Expression of activin subunits, activin receptors and follistatin in postimplantation mouse embryos suggests specific developmental functions for different activins

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SUMMARY

Using in situ hybridization we have studied the localization of the messenger RNAs encoding the inhibin/activin subunits (α, βA, βB), the activin-binding protein follistatin and activin receptors (IIA, IIB) in mouse embryos during postimplantation development.

From 6.5- to 9.5-days post coitum (p.c.) activin βA and βB subunit expression was restricted to the decidua, while activin receptor type IIB messages were exclusively detected in the embryo. Expression of activin receptor type IIA was apparent in the embryo as early as 9.5 days p.c. In contrast, follistatin transcripts were present in both the decidua and the embryo at the early postimplantation stages. In particular, the primitive streak region, specific rhombomeres in the developing hindbrain, somites, paraxial mesoderm and parietal endoderm cells attached to the Reichert’s membrane showed strong expression of follistatin.

In 10.5- and 12.5-day embryos expression of the βA subunit message was abundant in mesenchymal tissue, in particular in the developing face, the body wall, the heart, precartilage condensations in the limb and in the mesenchyme of structures that show both epithelial and mesenchymal components, including tissues of the embryonic digestive, respiratory and genital tracts. The distribution of βB transcripts was quite different from that observed for βA. βB is strongly expressed in selected regions of the brain, in particular the fore- and hindbrain, and in the spinal cord. Specific hybridization signals were also present in the epithelium of the stomach and oesophagus. Common sites of βA and βB expression are blood vessels, intervertebral disc anlagen, mesenchymal condensations in the flank region and the gonad primordium. The latter organ is the only site in the embryo where the α subunit is expressed, and thus where inhibin activity may be present.

During the period of organogenesis the sites of expression of activin receptors type IIA and IIB messenger RNA (mRNA) generally coincide with or are adjacent to the sites of β subunit expression. Differences in the expression patterns of the receptor RNAs are the whisker follicles, where type IIA is expressed, and the metanephros and the forebrain where type IIB transcripts are present.

Taken together, the present data suggest that follistatin, but not one of the known activin forms (A, B, AB) is involved in early postimplantation development. During organogenesis a role is suggested for (1) activin A in the formation of the inner ear, tongue and lung and during morphogenesis of craniofacial structures, (2) activin B in the development of the stomach and the central nervous system as well as in the development of the eyelids, and (3) activin AB in limb and shoulder development. However, in or adjacent to some of these developing structures follistatin is also produced. The different forms of follistatin have different capacities to regulate activin activity so that both the particular form of follistatin and its distribution in relation to that of activins will determine whether activins are indeed involved in the development or morphogenesis of specific organs.

Key words: activins, activin-binding proteins, murine embryogenesis, in situ hybridization

INTRODUCTION

Activins are now thought to be important regulators of early developmental processes in vertebrates. Originally, however, these factors and their relatives, the inhibins, were isolated as gonadal proteins from follicular fluid and purified on the basis of their capacity to regulate the release of follicle-stimulating hormone (FSH) from the pituitary (for a review see Ying, 1988 and Ling et al., 1988). Activins and inhibins are members of the transforming growth factor (TGF)β superfamily of structurally related, but functionally diverse proteins. The activins are dimeric proteins, composed of disulphide-linked βA or βB subunits. At least three different forms of activin are known to occur in vivo; the homodimeric activin A (βAβA) and activin B (βBβB) forms and the heterodimeric activin AB (βAβB; Ying, 1988; Ling et al., 1988; Mason et al., 1989; Nakamura...
et al., 1992a; Fukui et al., 1993). There are two forms of inhibin (A and B) consisting of a \(\beta A\) or \(\beta B\) subunit linked to a distantly related inhibin-specific \(\alpha\) subunit.

Activins bind to at least two prominent classes of cell surface proteins, type I receptors (50-55 x 10^3 M\(_{-1}\)) and type II receptors (70-75 x 10^3 M\(_{-1}\); Hino et al., 1989; Centrella et al., 1991; Mathews et al., 1991). Cloning of the activin type IIA receptor (Act R-IIA; Mathews and Vale, 1991; Kondo et al., 1991; Matzuk and Bradley, 1992 a;b; Donaldson et al., 1992; Shiozaki et al., 1992) and the activin type IIB receptors (Act R-IIB; Attisano et al., 1992; Mathews et al., 1992; Legerski et al., 1992; Nishimatsu et al., 1992) has shown that these receptors have intracellular kinase domains with predicted serine/threonine specificity. Recently a \textit{Drosophila} type II activin receptor, Atr-II, has been identified which might represent a third activin type II receptor isoform not yet identified in vertebrates (Childs et al., 1993).

Recently two human activin type I receptors, Act R-I (Attisano et al., 1993) and Act R-IB (Carcano et al., 1994) were cloned and shown to be essential for activin signalling. Act R-I and Act R-IB are identical to the activin receptor-like kinases 2 (ALK-2) and 4 (ALK-4), respectively (ten Djike et al., 1993, 1994). Also the sequences of the rat homologues of Act R-I and Act R-IB (Tsushida et al., 1993; R-1, He et al., 1993) and the mouse Act R-I homologue (Ebner et al., 1993a) have been reported. The latter murine receptor, Tsk-7L, was originally isolated as a TGFB type I receptor, but was later shown to be promiscuous in that it binds both activin and TGFB (Ebner et al., 1993b). Signalling, however, occurs only for activin (Attisano et al., 1993). In addition to these receptors a \textit{Drosophila} activin type I receptor (Atr-I; Wrana et al., 1994), and another shared TGFB/activin type I receptor from human (TSR-I, Attisano et al., 1993) or rat (R-3, He et al., 1993) have been identified. Whether these receptors also have signalling capacity is still unknown.

Apart from cell surface receptors, there are other activin-binding proteins known as follistatins: these are glycosylated polypeptides originally isolated from porcine follicular fluid, that, like the inhibins, inhibit FSH secretion (Ueno et al., 1987; Shimasaki et al., 1988a,b; for a review see Michel et al., 1993). At least six isoforms of follistatin have been identified that are generated by truncations in the C terminus and/or the presence of Asn-linked carbohydrate chains. The isoforms can be divided into three groups, representing follistatins of 315 amino acids (FS-315), 303 (FS-303) and 288 amino acids (FS-288). FS-303 is probably the major component in the follistatin preparation from porcine follicular fluid (Inoue et al., 1991; Sugino et al., 1993). This protein has a specific and high affinity for activin and neutralizes its effects in a variety of systems (Nakamura et al., 1990; Kagawa et al., 1991; Xiao and Findlay, 1991; Asashima et al., 1991; Hashimoto et al., 1992; Shiozaki et al., 1992). Although follistatin binds to both activin and inhibit through the common \(\beta\) subunit (Shimonaka et al., 1991), binding does not affect the biological activity of inhibit (Ying et al., 1987).

Activins are involved in many biological processes outside the pituitary-gonadal axis (for a review see Ueno et al., 1990; Vale et al., 1990). In particular, the different forms of activin have the capacity to act as mesoderm-inducing factors in amphibian development (Albano et al., 1990; Asashima et al., 1990; Smith et al., 1990; Thomsen et al., 1990; van den Eijnden-van Raaij et al., 1990; Nakamura et al., 1992a). The sharp thresholds and multiple stable responses to activin A indicated that this factor has the properties of a classical morphogen (Green and Smith, 1990). Recently it was found that activin A also induces axial structures, including notochord and somites in the chick epiblast (Mitrani and Shimoni, 1990; Mitrani et al., 1990) and newt presumptive ectoderm (Moriya and Asashima, 1992). Exposure of animal cap cells of zebrafish to activin A induces the zebrafish T gene (\(\text{T}-\text{T}\)), which is a marker for mesodermal tissue including notochord (Schulte-Merker et al., 1992). These results suggest that activin may be one of the natural inducers of mesoderm in a wide range of species. This hypothesis was strengthened by the observation that injection of a truncated activin type IIB receptor into \textit{Xenopus} embryos completely prevents mesoderm induction and dorsal body axis formation (Hemmatti-Brivianlou and Melton, 1992, 1994). In addition, it was shown that inhibition of activin receptor signalling promotes neuralization in \textit{Xenopus}, indicating a role for activin in the control of neural induction (Hemmatti-Brivianlou et al., 1994). Little is known about the function of activins and activin-binding proteins during murine embryogenesis. Using the P19 embryonal carcinoma (EC) cell line as a model for studying mesodermal and neural differentiation in the mouse, we have recently shown that activin A itself has no mesoderm-inducing activity in this system. In fact, activin A completely inhibits differentiation of P19 EC cells into derivatives of any of the three germ layers (van den Eijnden-van Raaij et al., 1991; Hashimoto et al., 1990). In addition, depending on the culture conditions, activin A acts as a potent mitogen for P19 EC cells or promotes their survival in monolayer (Schubert and kimura, 1991; Schubert et al., 1990). These results together with the identification of activin-binding sites on P19 EC cells (Kondo et al., 1989; Nakamura et al., 1992b) suggest that activins may have a regulatory function in differentiation during early murine development.

Expression studies in differentiating EC and embryonic stem (ES) cells, and in the mouse embryo itself showed that the expression of inhibin subunits and follistatin, but not of activin type IIA receptor is developmentally regulated (van den Eijnden-van Raaij et al., 1992; Albano et al., 1993; Lu et al., 1993). For the \(\beta A\) and \(\beta B\) subunits, this was confirmed at the protein level with subunit-specific antibodies (Paulusma et al., 1994). The detection of the inhibin subunits in early postimplantation mouse embryos by reverse transcription-polymerase chain reaction (RT-PCR) analysis contrasts with the results of in situ hybridization studies by Manova et al. (1992). These authors showed that in 5.5- to 9.5-day mouse embryos inhibit \(\beta A\) is expressed exclusively in maternal decidual tissue while \(\beta B\) and \(\alpha\) transcripts are not present in either the embryo proper or the decidua. The mRNA level of the inhibin subunits is probably below the detection limit of in situ hybridization. We have recently shown in some preliminary in situ hybridization studies of 12.5-day mouse embryos that there are characteristic and distinct expression patterns for the three inhibin subunits and for activin-binding proteins, which suggested that different forms of activin have different functions during murine development (Mummery and van den Eijnden-van Raaij, 1993). In the present paper we describe in detail the expression of the inhibin subunits, follistatin and activin...
receptors type IIA and IIB in histological sections of mouse embryos from 6.0- to 12.5-days post coitum (p.c.). The results are discussed in terms of the putative functions of the different forms of activin in mammalian embryonic processes in vivo.

MATERIALS AND METHODS

Embryos
Mouse embryos collected between 6.0- and 12.5-days post coitum (p.c.) were obtained from F1 crosses between C57BL6 females and CBA males (midday on the date of finding a vaginal plug was designated 0.5 day). 6.0- to 8.5-day embryos were left in the decidua and 9.5- to 12.5-day embryos were dissected free from their membranes.

Cell culture, RNA isolation and northern blotting
Culture of P19 embryonal carcinoma (EC) cells, embryonic stem cells (ES-5) and the P19-derived mesodermal cell line MES-1 was as described previously (Mummery et al., 1985, 1986, 1990a,b). Isolation of polyadenylated RNA and northern blotting were carried out as described by van den Eijnden-van Raaij et al. (1992).

Probe synthesis
Constructs for in situ hybridization were generated by cloning the following fragments into the pBluescript SK II+ vector (Stratagene) in anti-sense orientation with respect to the T7 promoter: βA, a 276 nucleotide fragment, spanning amino acid residues 309-399 (Albano et al., 1993); BB, a 350 nucleotide fragment, spanning amino acid residues 196-312 (Esch et al., 1987); α, a 249 nucleotide fragment, spanning amino acid residues 194-277 (Albano et al., 1993); follistatin, a 324 nucleotide fragment, spanning amino acid residues 171-279 (Shimasaki et al., 1988a); activin type IIA receptor, a 239 nucleotide SspI-KpnI fragment (Mathews and Vale, 1991); spanning amino acid residues 61-140; activin type IIB receptor, a 235 nucleotide fragment, spanning amino acid residues 75-153 (Attisano et al., 1992).

Except for the activin type IIA receptor fragment, all fragments were obtained by amplification of reverse transcriptase products of total RNA from mouse cells or tissue expressing the particular gene, using the polymerase chain reaction (PCR). In brief, first strand cDNA was synthesized using RNA isolated from P19 (Act R-IIB, follistatin), ES-5 (βB), MES-1 (βA) cells and mouse ovary (α) as template and oligo (dT) as primer. The cDNA was amplified in a PCR reaction using specific primers, containing unique cloning sites (BamHI site for 5′ primer; EcoRI site for 3′ primer).

All constructs were verified by sequencing qiaqen purified DNA preparations and tested on northern blots for specificity. RNA probes were generated by transcription of the T3 or T7 RNA polymerase promoter in the presence of α-35S-UTP (Amersham).

In situ hybridization
In situ hybridization analysis was performed as described by Wilkinson et al. (1990) with slight modification. Embryos were fixed in 4% paraformaldehyde, dehydrated through alcohol and embedded with haematoxylin.

Washing was repeated. The sections were washed in 2× SSC and 0.1× SSC for 15 minutes at room temperature and dehydrated in ethanol containing 300 mM ammonium acetate and air dried. Autoradiography was performed by using Ilford G5 photo emulsion 1:1 diluted with 2% glycerol/water. The sections were air dried and exposed for 2 weeks in a light-safe box containing silica gel at 4°C. Slides were developed in Kodak D19, fixed in Kodak UNIFIX and counterstained with haematoxylin.

RESULTS

Recent data on the expression of inhibin subunits, follistatin and type II activin receptors in differentiating murine EC and ES cells, and in the mouse embryo, pointed to a potential role for these factors during murine development (van den Eijnden-van Raaij et al., 1992; Albano et al., 1993, 1994; Mummery and van den Eijnden-van Raaij, 1993). In order to define more precisely the tissues and cell types expressing these genes we carried out an in situ hybridization study in 6.0- to 12.5-day mouse embryos, using 35S-labelled single-stranded antisense riboprobes. The specificity of the probes for the inhibin subunits and the activin receptors IIA and IIB was checked by using the cDNAs from which they were generated on northern blots of mouse cells expressing the different genes. As shown in Fig. 1 each probe detected only the predicted transcript sizes for the respective gene in the cell or tissue type expected (see also van den Eijnden-van Raaij et al., 1992); there is therefore no cross-reactivity between the different probes. This, together with the high stringency conditions used for in situ hybridization should result in the specific detection of the messenger RNAs (mRNAs) of interest. Indeed each gene shows a unique transcript distribution during murine embryogenesis. A comparison of the mRNA localization of the inhibin/activin subunits, activin receptors and follistatin in a 12.5-day mouse embryo is shown in Table 1. These expression patterns are quite similar to those observed in rat embryos (Roberts et al., 1991; Roberts and Barth, 1994). Control hybridizations using the corresponding sense RNA probes gave no specific signal above background (not shown).

Fig. 1. Northern blot analysis of the inhibin α, βA and βB subunit probes and the activin type IIA and IIB receptor probes used for this study. (A) βA subunit, (B) βB subunit, (C) α subunit, (D) activin type IIA receptor, (E) activin type IIB receptor. 1 and 3 refer to P19 EC, ES-5 and MES-1 cells, respectively. Ov refers to murine ovary. Each probe showed a different specificity. Transcript sizes (in kilobases) are indicated on the right, positions of ribosomal 18S and 28S subunits are shown on the left. Equal loading was confirmed using a glyceraldehyde phosphate dehydrogenase cDNA as probe (not shown).
Localization of βA subunit mRNA

A general observation from the in situ hybridization studies was that expression of the βA subunit mRNA was absent in early postimplantation mouse embryos (6.0 to 9.5 days p.c.), but was present in a specific subset of decidual cells, confirming the expression pattern described earlier (Manova et al., 1992; Albano et al., 1994).

In 10.5- and 12.5-day mouse embryos βA subunit mRNA was abundant in the mesenchymal cells of structures that show both epithelial and mesenchymal components (Figs 2, 3). In particular the condensed mesenchyme in the head, surrounding the olfactory epithelium (Fig. 2A,B,E) and Jacobson’s organ (Fig. 2B), and the mesenchyme adjacent to the epithelia of the cochlea (Fig. 2A,H) were positive. A strong hybridization signal was also present in the mesenchyme along the epithelium lining the nasal cavity (Fig. 2F), the nasopharynx (Fig. 2A,C,H) and lining the roof of the buccal cavity (Fig. 2A,E,H) and through the mesenchyme of the palatine processes (Fig. 2F). In addition, the mesenchyme of the tooth primordia in the upper and lower jaws (Fig. 2E,F), the mesenchyme in the developing vibrissae (Fig. 2G), the condensed mesenchyme in the orbita around the developing eye (Fig. 2F) and mesenchymal structures in the tongue (Fig. 2A,E) express the βA message. βA subunit mRNA is also localized on the dorsal side of the genital eminence and the septum urogenitale (Figs 2A, 3A), and is present in tissues of the embryonic digestive and respiratory tract. βA transcripts are seen in the mesenchyme in the hilus of the lung (Fig. 3C) and in the mesenchymal tissue underlying the epithelial layer of the esophagus, rectum and trachea (Fig. 3A,B,D). In the alveoli, stomach, liver, metanephros and intestine no specific hybridization signal was observed (Figs 2, 3). Also the central nervous system, including brain and spinal cord was completely negative (Fig. 2).

The data further show that βA subunit mRNA is present in the mesenchyme of the anterior body wall (Fig. 2A,E,F), in the pleuropertitoneal membrane (Figs 2A,D, 3G,H) and in the wall of large blood vessels, including the aorta (Fig. 3B,D), the truncus arteriosus and truncus pulmonalis (Fig. 3G), the carotid artery (Fig. 2H) and blood vessels in the umbilical stalk (Fig. 2E). In the heart, expression is seen in the atrioventricular bulbar cushion tissue, while the walls of the heart ventricles are negative (Fig. 3D). High levels of βA subunit transcripts were visible in the intervertebral disc anlagen (Figs 2A, 3B,D) and mesenchymal condensations in the cervical region (Fig. 3E), shoulder girdle (Fig. 3E) and groin region (Fig. 2B). In the limbs, βA expression was restricted to precartilage condensations (Fig. 3F). A striking observation was that the gonad primordium was either positive (Fig. 3G) or negative (not shown) for βA transcripts. In the latter case the mesonephros was positive. This variation in βA expression in the developing gonad might be due to sex differences between embryos and will be further investigated.

Localization of βB subunit mRNA

The distribution of βB transcripts is quite different from that of βA. Consistent with the results of Albano et al. (1994) activin B subunits are absent in the embryo, but are expressed in a broad zone of decidual cells underlying the uterine lumen at 6.0 days p.c. Decidual cells located at the position of the embryo are negative for βB transcripts, which is in contrast with the expression pattern of the βA subunits (Manova et al., 1992). During further development βB expression in the decidua is slightly decreased.

In 10.5- and 12.5-day mouse embryos βB is strongly expressed in certain parts of the brain. In particular the neopallial cortex (telencephalon, anterior of the choroid plexus), the intraventricular portion of the cerebellum and the floor of the rhombencephalon and diencephalon are strongly positive (Figs 4, 5A). The choroid plexus, and the mesencephalon are negative. High expression of the βB subunit was also observed around the lumen of the spinal cord (Fig. 5B). It is striking that only the rapidly dividing cells of the ependymal layer of the neural tube and the brain regions contain the βB message, while the mantle layer and marginal layer are negative.

Table 1. Distribution of inhibin/activin subunits, follistatin and activin type IIα and IIβ receptor in 12.5-day p.c. mouse embryos determined by in situ hybridization

<table>
<thead>
<tr>
<th>Tissue</th>
<th>βA</th>
<th>βB</th>
<th>α</th>
<th>Foll</th>
<th>R-IIα</th>
<th>R-IIβ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olfactory</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>+1/2</td>
<td>+1/2</td>
<td>+1/2</td>
</tr>
<tr>
<td>Cochlea</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>+1</td>
<td>+1/2</td>
<td>+1/2</td>
</tr>
<tr>
<td>Trachea</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>+1</td>
<td>+1/2</td>
<td>+1/2</td>
</tr>
<tr>
<td>Stomach</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>+1</td>
<td>+1/2</td>
<td>+1/2</td>
</tr>
<tr>
<td>Liver</td>
<td>−</td>
<td>+1</td>
<td>−</td>
<td>+1</td>
<td>+1/2</td>
<td>+1/2</td>
</tr>
<tr>
<td>Metanephros</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Intestine</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Spinal cord</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Body wall</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Blood vessels</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Heart</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Interv. discs</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Gonad primordium</td>
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<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Pleuroperit. membr.</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Fascia</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Limb/shoulder</td>
<td>+1</td>
<td>+1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

1Restricted to mesenchyme.
2Restricted to epithelium.
3Inhibition of specific regions (see text).
4Restricted to precartilage condensations.
5+1− means either + or −, possibly by sex difference.
Fig. 3. Inhibin/activin βA subunit mRNA expression in sagittal (A,B,D,F,H) and frontal (C,E,G) sections through the thoracic and abdominal region (A-D) and through the shoulder/cervical region (E), limb (F) and gonad primordium (G,H) of a 12.5 day p.c. mouse embryo. Dark-field micrographs (left) and corresponding bright-field images (right). ao, aorta; bv, blood vessel; bw, body wall; cr, cervical region; ct, cushion tissue; ge, genital eminence; go, gonad primordium; h, heart; hi, hilus of the lung; id, intervertebral disc primordium; lb, limb bud; lu, lung; ma, metanephros; oe, oesophagus; pc, precartilage condensation; pm, pleuroperitoneal membrane; re, rectum; se, spinal cord; sr, shoulder region; su, septum urogenitale; st, stomach; ta, truncus arteriosus; tp, truncus pulmonalis; tr, trachea; ve, ventricle.

Localization of a subunit mRNA
In contrast to the βA and βB subunit mRNAs the α message was absent in the decidua and the embryo at early postimplantation stages and was found in only one developing organ in 10.5- and 12.5-day mouse embryos, namely the gonad primordium (Fig. 6). However, the cellular localization of this message could not be clearly determined. Comparison of the expression patterns of the three inhibin subunits in the developing gonads of male and female mice is under investigation.

Localization of follistatin mRNA
The expression pattern of follistatin showed little overlap with those of inhibin βA and βB subunits. In early postimplantation embryos follistatin is expressed both in the embryo and the decidua. Fig. 7C shows that, except for a narrow zone of decidua cells around the embryo, the whole decidua is strongly positive for follistatin mRNA. Striking sites of follistatin expression in the 7.5-day embryo are the primitive streak region and the parietal endoderm cells in the Reichert’s membrane surrounding the embryo (Fig. 7C). Although similar results were obtained by Albano et al. (1994), the levels of follistatin expression in the present study are dramatically higher. Furthermore, as shown in Fig. 7A,B parietal endoderm of 6.0 and 6.5-day embryos contains high levels of follistatin transcripts. In these embryos also an asymmetric expression pattern in the egg cylinder was observed. In 8.5-day embryos a strong hybridization signal was still present in the parietal endoderm, and in somites, paraxial mesoderm and developing hindbrain, while the developing forebrain, spinal cord and neural plate were negative (Fig. 7D-F). As shown in Fig. 7E follistatin was expressed in specific rhombomeres of the developing hindbrain, in particular rhombomeres 2, 4 and 6 (Albano et al., 1994). In 9.5-day embryos follistatin transcripts appear in the mesencephalon and diencephalon, while the telencephalon remains negative (not shown).

Fig. 8 shows that in 10.5- and 12.5-day embryos follistatin is expressed in mesoderm-and ectoderm-derived tissues. In the developing nervous system the most predominant hybridization signal is seen in regions where βB mRNA is absent or very weakly expressed, namely in the ependymal layer of the diencephalon (Figs 8, 9C) and the roof of the mesencephalon (Figs 8, 9A). It is striking that a small region in the developing midbrain is negative. A weak signal is also visible in the floor of the rhombencephalon (Figs 8, 9C), the roof of the metencephalon (Fig. 9A) and around the lumen of the spinal cord in the tail region (not shown) where βB is also expressed.

In the snout, follistatin mRNA is present in the roof of the nasal cavity, in particular in the mesenchyme surrounding the olfactory epithelium as well as in mesenchymal structures in the tongue (Fig. 9B). Although βA is also expressed in these tissues, the messages do not appear to be colocalized. Follis-
In 12.5-day mouse embryos there are many sites where activin receptor type IIA and IIB are coexpressed. As shown in Fig. 10 both receptors are predominantly present in the central nervous system, including the brain, ganglia and spinal cord. Furthermore, the mRNA for the type II receptors is colocated in several mesenchymal and epithelial cell types outside the central nervous system. There are, however, a number of striking differences between the expression patterns of the two receptors. While activin receptor type IIA is selectively expressed in the mantle layer of the brain and spinal cord (Fig. 10B,C), activin receptor type IIB mRNA is also present in the ependymal layer (Fig. 10E-G). Furthermore, type IIB activin receptor is expressed in the telencephalon and diencephalon (Fig. 10E,F), while type IIA receptor is expressed only in the mantle layer of the corpus striatum and the diencephalon (Fig. 10B). Another difference is the expression pattern in the developing eye. A specific hybridization signal for the activin type IIB receptor was seen in the neural layer of the retina (Fig. 10H), where the type IIA receptor is absent. The latter receptor was present in the fascia of the developing ocular muscles (Fig. 10H). In addition, developing vibrissae only express type IIA (Fig. 10D), but not type IIB activin receptor. As shown in Fig. 10E,G the peripheral structures in the mesonephros are positive for the type IIB receptor, while no signal was observed for type IIA. Furthermore, activin type IIB receptor transcripts were absent in some embryos and present in others in the developing gonads, while type IIA receptor expression was never observed in the gonad primordium (not shown). Possible sex-related differences in the activin type II receptor expression patterns cannot be excluded. The mesonephros was negative for both receptor types.

Colocalization of the receptor type IIA and IIB messages in the peripheral structures of the developing conchae (Fig. 9B), whereas βA subunits are expressed in the actively dividing mesenchymal cells. Another difference with βA subunit expression is the presence of follistatin mRNA in the sensory epithelia of the cochlea and its absence in the surrounding mesenchyme (Fig. 9D). Furthermore, while βB is expressed in the stomach epithelium, follistatin is strongly expressed in the underlying mesenchymal layer, but not in the muscle tissue (Fig. 9E). In the body wall follistatin is expressed in the epidermis (Fig. 9B,H), while βA subunit mRNA is present in the underlying mesenchymal tissue. These results indicate that in certain epithelial/mesenchymal structures there is a reciprocal expression pattern for inhibin β subunit and follistatin mRNA.

Striking sites of follistatin expression are the sinoauricular septum of the heart (Fig. 9H), the mesenchyme of the intestine (Fig. 9F) and the fascia in the flanks of the embryo (Fig. 9E). Other specific expression sites are the mesenchymal condensations in the limbs (Fig. 9E) and in the developing pelvis (Fig. 9E), as well as the sclera of the developing eye (Fig. 9G) and the peripheral blood vessels (Fig. 8A). The intervertebral disc anlagen (Fig. 9F), the pleuroperitoneal membrane (Fig. 9F), the developing vibrissae (not shown) and the gonads (Fig. 9H) form common sites of follistatin, βA and/or βB subunit expression.

**Localization of activin receptors**

The distribution of the type IIA and IIB receptors in postimplantation mouse embryos has been investigated in order to determine possible target cells for activins. In 6.0- to 8.5-day embryos, type IIB activin receptor was strongly expressed in embryonic and extraembryonic tissue, while no transcripts for the activin type IIA receptor could be observed. Type IIA receptor could be detected in the mouse embryo as early as 9.5 days p.c. (not shown). Both receptors were absent in the decidua. These results confirm the hypothesis of Blum et al. (1992) that activin receptors are present in early postimplantation embryos.

In 12.5-day mouse embryos there are many sites where activin receptor type IIA and IIB are coexpressed. As shown in Fig. 10 both receptors are predominantly present in the central nervous system, including the brain, ganglia and spinal cord. Furthermore, the mRNA for the type II receptors is colocalized in several mesenchymal and epithelial cell types outside the central nervous system. There are, however, a number of striking differences between the expression patterns of the two receptors. While activin receptor type IIA is selectively expressed in the mantle layer of the brain and spinal cord (Fig. 10B,C), activin receptor type IIB mRNA is also present in the ependymal layer (Fig. 10E-G). Furthermore, type IIB activin receptor is expressed in the telencephalon and diencephalon (Fig. 10E,F), while type IIA receptor is expressed only in the mantle layer of the corpus striatum and the diencephalon (Fig. 10B). Another difference is the expression pattern in the developing eye. A specific hybridization signal for the activin type IIB receptor was seen in the neural layer of the retina (Fig. 10H), where the type IIA receptor is absent. The latter receptor was present in the fascia of the developing ocular muscles (Fig. 10A). In addition, developing vibrissae only express type IIA (Fig. 10D), but not type IIB activin receptor. As shown in Fig. 10E,G the peripheral structures in the mesonephros are positive for the type IIB receptor, while no signal was observed for type IIA. Furthermore, activin type IIB receptor transcripts were absent in some embryos and present in others in the developing gonads, while type IIA receptor expression was never observed in the gonad primordium (not shown). Possible sex-related differences in the activin type II receptor expression patterns cannot be excluded. The mesonephros was negative for both receptor types.

Colocalization of the receptor type IIA and IIB messages in the ependymal layer (Fig. 10E-G). Furthermore, type IIB activin receptor is expressed in the telencephalon and diencephalon (Fig. 10E,F), while type IIA receptor is expressed only in the mantle layer of the corpus striatum and the diencephalon (Fig. 10B). Another difference is the expression pattern in the developing eye. A specific hybridization signal for the activin type IIB receptor was seen in the neural layer of the retina (Fig. 10H), where the type IIA receptor is absent. The latter receptor was present in the fascia of the developing ocular muscles (Fig. 10A). In addition, developing vibrissae only express type IIA (Fig. 10D), but not type IIB activin receptor. As shown in Fig. 10E,G the peripheral structures in the mesonephros are positive for the type IIB receptor, while no signal was observed for type IIA. Furthermore, activin type IIB receptor transcripts were absent in some embryos and present in others in the developing gonads, while type IIA receptor expression was never observed in the gonad primordium (not shown). Possible sex-related differences in the activin type II receptor expression patterns cannot be excluded. The mesonephros was negative for both receptor types.

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was observed in the epidermis of the developing eye (Fig. 10D,H), the epithelium of the cochlea (Fig. 10A,F) and the epithelium of the semicircular canals (Fig. 10F). The two receptors are also coexpressed in the mesenchyme and devel-
In this paper we have described the first comparative analysis of the localization of inhibin/activin α-, βA- and βB-subunit, follistatin and activin type II receptor mRNA in postimplantation mouse embryos. The data presented in this study suggest a role for activins in a variety of developmental processes during the period of organogenesis.

In early postimplantation embryos (6.0- to 9.5-days p.c.) activin β subunits are exclusively expressed in specific regions of the decidua, not in the embryo. Manova et al. (1992) have suggested that activin, produced by the decidua, might reach the embryo and function during mesoderm formation and gastrulation. However, because of the spectacular expression levels of follistatin in the decidua and also in the parietal endoderm surrounding the embryo (this study) it is very unlikely that the embryo is exposed to biologically active activin. We therefore suggest that at least the known forms of activin are not involved in early postimplantation development. However, recently it has been shown that different follistatin forms have different activin-neutralizing capacity, which might be due to differences in affinity for cell surface proteoglycans (Nakamura et al., 1991; Sugino et al., 1993). For this reason the exact protein form present in the embryo and decidua needs to be established. In addition, as at least type IIB activin receptors are present in the embryo, the occurrence of new members of the activin family cannot be excluded at these stages. Knowledge of the appearance of signalling type I activin receptors will also help to establish whether activins are functional in early postimplantation development.

A striking observation was the high level of follistatin expression in the primitive streak region of 6.5- and 7.5-day embryos. Although follistatin effects are always coupled to activin neutralization, it was shown recently that follistatin itself can act as a paracrine modulator upon thecal cells to directly stimulate the production of progesterone, independently of activin (Shukovski et al., 1993). These results suggest the presence of a signalling pathway for follistatin in certain cells. We are now studying the involvement of follistatin in mesoderm induction in the mouse embryo. In 8.5-day embryos follistatin is expressed in specific rhombomeres, paraxial mesoderm and somites, indicating a role for this protein in the development of the hindbrain, and in somite development.

In 10.5- and 12.5-day embryos βA subunit transcripts are expressed predominantly in mesenchymal structures, including those surrounding the epithelia of several internal organs. It is striking that other members of the TGFβ superfamily, in particular TGFβ2 and TGFβ3 are either expressed in the same region or in tissues adjacent to the site of βA expression in the mouse embryo. Like the βA subunit, TGFβ3 is expressed in the tracheal mesenchyme and in the intervertebral disc anlagen (Schmid et al., 1991; Millan et al., 1991). A coordinated expression of βA and TGFβ2 was found in the nasal and mandibular mesenchyme that forms the soft tissue components of the face (Schmid et al., 1991). In addition, Pelton et al. (1989) reported the presence of TGFβ2 RNA in mesenchymal cells of the embryonic esophagus where βA is also expressed. In several structures where TGFβ2 is expressed in the epithelial component, including cochlear epithelium and olfactory epithelium, the βA subunit is present in the adjacent mesenchymal tissue (Schmid et al., 1991; Millan et al., 1991). These results together with the recent finding that TGFβ influences the expression of activin β subunits in mesodermal cell lines (van der Kruijssen et al., 1993) suggest that the activin β
Fig. 9. For legend see p. 3634
Fig. 10. For legend see p. 3634
β subunit expression levels may be regulated by TGFβ. Note: The sagittal sections are serial sections from the same cord; se, semicircular canal; sg, spinal ganglion; st, stomach; te, epidermis; fa, fascia; gs, ganglion statoacousticon; le, lens; lu, lung; striatum; dg, dorsal root ganglion; di, diencephalon; e, eye; ep, epidermis; fa, fascia; gs, ganglion statoacousticon; le, lens; lu, lung; ma, metanephros; me, mesencephalon; mt, metencephalon; ol, olfactory epithelium; pe, pelvis; pm, pleuroperitoneal membrane; rh, rhombencephalon; sl, sclera; ss, sinoauricular septum; st, stomach; te, telencephalon; to, tongue.

Fig. 9. Follistatin mRNA expression in sagittal (B,D,E,H) and transverse (A,C) sections through the brain (A,C), snout (B), cochlea (D), abdominal region (E,F), eye (G) and thoracic region (H) of a 12.5-day p.c. mouse embryo. Dark-field micrographs (left) and corresponding bright-field images (right). bw, body wall; ch, developing conchae; co, cochlea; di, diencephalon; ep, epidermis; fa, fascia; go, gonad primordium; h, heart; id, intervertebral disc primordium; in, intestine; lb, limb bud; le, lens; li, liver; ma, metanephros; me, mesencephalon; mt, metencephalon; ol, olfactory epithelium; pe, pelvis; pm, pleuroperitoneal membrane; rh, rhombencephalon; sl, sclera; ss, sinoauricular septum; st, stomach; te, telencephalon; to, tongue.

Fig. 10. Activin receptor type IIA (A-D) and type IIB (E-H) mRNA expression in sagittal (A,D,E,H) and transverse (B,C,F,G) sections of a 12.5-day p.c. mouse embryo. Dark-field micrographs (left) and corresponding bright-field images (right). co, cochlea; cs, corpus striatum; dg, dorsal root ganglion; di, diencephalon; e, eye; ep, epidermis; fa, fascia; gs, ganglion statoacousticon; le, lens; lu, lung; ma, metanephros; mo, medulla oblongata; nr, neural retina; sc, spinal cord; se, semicircular canal; sg, spinal ganglion; st, stomach; te, telencephalon; tg, trigeminal ganglion; tm, muscle of the tongue; vi, vibrissa. Note: The sagittal sections are serial sections from the same embryo.

Activin receptor type IIA and IIB activin receptors is observed in the roof of the telencephalon, where receptor IIB is strongly expressed and receptor IIA is completely absent. Coexpression of the βB subunit in the forebrain strongly suggests that activin B might be involved in forebrain development, thereby exerting its function via the activin type IIB receptor. Developing whisker follicles only express type IIA, not type IIB receptor. Coexpression of the βA subunit mRNA in these structures suggests that activin A might play a role in their differentiation to mature follicles via the type IIA activin receptor. Some tissues, including spinal ganglia and metanephros (for type IIB) display a high hybridization signal of the type II activin receptor mRNA, whereas they exhibit undetectable levels of βB subunit mRNA. This might indicate that yet unknown ligands exist for these receptors that are expressed in these regions. On the other hand, the absence of type II activin receptor mRNA in tissues expressing βB subunits, suggests the existence of related receptors that mediate activin function. Comparison of the type II activin receptor expression patterns with that recently described for the type IIG/TGFβ receptor during a similar period of development (Lawler et al., 1994) has revealed that there is no overlapping hybridization signal. As TGFβ1 is the major ligand for the type II TGFβ receptor these results suggest that TGFβ1 and activins have completely different functions during murine embryogenesis.

In addition to a type II activin receptor several type I receptors that are also putative transmembrane serine/threonine kinases, were shown to be essential for activin signalling (Attisano et al., 1993; Carcamo et al., 1994). Preliminary studies on the expression of one of the type I receptors (Act R-I/ALK-2) have indicated that there are only a few sites in common with those of the type II receptors. These include the floor of the mesencephalon, rhombencephalon and diencephalon in the brain and the mesenchymal condensations in the limb and shoulder. For this reason the expression patterns of other signalling type I receptors, including ALK-4, will be studied for possible colocalization with the type II activin receptors.

Although specific functions could be suggested for the different activin forms on the basis of the colocalization of activin subunits and type II activin receptors, there are several tissues in the developing mouse embryo in which the activin-neutralizing protein follistatin is colocalized or expressed in an adjacent cell layer. These tissues include various parts of the developing brain, mesenchymal structures in the snout, the cochlea, stomach, whisker follicles, and the gonads. Therefore, until the distribution of activin and follistatin proteins and their ratios is known it will be difficult to establish whether activins are involved in the maturation of some or all of these tissues or not. Furthermore, it is important to know which form of the follistatin protein is present. In addition to the sites of common expression with activins and their receptors, follistatin mRNA...
was also detected at very specific sites, including the mesencephalon, intestine, fascia and the sinusauric septum of the heart. This might indicate that other (unknown) activities are expressed at these sites, and that their activity is regulated by follistatin. Another possibility is that follistatin itself, independent of activins, might function as a regulator of tissue development.

In conclusion, the present results indicate that follistatin, and not the known activin forms (A,B,AB) are involved in early postimplantation development. However, based on their expression patterns, different types of activin might have different functions during the period of organogenesis. Further studies will be needed to determine the protein localization of activins and activin-binding proteins in the developing mouse embryo. In addition, the precise combination of the different activin receptors through which the different ligands might exert their function remains to be established.

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