1 mM EDTA pH 8.0, 0.5% Tween 20, 200 µg/ml Proteinase K (Amresco)) at 55°C followed by a heat treatment at 95°C for 5-10 minutes. The genotype (Gsc\textsuperscript{+/-}, Gsc\textsuperscript{+/-} or Gsc\textsuperscript{+/-}) of the embryo was determined by PCR using specific primers for: wild-type allele (5'-GAGCTCAGCTGCTCAACCAGCTGC-3' and 5'-TAGCATCGACTGTCGCAAGTCC-3') and mutant allele (5'-AATCCACCTTGTTCAATGGCGATC-3' and 5'-TTACAGCTAGCTCCTGTG-3'). The PCR was performed in 10× PCR buffer (1.7 mg/ml BSA, 0.67 M Tris-HCl pH 8.8, 0.067 M MgCl₂, 0.166 M (NH₄)₂SO₄) containing 10% DMSO, 1.5 mM dNTP and 200 ng/µl of each of the four primers and 3-5 µl of DNA preparation, for 35 cycles with annealing temperature set at 60°C. The size of the wild-type product was 743 bp and that of the mutant was 696 bp. Several litters were also collected from 7.5 dpc pregnant mice produced by Gsc\textsuperscript{+/-} lacZ x Gsc\textsuperscript{+/-} lacZ matings. The Gsc\textsuperscript{lacZ} allele was generated by insertion of the nls-lacZ-SV40pA-flx neo cassette into the second exon followed by CRE excision of the neo gene (M. W. and R. R. B., unpublished). AML-ablated and control embryos were X-gal stained to reveal lacZ-expressing cells.

**RESULTS**

The loss of AML disrupts morphogenesis of cephalic neural tube

The morphogenesis of the neural tube was examined at early somite stage after removing different midline structures of the late gastrula, such as the PS, the node and the AML. Ablation of the anterior third of the PS did not affect the elongation or the morphogenesis of the neural tube but led to the loss of the
paraxial mesoderm caudal to the 4-5th somite (data not shown). These PS-ablated embryos formed 4.4±0.6 (n=12) pairs of somites significantly fewer in number than in control embryos (11.0±0.4, n=7). Consistent with the finding of Davidson et al. (1999), ablation of the node had no significant impact on the development of the cephalic part of the neural tube, although the overall development of the neural axis and the somites of the trunk was retarded. Node-ablated embryos developed intact axial mesendoderm underneath the headfolds but the notochord in the trunk was often abnormal or absent (Davidson et al., 1999). In contrast to the node- and PS-ablation, the removal of the entire AML that contains axial mesendoderm and ventral neuroectoderm of the prospective forebrain, midbrain and rostral hindbrain (A1+A2; Fig. 1A) resulted in the truncation of the cephalic neural tube (Fig. 2A,B). A longitudinally split head region was found in about 43% of the AML-ablated embryos (Fig. 2B-E).

A preliminary study of region-specific markers showed that AML-ablated embryos did not express the forebrain markers Fgf8, Six3 and Hesx1 (Fig. 2C-E, respectively). However, posterior neural tube developed normally and somite number (9.8±0.2, n=19) was similar to that of control embryos (10.3±0.4, n=24). These results show that morphogenesis of the cephalic neural tube is critically dependent on the presence of the AML.

Ablation deletes the axial tissues without significant loss of the neural progenitor population

In order to understand the relative role of different segments of the AML on cephalic development, microsurgical ablation was performed on early neural plate stage embryos to remove either the axial tissues associated with the prospective forebrain and rostral midbrain (A1 segment) or those associated with the prospective caudal midbrain and the hindbrain (A2 segment; Tam, 1989; Fig. 1A). Embryos with deleted A1 segment (designated as A1 embryos) lose the anteriormost Lim1- and Cer1-expressing mesendoderm (Shawlot et al., 1998; Perea-Gomez et al., 1999) when examined immediately after ablation (Fig. 3A,B) and the Hnf3β-expressing anterior midline tissues, but not the T-expressing tissues immediately anterior to the node (at 4-6 hours; Fig. 4A,B,E). The majority (90%) of embryos with deleted A2 segment (designated as A2 embryos) completely lost Hnf3β-expressing tissues in the A2 region (Fig. 4A,C) and T activity was absent in the midline anterior to the node (Fig. 4D-F). These results demonstrate that the microsurgery has ablated the specific AML segment and that the missing tissues were not reconstituted 4-6 hours following ablation.

A1 and A2 embryos were also examined 4-6 hours after ablation for the expression of Otx2 and Hesx1 (Thomas et al., 1995). Both gene activities were detected in the anterior ectoderm of all ablated embryos examined, although Otx2 and Hesx1 expression were diminished in 4/9 and 3/15 A1 embryos, respectively (Fig. 4G-L). These results indicate that
The ablation has not significantly depleted anterior neural progenitors.

**The pattern of displacement of cells in the midline is not affected by tissue ablation**

During the 6-7 hours of in vitro development after dye labelling, A1-labelled ectodermal and mesodermal cells of the intact embryo were displaced anteriorly to the anterior margin of the headfolds (Fig. 5A; n=5). The labelled endodermal cells were displaced more rostrally beyond the neural plate to the region underlying the prospective cardiogenic mesoderm. A2-labelled cells were distributed to the prospective midbrain and upper hindbrain of the embryo (n=6; data not shown). The A1- and A2-labelled cells remained separate from one another at the end of the 6-7 hours of in vitro development (Fig. 5B; n=8), suggesting that during the initial phase of the formation of the headfolds, cells from the two different segments of the AML do not intermingle when they are displaced anteriorly. The normal pattern of displacement of the A1 cells was not affected by A2 ablation (Fig. 5C; n=5). Following A1 ablation, A2-labelled cells did not migrate anteriorly to take the place of the A1 cells but remained in the caudal margin of the ablation (Fig. 5D; n=6).
Compensatory gene activity occurs in the remaining AML and adjacent tissues after A1 ablation

Between the late-gastrula and early-nerual-plate stages, Gsc gene activity is transiently detected in the presumptive prechordal plate (Filosa et al., 1997; Nakamiya et al., 1997; Belo et al., 1998). Although no expression of Hnf3β was detected in the healed wound 4–6 hours after ablation, when A1 embryos were examined for Gsc expression, more than 85% of them displayed de novo Gsc activity in the headfold, suggesting that some non-A1 tissues adopted prechordal characteristics (Table 1A; Fig. 6B). At the early-somite-stage, Gsc expression is restricted to the prechordal plate and the ventral diencephalon (Fig. 7A) and Shh is expressed in the axial mesendoderm along the entire length of the axis and in the ventral neural tube from the anterior forebrain to the anterior hindbrain (Fig. 7D,G). In the majority of the early-somite-stage A1 embryos, developed in vitro for 24–30 hours, Gsc (in 87% of embryo) and Shh (in all embryos) activities were expressed in the ventral tissues at the rostral end of the foreshortened neural axis (Table 2; Fig. 7B,E,H). Histological analysis demonstrated that in A1 embryos, Shh expression was enhanced in the ventral neuroectoderm (Fig. 7K compare 7J) and in the anterior mesendoderm (data not shown) of the truncated headfold. Normally, Nkx2.1 expression is first detected at about the 3-somite stage in the ventral diencephalon (Fig. 7P; Shimamura and Rubenstein, 1997) and Nkx2.1 activity is thought to be regulated by signals emanating from the prechordal plate (Shimamura et al., 1995; Kimura et al., 1996; Dale et al., 1997; Pera and Kessel, 1997; Shimamura and Rubenstein, 1997; Qiu et al., 1998). In A1 embryos, Nkx2.1 expression was detected in the ventral neural tube (Fig. 7Q and histological data not shown; Table 2). The upregulation of Gsc and Shh activity implies that tissues that show similar molecular activity as the anterior mesendoderm may have been reconstituted in response to the absence of A1 tissues. This is accompanied by the differentiation of brain tissues that have ventral forebrain characteristic as demonstrated by Nkx2.1 activity.

Gsc activity is required for the regulation of Nkx2.1 in the ventral neuroectoderm

To test whether Gsc activity is critical for the regulation of Shh and Nkx2.1 activity, we firstly examined the impact of the loss of Gsc in intact Gsc+/+, Gsc−/+ and Gsc−/− early-somite-stage embryos. We found that the complete loss of Gsc activity was associated with the absence of Nkx2.1 expression (Fig. 8) whereas Shh was not affected (Table 3). Embryos of the three genotypes were then subjected to A1 ablation to determine whether, in the absence of Gsc activity, there may be a different genetic response. All six Gsc−/− A1 embryos examined exhibited Shh activity in the notochord but only two of them expressed Shh activity in AML (Table 3; histological data not shown). Therefore, the lack of Gsc activity may compromise, but does not totally abrogate, the compensatory regulation of Shh activity observed in the wild-type A1 embryo. Four of the seven Gsc−/− A1 embryos showed no Nkx2.1 activity (Table 3). Interestingly, the remaining three Gsc−/− A1 embryos did express Nkx2.1 gene in the ventral neural tube (Fig. 8 and

### Table 2. The expression of molecular markers in anterior mesendoderm and ventral neuroectoderm in intact and AML-ablated embryos

<table>
<thead>
<tr>
<th>Ablation</th>
<th>Gene expression (% of embryos)</th>
<th>Control</th>
<th>A1</th>
<th>A2</th>
<th>Somite no.</th>
<th>Increased</th>
<th>Normal</th>
<th>Reduced</th>
<th>Absent</th>
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<tr>
<td>Gsc</td>
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<td>18</td>
<td>23</td>
<td>14</td>
<td>10.2±0.5</td>
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<td></td>
<td>11.4±0.4</td>
<td>–</td>
<td>7</td>
<td>93</td>
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<td>Shh</td>
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<td>16</td>
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<td>10.2±0.4</td>
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<td>65</td>
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<td>11.7±0.3</td>
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<td>Hnf3β</td>
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<td>3</td>
<td>4</td>
<td>9</td>
<td>8.9±0.4</td>
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<td>9.3±0.9</td>
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<td></td>
<td>10.8±0.6</td>
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<td>22</td>
<td>78</td>
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<td>Nkx2.1</td>
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<td>21</td>
<td>21</td>
<td>17</td>
<td>9.0±0.2</td>
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<td>8.6±0.3</td>
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Fig. 6. Gsc activity revealed by whole-mount in situ hybridisation and lacZ reporter expression. (A) Gsc gene expression marks the prechordal plate in the intact embryo (arrowhead). At 6 hours after ablation (B), A1 embryos display strong Gsc expression (arrowhead) whilst (C) A2 embryos show a loss of Gsc expression in the anterior region (asterisk). (D) Gsc+/lacZ A2-ablated embryo at 4–6 hours. The star marks the healed midline. β-galactosidase-positive cells are present in the remaining A1 segment (dashed line), although the transcription is of the normal Gsc allele is no longer detectable by in situ hybridisation (see Fig. 4C). Embryos are orientated with anterior to the left. Scale bar, 25 μm for (A–C) and 15 μm for (D).
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histology not shown; Table 3). This suggests that, although during normal development Gsc activity is required for Nkx2.1 expression, in the course of the compensatory response to A1 ablation, a different but less effective mechanism results in the activation of Nkx2.1 gene.

The loss of A2 segment results in the downregulation of gene activity in axial mesendoderm and ventral forebrain

In contrast to Gsc activation in A1 embryos, Gsc expression was downregulated (reduced in 33% and not detectable in 52% of embryos) in A2 embryos 6 hours after ablation (Table 1A; Fig. 6C). Embryos that carry one Gsc\textsubscript{lacZ} allele (M. W. and R. R. B., unpublished data) were analysed for β-galactosidase activity to monitor the distribution of the Gsc-expressing cells (i.e. the presumptive prechordal plate). When the expression of the lacZ reporter gene was examined in heterozygous Gsc\textsubscript{+/lacZ} A2 embryos after 4-6 hours of in vitro development, lacZ-expressing cells were detected in these embryos (n=6) demonstrating that A2 ablation has not removed the presumptive prechordal tissue (Fig. 6D). The lack of Gsc expression in A2 embryos is therefore likely due to the inability

Fig. 7. Development of the midline tissues of the early-somite-stage embryo after A1 or A2 ablation. (A) Gsc expression is detected in the prechordal plate and ventral forebrain. (B) A1 embryo displays an enhanced Gsc activity in the anterior AML (arrowhead). (C) Asterisk marks the lack of Gsc expression in the anterior tissues of the A2 embryo. (D,G,J) Shh expression is detected in the anterior mesendoderm and ventral forebrain. (E,H) Enhanced Shh expression is found in the headfolds of A1 embryos (arrowhead). (K) Transverse section showing the expression of Shh in the ventral forebrain of A1 embryo. (F,I,L) A2 ablation abrogates the expression of Shh in the mesendoderm and in the ventral neural tube in regions anterior to the 4th somite. Asterisk marks regions that lack Shh activity. (M,N,O) At the level of the trunk, Shh is expressed in the gut endoderm (arrows) and notochord of (M) intact, (N) A1 and (O) A2 embryos. (P) Nkx2.1 is expressed in the ventral forebrain of the control embryo. (Q) Nkx2.1 activity is detected in A1 embryo (arrow head) but absent in (R) A2 embryos (asterisk marks the false positive signal created by the tissue shadow). Embryos are shown with anterior to the left, and either in lateral (A-F,P-R) or ventral (G-I) view. Abbreviations: fb, forebrain; hb, hindbrain; hf, headfold; lm, lateral plate mesoderm; nd, notochord; nt, neural tube; sm, somite. Scale bar, 100 μm for (A-I), 125 μm for (P-R) and 50 μm for (J-O).
to maintain \( Gsc \) activity in the rostral AML beyond the first 4-6 hours after ablation rather than the removal of \( Gsc \)-expressing cells.

At the early-somite-stage, in contrast to A1 ablation findings, the AML tissue left behind after A2 ablation did not display any \( Gsc \) and \( Shh \) activity even though the ablation had not removed the tissues that normally express these two genes (Table 2; Fig. 7C,F,I). The loss of \( Shh \) and \( Gsc \) activity in the ventral forebrain and axial mesendoderm was accompanied by the lack of \( Nkx2.1 \) expression (Table 2; Fig. 7R). In addition, \( T \) and \( Hnf3b \) were not detected in the midline anterior to the fourth somite (Table 2). Consistent with the lack of expression of the markers, histological examination of A2 embryos revealed that tissues that morphologically resemble the floor plate and the axial mesoderm were absent in the head region (Fig. 7L). Ablation of midline tissues posterior to A2 produced different defects of the axial mesendoderm. Eight of ten node-ablated embryos showed normal \( Gsc \) expression in the AML (data not shown) and only the notochord and the floor plate in the trunk were affected (Davidson et al., 1999). Ablation of the anterior third of the PS had no effect on the formation of midline structures as demonstrated by the appropriate expression of \( Hnf3b \) (\( n=10; \) data not shown). Thus, the maintenance of rostral axial mesendoderm seems to specifically require an intact A2 segment and not other more posterior midline structures.

### Defective development of the forebrain and midbrain in the absence of AML

When examined after 24-30 hours of in vitro development, A1 embryos displayed variable deficiencies of anterior structures, ranging from absence of the optic eminence and small headfold to a severe truncation of the anterior neural axis (Figs 7, 9). Nevertheless, appropriate region-specific neural markers were still expressed in the truncated neural axis, although the expression domains were often altered. The expression domain of \( En1 \), a marker for the midbrain (Davis and Joyner, 1988), was shifted rostrally suggesting that the dorsal and rostral forebrain domains were significantly reduced (Fig. 9N,M). In some A1 embryos, \( Hexx1 \) and \( Wnt1 \) expression domains (Parr et al., 1993) were juxtaposed, indicating that the neural tissue normally found between these brain segments was either absent or severely reduced (Fig. 10). Moreover, the \( Hexx1 \) domain itself was reduced or absent in A1 embryos (Table 4; Fig. 9G,H) while the expression of \( Six3 \) (Oliver et al., 1995) and \( Fgf8 \) (Crossley and Martin, 1995) was either markedly reduced or missing in more than 89% of A1 embryos (Table 4; Fig. 9A,B,D,E). This specific loss of \( Six3 \) and \( Fgf8 \) expression suggests that the differentiation of the rostral forebrain is impaired in the A1 embryos.

\( Hexx1 \) expression was substantially reduced or extinguished in the forebrain of the A2 embryos examined after 24-30 hours of in vitro development (Table 4; Fig. 9I). Moreover, \( Fgf8 \) activity in the forebrain was absent (\( n=4 \)) or was expressed unilaterally (\( n=4 \)) in some A2 embryos (for a total of 11 embryos examined; Table 4; Fig. 9C). \( Fgf8 \) expression was also reduced or absent at the midbrain-hindbrain junction (\( n=9; \) Fig. 9C) but \( Wnt1 \) expression was normal (data not shown). Despite these defects in neural patterning, morphogenesis of the neural tube was not overtly affected in A2 embryos (Table 4). The results suggest that the maintenance of \( Hexx1 \) and \( Fgf8 \) activities in the brain is dependent on the functional integrity of the AML, which may be disrupted just by A2 ablation. When \( Gsc^{-/-} \) mutant embryos were analysed for \( Hexx1 \) activity, we found no difference in expression among embryos of the three genotypes (\( Gsc^{+/+} n=9; Gsc^{-/-} n=24; Gsc^{+/-} n=4, \) data not shown). This result indicates that the loss of \( Gsc \) activity in the rostral AML could not account for the downregulation of the expression of the forebrain marker \( Hexx1 \) in A2-ablated embryos.

### AML can induce ectopic neural gene expression

Transplantation experiments were performed to test the ability of the AML tissues to induce region-specific neural gene activity. A1 segment, containing the prechordal plate, and the A2 segment, containing the notochord, were grafted separately to the lateral region of host embryos (Fig. 1B).

To determine whether the grafted segments retain their regional characteristics in ectopic sites, A1 and A2 grafts were assessed for \( Hnf3b \) and \( Gsc \) activity 6 hours after transplantation. Both A1 and A2 tissues expressed \( Hnf3b \) activity normally associated with midline tissues (\( n=2, \) data not shown). Only 3 of 8 A1 grafts contained a weak \( Gsc \) activity, while all A2 grafts strongly expressed \( Gsc \) (Table 1B; Fig. 11A-C). Therefore A1 tissues, when isolated from other AML, failed to maintain the prechordal property, a finding consistent

#### Table 3. Expression of \( Shh \) and \( Nkx2.1 \) in anterior mesendoderm and ventral neural tube in intact and A1 embryos of different \( Gsc \) genotypes

<table>
<thead>
<tr>
<th>Gsc embryos</th>
<th>(+/+)</th>
<th>(+/-)</th>
<th>(-/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>A1</td>
<td>Intact</td>
</tr>
<tr>
<td>( Shh ) expression in anterior neural tube</td>
<td>8/8</td>
<td>10/11</td>
<td>12/12</td>
</tr>
<tr>
<td>( Nkx2.1 ) expression in ventral forebrain</td>
<td>14/14</td>
<td>12/16</td>
<td>8/8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Intact</th>
<th>A1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Shh ) expression in anterior neural tube</td>
<td>7/7</td>
<td>2/6*#</td>
</tr>
<tr>
<td>( Nkx2.1 ) expression in ventral forebrain</td>
<td>1/10#</td>
<td>3/7</td>
</tr>
</tbody>
</table>

Significant difference from * intact \( Gsc^{-/-} \) group and # intact \( Gsc^{+/-} \) and \( Gsc^{+/-} \) groups by \( \chi^2 \) 2x2 test at \( P<0.01 \).
with the loss of Gsc expression in the remaining A1 tissues after removing A2 tissues. The upregulation of Gsc activity in the transplanted A2 tissue is reminiscent of the compensatory upregulation of Gsc observed in the remaining AML tissues after A1 ablation (Table 1A).

After transplantation, more than 87% of the A1 and all A2 fragments were incorporated in the brain region of the early-somite-stage host embryo. When fragments of lateral germ layer (LG) tissues of the late gastrula embryo were transplanted, only 49% of the grafts were found in the host neural tube. The A1, A2 and LG grafts were examined for the expression of the pan-neural marker Sox2 (Wood and Episkopou, 1999) and regional markers such as Hesx1, Otx2 and En1 (Table 5). Sox2 expression was found in most A1 and A2 grafted tissues (about 66%) and in 71% of LG grafts. However, only 13% of LG grafts expressed Otx2 whereas this activity was detected in 72% of A1 and A2 grafts. Both A1 and A2 grafts also expressed En1 but only A1 grafts expressed Hesx1. En1 or Hesx1 activity was never detected within LG grafts. These findings indicate that, upon transplantation, the AML tissues retain their original segment-specific neural characteristics whereas LG tissues, although expressing Sox2, did not display any consistent regional neural gene activity.
In the presence of either A1 and A2 grafts, an extra headfold or broadened host neural plate was often observed in the host embryo (Fig. 11D,E), whereas none of the LG grafts had elicited the differentiation of extra neural tissue. Analyses of the host tissues in the vicinity of the grafts revealed that Sox2 expression was detected in 50% and 17% of embryos receiving A1 and A2 graft respectively (Table 5; Fig. 12B,C). An expansion of Otx2 expression was observed in the host neural tube in 27% of A1 grafts and 36% of A2 grafts (Table 5, Fig. 12E,F). However, no de novo Hesx1 activity was induced in the host tissues by either A1 or A2 grafts (Table 5). A2 grafts elicited ectopic expression of En1 activity more frequently (77%; Fig. 12I) than A1 grafts (15%). Interestingly, in 61% of the cases where the A1 graft had been incorporated into the host midbrain, En1 expression in the host tissue was suppressed (Fig. 12H). Control LG grafts never induced de novo expression of segment-specific neural genes in the host tissue (Table 5; Fig. 12A,D,G). Our results show that, although both A1 and A2 grafts can elicit de novo expression of particular neural genes, they are unable to impart any patterning activity on the host neural axis under these experimental conditions.

Table 4. The expression of markers in the forebrain of A1- and A2-ablated embryos

<table>
<thead>
<tr>
<th>Morphology</th>
<th>Gene expression: % of embryos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Somites</td>
<td>Anterior truncation</td>
</tr>
<tr>
<td></td>
<td>Eye eminence</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>Reduced</td>
</tr>
<tr>
<td></td>
<td>Absent</td>
</tr>
</tbody>
</table>

Table 5. Expression neural markers in the grafts of anterior midline (AML) fragments and the host tissues

<table>
<thead>
<tr>
<th>Transplantation</th>
<th>Sox2</th>
<th>Otx2</th>
<th>Hesx1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
<td>LG</td>
</tr>
<tr>
<td></td>
<td>Graft</td>
<td>Host</td>
<td>Graft</td>
</tr>
<tr>
<td>A1</td>
<td>6</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>A2</td>
<td>6</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>LG</td>
<td>14</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

A1, rostral AML fragment; A2, caudal AML fragment; LG, lateral germ layers; see Fig. 1. Numbers in the “Total” column indicate the number of grafts conducted with each tissue fragment, “Graft” indicates the number of grafted fragments expressing the marker whereas the “host” indicates the number of specimen showing expression in the host tissues.

In the presence of either A1 and A2 grafts, an extra headfold or broadened host neural plate was often observed in the host embryo (Fig. 11D,E), whereas none of the LG grafts had elicited the differentiation of extra neural tissue. Analyses of the host tissues in the vicinity of the grafts revealed that Sox2 expression was detected in 50% and 17% of embryos receiving A1 and A2 graft respectively (Table 5; Fig. 12B,C). An expansion of Otx2 expression was observed in the host neural tube in 27% of A1 grafts and 36% of A2 grafts (Table 5, Fig. 12E,F). However, no de novo Hesx1 activity was induced in the host tissues by either A1 or A2 grafts (Table 5). A2 grafts elicited ectopic expression of En1 activity more frequently (77%; Fig. 12I) than A1 grafts (15%). Interestingly, in 61% of the cases where the A1 graft had been incorporated into the host midbrain, En1 expression in the host tissue was suppressed (Fig. 12H). Control LG grafts never induced de novo expression of segment-specific neural genes in the host tissue (Table 5; Fig. 12A,D,G). Our results show that, although both A1 and A2 grafts can elicit de novo expression of particular neural genes, they are unable to impart any patterning activity on the host neural axis under these experimental conditions.

Fig. 10. Regionalisation of the neural tube of A1 embryos assessed by double in situ hybridisation of Hesx1 and Wnt1. Hesx1 is normally expressed in the ventral forebrain and Wnt1 is expressed in the midbrain, upper hindbrain, the dorsal region of the lower hindbrain and spinal cord (left panel). A1 ablation (right panel) results in a rostral expansion of the Hesx1 domain of expression leaving a markedly reduced amount of Hesx1-free tissue (dashed line). The expression domain of the Wnt1 gene shifts rostrally and the normally separate expression domains in the dorsal neural tube (marked with an asterisk in the intact embryo) merge together. Arrowhead marks the first branchial arch. Scale bar, 100 μm.
DISCUSSION

Whether the correct patterning and morphogenesis of the anterior neural plate of the mouse embryo are dependent on the inductive interaction with the anterior mesendodermal tissues has been a contentious issue (Bally-Cuif and Boncinelli, 1997). In this study, we have investigated the impact of removing either the AML, the node or the anterior PS of the early neural plate stage mouse embryo and the subsequent effects on anterior development. We have shown that the removal of the AML leads to defective morphogenesis of the anterior neural tube during neurulation. Furthermore, the ablation of specific
segments of the AML has differential effects on the regionalisation of the neural tube and the differentiation of the midline tissues (Fig. 13). The ablation of the rostral AML disrupts morphogenesis and regionalisation of the forebrain. However, a compensatory molecular mechanism leads to the upregulation of genes specifically expressed in the rostral AML and the specification of ventral forebrain tissues takes place. We further showed that Gsc is required for the morphogenetic activity of the rostral AML. The ablation of the caudal AML does not cause the truncation of the neural axis but leads to the failure of the differentiation of the axial mesendoderm, ventral diencephalon and floor plate of the head region. The functional requirement of this caudal segment for the maintenance of the prechordal plate and the ventral forebrain development represents a previously unexpected role. Finally, transplantation experiments have shown that both segments of the AML can induce neural gene activity but exhibit limited patterning activity.

**Development of the forebrain and midbrain require AML activity**

The expression analysis of region-specific markers has shown that A1 ablation leads to a reduction or absence of expression of forebrain markers, Hexx1, Six3 and Fgf8. These findings indicate a requirement of the rostral AML for the patterning of the forebrain neural precursors during neurulation. The ablation of the rostral segment of the AML may also have removed the anterior neural ridge (ANR) precursor cells at the junction of the anterior neural plate and the non-neural ectoderm. Specific signals emanating from the ANR have been shown to play a role in growth and regional specification within the forebrain (Shimamura and Rubenstein, 1997; Houart et al., 1998) and their removal may affect the growth of the forebrain tissues and result in truncation of the cephalic neural tube. Interestingly, in A1 embryos, the En1- and Wnt1-expressing midbrain tissues seem to merge with the Hexx1-expressing forebrain tissues. The loss of rostral midline tissues therefore seems to cause a deficiency of forebrain tissues. The deficiency in forebrain tissues may reflect a predominant differentiation of the neural precursors into midbrain tissues in the absence of rostral AML at the early neural plate stage. A potential role for the AML that contains the prechordal plate is the maintenance of an anteriorising signal to counteract the posteriorising signals imposed on the forebrain (Ang et al., 1994; Bally-Cuif and Boncinelli, 1997; Bang et al., 1997; Foley et al., 1997; Rowan et al., 1999).

Ablation of the caudal segment of the AML also leads to significant changes in the patterning of the forebrain. The anterior marker Hexx1 is downregulated or absent in the early-somite-stage A2 embryos. Moreover, A2 ablation results in the loss of Gsc and absence of Nkx2.1 activity in the forebrain. However, only Nkx2.1 expression is affected in Gsc-deficient embryos while Hexx1 expression is unaffected. These findings strongly suggest a requirement for Gsc activity in the specification of the ventral forebrain. In contrast, Gsc activity is not essential for the morphogenetic activity of the AML responsible for maintenance of the early anterior regional neural marker Hexx1 (Thomas and Beddington, 1996).

**Caudal AML activity is required for the maintenance of the prechordal mesendoderm and can compensate for the loss of rostral AML tissues**

The loss of Gsc, Shh, Hnf3β and T activity in the axial
mesendoderm and floor plate in the head region in the A2 embryo (Fig. 13) suggest that the caudal AML is required for the maintenance of the prechordal plate and the ventral neuroectoderm of the anterior neural tube. In this study, since the ablation removes the axial mesendoderm and neuroectoderm precursors, we were not able to discriminate the relative role of the two tissue components in the maintenance of the rostral AML. The disruption of the specification of ventral neural fates and the absence of Nkx2.1 activity in the forebrain can be related to the loss of anterior mesendoderm in A2 embryos. This role of the AML on dorsoventral patterning is consistent with the notion that axial mesendoderm provides inductive signals for the establishment of dorsoventral polarity and the specification of neuronal types in the neural tube (Ruiz i Altaba, 1994; Tanabe and Jessell, 1996; Dale et al., 1997, 1999; Shimamura and Rubenstein, 1997).

In contrast to A2 embryos, A1 embryos express Shh, Hnf3β and T in the midline and are able to reconstitute the Gsc activity after the ablation of the Gsc-expressing rostral AML (Fig. 13). Moreover, the presence of Nkx2.1-expressing cells in A1 embryos suggests that the reconstituted AML has the ability to differentiate into ventral forebrain tissue. Consistent with the response of the caudal AML in the embryo following A1 ablation, the same tissue fragment expresses Gsc strongly after its separation from the rostral AML and transplantation to ectopic site. This raises the intriguing possibility of the existence of morphogenetic interactions between the two segments of the AML, which serve to maintain their segment-specific genetic activity and tissue potency.

Collectively, these results suggest that the rostral segment is dependent on signals emanating from the caudal segment to maintain its function. In return, the rostral AML may act to inhibit the caudal AML from adopting a prechordal fate. When the caudal AML is released from this constraint it will activate de novo genetic activity to restore the patterning role that normally resides within the rostral AML.

Goosecoid is essential for the specification of the ventral forebrain and is involved in the regulatory mechanisms leading to the reconstitution of rostral AML activity

Several studies have supported a role for Shh acting alone (Roelink et al., 1994; Ericson et al., 1995, 1996; Shimamura and Rubenstein, 1997) or with Bmp7 (Dale et al., 1997, 1999) in the regulation of the Nkx2.1 activity. In this study, a molecular analysis performed on early-somite-stage Gsc-deficient embryos demonstrates an absence of Nkx2.1 expression within the ventral neural tube. Since Shh expression appears normal in these Nkx2.1 embryos, we conclude that Shh activity is not sufficient and that Gsc activity is required for Nkx2.1 expression in the ventral diencephalon.

In wild-type embryos, both Shh and Gsc expressions are enhanced in the AML following A1 ablation. Interestingly, the same ablation performed on Gsc−/− embryos provides evidence that these embryos are compromised in their ability to upregulate Shh activity in the anterior neural tube, although expression in the mesendoderm appears unaffected. This finding supports a requirement for Gsc in the mechanism leading to the reconstitution of the AML activity. Surprisingly, we found that some Gsc−/− embryos display Nkx2.1 expression within the ventral neural tube following A1 ablation. An initial interpretation of these observations may be that a parallel molecular mechanism is promoted for the reconstitution of the AML and the specification of ventral diencephalon fate within Gsc−/− A1 embryos. An alternative interpretation may be that the compensatory expression of Shh activity that occurs in some Gsc−/− A1 embryos is sufficient to elicit Nkx2.1 expression.

Does the mouse AML possess neural-inducing and regionalising properties?

Results of our transplantation experiments show that both rostral and caudal AML possess neural-inducing ability (formation of extra neuroectoderm and induction of Sox2) and patterning activity (ectopic induction of regional markers such as Otx2 and En1). This finding is reminiscent of those of other studies in which the anterior mesendoderm (including some axial, paraxial and lateral tissues) from neural-fold-stage mouse embryos can induce the expression of Otx2 and En1 in the early gastrula epiblast (Ang and Rossant, 1993; Ang et al., 1994). In our experiments, we found that the lateral germ layers, which contain neuroectoderm precursors but lack axial mesendoderm, display no inductive activity. This strongly suggests that the neural inductive activity is provided by the axial mesendoderm in the AML fragment and is not brought about by homeogenetic induction by the neural precursors in the graft.

Contrasting results on the anteriorizing and ventralising activity of the prechordal plate have been reported for the mouse and the rat embryo (Dale et al., 1997; Shimamura and Rubenstein, 1997). In our study, an inhibition of En1 expression is found adjacent to rostral AML grafts in the host midbrain. However, we found that neither segment of the AML has the ability to impart anterior forebrain identity to the host neural plate (no ectopic induction of the anterior marker Hesx1). The suppression of En1 but not induction of Hesx1 in the host midbrain by A1 grafts suggest that rostral AML may modify but cannot impart novel anterior regional characteristics to more posterior levels of the host neural tube. This finding may reflect a restriction in the competence of the neural plate to respond to inducing signals. It has been demonstrated that the germ layers of the late primitive streak embryo can respond to inducing signals by expressing region-specific neural markers, Otx2, En1 and Krox20 (Tam and Steiner, 1999), and that later the headfold stage ectoderm retains the ability to respond to En2-inducing signals in explant-recombination assays (Ang and Rossant, 1993). Nevertheless, the window of time during development when the neuroectoderm remains competent to respond to specific inducing signals is not yet established in the mouse.

Results of our study point to a role of the AML in the maintenance of the segmental characteristics of the neural axis and subsequent regionalisation of the developing forebrain. Furthermore, our findings provide evidence that continuous interactions between the rostral and caudal segments of the AML are essential for the regionalisation and patterning activity of the anterior mesendoderm.

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