Immunohistochemical Localization of TGFβ1, TGFβ2, and TGFβ3 in the Mouse Embryo: Expression Patterns Suggest Multiple Roles during Embryonic Development

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Abstract. Isoform-specific antibodies to TGFβ1, TGFβ2, and TGFβ3 proteins were generated and have been used to examine the expression of these factors in the developing mouse embryo from 12.5–18.5 d post coitum (d.p.c.). These studies demonstrate the initial characterization of both TGFβ2 and β3 in mammalian embryogenesis and are compared with TGFβ1. Expression of one or all three TGFβ proteins was observed in many tissues, e.g., cartilage, bone, teeth, muscle, heart, blood vessels, lung, kidney, gut, liver, eye, ear, skin, and nervous tissue. Furthermore, all three TGFβ proteins demonstrated discrete cell-specific patterns of expression at various stages of development and the wide variety of tissues expressing TGFβ proteins represent all three primary embryonic germ layers. For example, specific localization of TGFβ1 was observed in the lens fibers of the eye (ectoderm), TGFβ2 in the cortex of the adrenal gland (mesoderm), and TGFβ3 in the cochlear epithelium of the inner ear (endoderm). Compared to the expression of TGFβ mRNA transcripts in a given embryonic tissue, TGFβ proteins were frequently colocalized within the same cell type as the mRNA, but in some cases were observed to localize to different cells than the mRNA, thereby indicating that a complex pattern of transcription, translation, and secretion for TGFβs 1–3 exists in the mouse embryo. This also indicates that TGFβ1, β2, and β3 act through both paracrine and autocrine mechanisms during mammalian embryogenesis.

Polypeptide growth factors such as the β-type transforming growth factors (TGFβs) mediate many cell-cell interactions that occur during embryonic development (reviewed in Mercola and Stiles, 1988; Whitman and Melton, 1989; Nilsen-Hamilton, 1990). Complementary DNA clones have been isolated for five TGFβ species (TGFβs 1-5); however, purified or recombinant protein has been obtained only for TGFβs 1-3 (Derynck et al., 1985, 1988; Madisen et al., 1988; ten Dijke et al., 1988; Jakowlew et al., 1988). Moreover, only TGFβs 1-3 have been found in mammals. The molecular structures of TGFβ1, β2, and β3 are very similar in that each polypeptide is synthesized as a prepro monomeric protein and is cleaved to yield a 112-amino acid polypeptide that remains associated with the latent (pro) portion of the molecule (reviewed in Lyons and Moses, 1990 or Miller et al., 1990). Biologically active TGFβ protein results from dimerization of the monomers (usually homodimers) and release of the latent peptide portion. Overall, the mature region of the TGFβ3 protein has ∼80% identity to the mature regions of both TGFβ1 and TGFβ2, however, the NH_2-terminal or precursor regions of these three molecules share only 27% sequence identity (ten Dijke et al., 1988; Derynck et al., 1988). Some differences in the in vitro biological activities of TGFβ1 and TGFβ2 have been reported (Ohta et al., 1987; Jennings et al., 1988; Rosa et al., 1988; Merwin et al., 1991), however, in general, TGFβs 1, 2, and 3 have qualitatively similar activities when added to cells in culture (Graycar et al., 1989). In addition, competition studies with TGFβ1, TGFβ2, and TGFβ3 suggest that these proteins interact with the same cell-surface binding molecules (Graycar et al., 1989), although in some cell types, a given TGFβ isoform may preferentially bind to an individual subset of these presumptive receptors (Segarini, 1990).

In recent years, several converging lines of evidence have indicated that members of the TGFβ family play important roles in many different embryonic processes (reviewed in Akhurst et al., 1991 or in Pelton and Moses, 1990*a*). For example, in vitro TGFβs are mitogenic for cells derived from supporting tissues such as bone and cartilage but are inhibitory for many other cell types. The TGFβs also regulate differentiation (which may be stimulatory or inhibitory depending on the cell type), stimulate extracellular matrix deposition, are chemotactic for certain cells, and induce mesoderm formation during early embryogenesis. In an attempt to elucidate the in vivo activities of the TGFβs, we and

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others have investigated the expression patterns of TGFβ genes during embryonic development and a number of studies have now described the in vivo localization of mRNAs for TGFβs 1-3 during murine embryogenesis (Lehnert and Akhurst, 1988; Pelton et al., 1989, 1990*a*,*b*; Akhurst et al., 1990; Miller et al., 1990; Fitzpatrick et al., 1990; Millan et al., 1991; Schmid et al., 1991). Recently we used in situ hybridization to directly compare the localization of TGFβ1, β2, and β3 mRNA transcripts in the mouse embryo (Pelton et al., 1990*a*,*b*). During mid to late embryogenesis, the murine TGFβs 1-3 were shown to have overlapping but distinct patterns of mRNA expression. These patterns changed as development progressed and were often found in tissues undergoing morphogenetic alterations. For example, during the development of the whisker follicles of the mouse, the mRNA expression patterns for TGFβs 1-3 were all different in the immature follicle but were very similar in the mature follicle (Lyons et al., 1990). In situ hybridization studies with human embryonic tissue have produced results similar to those obtained with mouse embryos (Sandberg et al., 1988*a*,*b*; Gatherer et al., 1990).

Although in situ hybridization experiments designate which cells and tissues synthesize mRNA transcripts for a given gene, these studies cannot determine if the mRNAs are translated into proteins; hence the relative amount of mRNA may not reflect similar amounts of protein. This phenomenon may have particular relevance in the study of TGFβ expression. For example, Madisen et al. (1988) demonstrated that a human prostatic adenocarcinoma cell line produces higher levels of TGFβ1 and TGFβ2 mRNA but significantly higher levels of TGFβ2 than TGFβ1 protein. In addition, because the TGFβs 1-3 are secreted proteins, TGFβ mRNAs may not colocalize with TGFβ proteins. Indeed, by comparing their in situ hybridization studies with published immunohistochemistry data (Heine et al., 1987), Akhurst and coworkers have already shown this to be true for TGFβ1 mRNA and protein (Lehnert and Akhurst, 1988; Akhurst et al., 1990, 1991).

Using isoform-specific antibodies for TGFβ1, β2, and β3, we have investigated the expression of TGFβ proteins in the mouse embryo and compared the distribution of these proteins with their respective mRNAs. Our results show that TGFβs 1-3 are expressed in unique temporal and spatial patterns in a wide range of embryonic tissues, suggesting that these factors play multiple roles during morphogenesis and organogenesis. Moreover, when compared with the TGFβ in situ hybridization studies, the data presented here indicate that all three mammalian forms of TGFβ (β1, β2, and β3) act through both paracrine and autocrine mechanisms during murine embryonic development.

Materials and Methods

Mouse Tissues

Staged embryos (Theiler, 1989) were obtained from matings of ICR outbred female (Harland Sprague Dawley) and Swiss-Webster male mice (Taconic Farms, Germantown, NY). Noon on the day of vaginal plug was considered 0.5 days p.c. Pregnant females were killed via cervical dislocation and the 12.5-18.5 d.p.c. embryos were placed immediately in ice-cold 4% paraformaldehyde/PBS.

Antibody Preparation

Peptides of each TGFβ isoform were synthesized using a 430A peptide synthesizer (Applied Biosystems, Inc., Foster City, CA), incorporating the t-boc solid phase synthesis method followed by hydrofluoride cleavage. The following amino acid residues were used: TGFβ1 and TGFβ2, residues 4-19; TGFβ3, residues 9-20. The peptides were purified by high pressure liquid chromatography using a gradient composed of 0.1% trifluoracetic acid and 100% acetonitrile. Each peptide (5.0 mg) was dissolved in 0.1 M $NaHCO_3$ and coupled to KLH at a 1:1 ratio (wt/wt), by adding 3-μl vol of 1.25% glutaraldehyde 10 times over a period of 3 h. Rabbits were initially immunized with 500 μg of each peptide and subsequently boosted with 250 μg every 2.5 wk. Antibody titer was determined by ELISA using the appropriate corresponding uncoupled peptide and alkaline phosphatase goat anti-rabbit IgG as the second antibody (Promega Biotec, Madison, WI). The antisera did not cross-react with the TGFβ peptides that were not used as immunogen. Each antiserum was purified by ammonium sulfate precipitation (31.3%), followed by affinity chromatography using the respective immunogenic peptide. The peptide (8.0 mg) was coupled to 2 ml of Tresyl-Sepharose (Pharmacia Fine Chemicals, Piscataway, NJ) overnight according to the manufacturer's instructions. The purified IgG was eluted with 50 mM glycine (pH 2.5) into Tris buffer (pH 7.2) for neutralization, dialyzed against TBS, aliquoted, and stored frozen. Each antipeptide antiserum was tested for both immunoreactivity with the corresponding mature isoform of the TGFβ molecule and for cross-reactivity with each other TGFβ isoform by Western blot analysis.

Western Blot Analysis

Recombinant human TGFβ1 and TGFβ3 were generously provided by Dr. Michael Palladino and Dr. Rik Derynck, respectively, of Genentech, Inc. (Palo Alto, CA). Native porcine TGFβ2 was purchased from R & D Systems (Minneapolis, MN). Human and porcine TGFβ amino acid sequences are identical. Each TGFβ molecule was reduced with a final concentration of 0.1 M DTT, subjected to SDS-PAGE using a gradient polyacrylamide gel of 10-20% and subsequently transferred to a nitrocellulose membrane for 1 h at 100 V using the Biorad Miniblot System (Bio-Rad Laboratories, Cambridge, MA). The membranes were blocked with 3% non-fat dry milk in TBS (0.01 M Tris, 0.15 M NaCl, pH 8.0) for 1 h and directly incubated overnight in purified anti-peptide IgG in TBS containing 0.1% Tween 20 (TBST) at the following dilutions: TGFβ1, 1:50; TGFβ2 and TGFβ3, 1:25. The membranes were washed with TBST and incubated with alkaline phosphatase-labeled goat anti-rabbit IgG (Promega Biotec) at a dilution of 1:3,000 for 1 h. The blot was developed with NBT/BCIP (Promega Biotec).

Immunohistochemistry

The protocol used for these studies was a modified version of the method reported in Heine et al. (1987). Tissues were fixed overnight in 4% paraformaldehyde/PBS, dehydrated in increasing concentrations of ethanol, and embedded in paraffin wax (Fischer Scientific Co., Pittsburgh, PA). Sections of 5-7 μm were cut and floated onto slides coated with 3-triethoxysilylpropylamide (Sigma Chemical Co.). The sections were submerged in TBS/0.1% (vol/vol) Triton X-100 at room temperature for 15 min followed by TBS for 5 min, methanol for 2 min, and methanol/0.6% (vol/vol) hydrogen peroxide for 30 min. Slides were subsequently washed at room temperature in methanol for 2 min, TBS for 5 min, and three times in TBS/0.1% (wt/vol) BSA for 3 min. After treatment with hyaluronidase (1 mg/ml in 100 mM sodium acetate, 0.85% (wt/vol) NaCl) and three washes in TBS/0.1% BSA, excess protein was blocked with 5% normal swine serum in TBS/0.5% BSA for 15 min at room temperature. Tissue sections were incubated with primary antibodies at a concentration of 5 μg/ml (diluted in TBS containing 5% swine serum and 0.1% BSA) overnight at 4°C. Control slides were incubated with either an IgG fraction of normal rabbit serum at 5 μg/ml (diluted in TBS containing 5% swine serum and 0.1% BSA) or without primary antibodies. Tissues were then washed in TBS/0.1% BSA and incubated for 60 min at room temperature with biotinylated swine antirabbit secondary antibody in TBS/0.1% BSA. After washes in TBS/0.1% BSA, the sections were exposed to avidin-biotin complex for 60 min at room temperature and again washed in TBS/0.1% BSA. Slides were reacted with 0.05% (wt/vol) DAB in 50 mM Tris-HCl (pH 7.4) with 0.1% (vol/vol) hydrogen peroxide for 5 min and counterstained in haematoxylin.

Results

Antibody Specificity

Western Blot Analysis. The specific immunoreactivity of

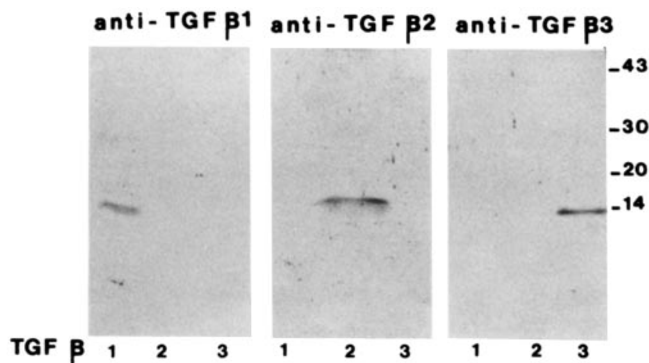


Figure 1. Western blot analysis demonstrating the specificity of TGFβ antipeptide antibodies. Recombinant TGFβ1 and TGFβ3 proteins and porcine platelet TGFβ2 (50 ng each) were electrophoresed and transferred to nitrocellulose. Each TGFβ protein was reacted with each antiserum to TGFβ overnight. Dilution for antisera/anti-TGFβ1 was 1:50; and 1:25 for anti-TGFβ2 and anti-TGFβ3. Molecular weight markers are shown on the right.

each antipeptide antiserum with its respective TGFβ isoform was demonstrated by Western blot analysis as depicted in Fig. 1. Each purified IgG to TGFβ1, β2, or β3 reacted only with the appropriate and corresponding native or recombinant molecules – (50 ng) of rTGFβ1 (Fig. 1, lane *1*), TGFβ2 (Fig. 1, lane *2*), or rTGFβ3 (Fig. 1, lane *3*). No cross-reactivity was observed among any of the TGFβ isoforms. The specificity of the individual antisera was further demonstrated after complete absorption of the immunoreactivity with 10 M excess of the corresponding peptide (data not shown). Lastly, the ability of the antipeptide antibodies to react (but not cross react) on a Western blot with the appropriate native TGFβ1, TGFβ2, and TGFβ3 molecules purified from human umbilical cord tissue further suggests that these antibodies are specific for their respective proteins (L. I. Gold, manuscript in preparation).

Immunohistochemistry. To ensure the specificity of the anti-TGFβ antisera for immunohistochemical studies, serial tissue sections were used for control and experimental slides. Control slides were reacted with either (*a*) the IgG fraction of normal rabbit serum (at the same concentration as the primary antibody) in place of the peptide antibodies; or (*b*) no primary antibody. Fig. 2 shows examples of control sections directly compared against experimental sections. The epidermis and hair follicles in the skin of a 17.5 d.p.c. mouse showed strong immunoreactivity with TGFβ1 antibodies (Fig. 2 *B*), while absolutely no staining was observed with normal rabbit IgGs (Fig. 2 *A*). Similarly, while the keratinized epithelium of the palate and tongue of a 17.5 d.p.c embryo showed intense staining with TGFβ1 antibodies, no staining was observed using the normal rabbit IgGs (com-

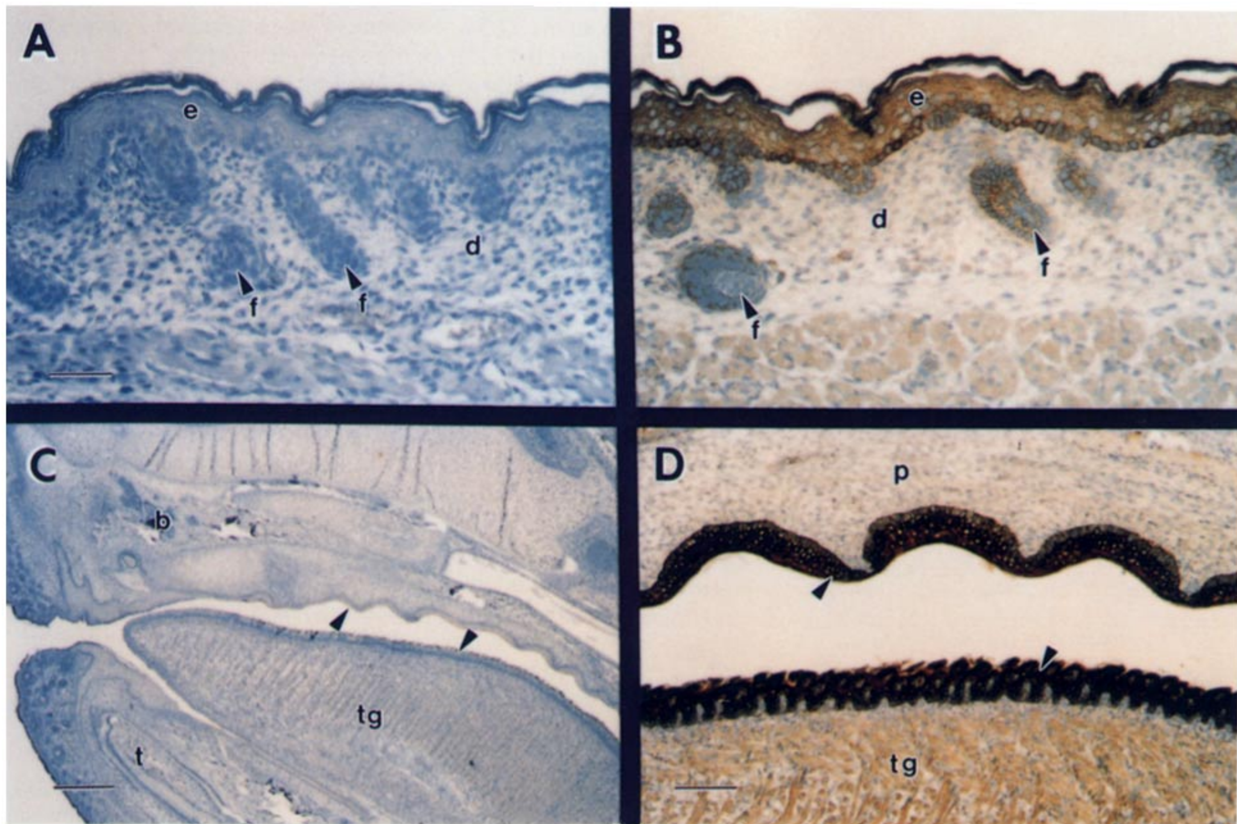


Figure 2. Comparison of embryo sections incubated with either normal rabbit IgGs or with antibodies to TGFβ1. (*A* and *B*) Section of 17.5 d.p.c. mouse skin incubated with normal rabbit IgGs (*A*) or with TGFβ1 antibody (*B*). Staining is seen only in the epidermis and hair follicles of *B*. (*C* and *D*) Section through the oral region of a 17.5 d.p.c. mouse embryo incubated with normal rabbit IgGs (*C*) or with TGFβ1 antibody (*D*). Staining is seen only in the keratinized epithelium of the palate and tongue of *D*. e, epidermis; d, dermis; f, follicle; b, bone; t, tooth; tg, tongue; p, palate. Bars: (*A*) 35 μm; (*C*) 175 μm; (*D*) 55 μm.

Table I. Embryonic Cell Types Expressing TGFβ Proteins

Cell type	TGFβ1	TGFβ2	TGFβ3
Cartilage			
perichondrium	+++	+	++
chondrocytes	+	++	++
Bone			
periosteum	++	−	+
osteocytes	++	++	++
Tooth			
ameloblasts	++	−	+
odontoblasts	−	++	−
pulp	+	+++	+
Muscle			
smooth	+	+	++
cardiac	+	+	+++
skeletal	+	+	++
Heart			
endothelium	−	−	−
myocytes	+	+	+++
Lung			
bronchi	++	++	++
alveoli	−	−	−
Blood vessels			
endothelium	−	−	++
smooth muscle	+	+	+++
Kidney			
tubules	++	++	++
basement membrane	−	+++	−
Adrenal			
cortex	+++	+++	−
medulla	−	−	−
Gut			
esophageal epithelium	+++	+	+
stomach epithelium	+++	+	+
intestinal epithelium	++	+	+
basement membrane	−	+++	−
muscularis	+	+	++
Liver			
capsule	−	−	++
parenchyma	−	−	−
megakaryocytes	+	−	++
Eye			
lens epithelium	−	−	−
lens fibers	+++	+	+
Ear			
cochlear epithelium	−	+	+++
basement membrane	−	+++	−
CNS			
meninges	+	+++	+
glia	−	++	++
choroid plexus	−	−	++
Skin			
periderm	++	+	++
epidermis	+++	+++	+++
dermis	+	+++	+
hair follicles	++	++	+

Immunolocalization of TGFβ1, β2, and β3 proteins in the 12.5–18.5 d.p.c. mouse embryo. A + indicates that positive staining was seen in this tissue at some stage between 12.5 and 18.5 d.p.c., while a − means that no staining was detected. The number of + signs denotes relative intensity of staining when compared against the other TGFβ antibodies in that particular tissue and should not be compared against the staining intensity in other tissues. See text for a more detailed description of the temporal and spatial expression patterns. To compare the immunohistochemical expression of TGFβ proteins with TGFβ RNAs, the reader is referred to Table I of Millan et al. (1991).

pare Fig. 2, *D* with *C*). Although the control data for each tissue is not shown, in all cases examined the control slides were negative.

Immunohistochemical Localization of TGFβ Proteins

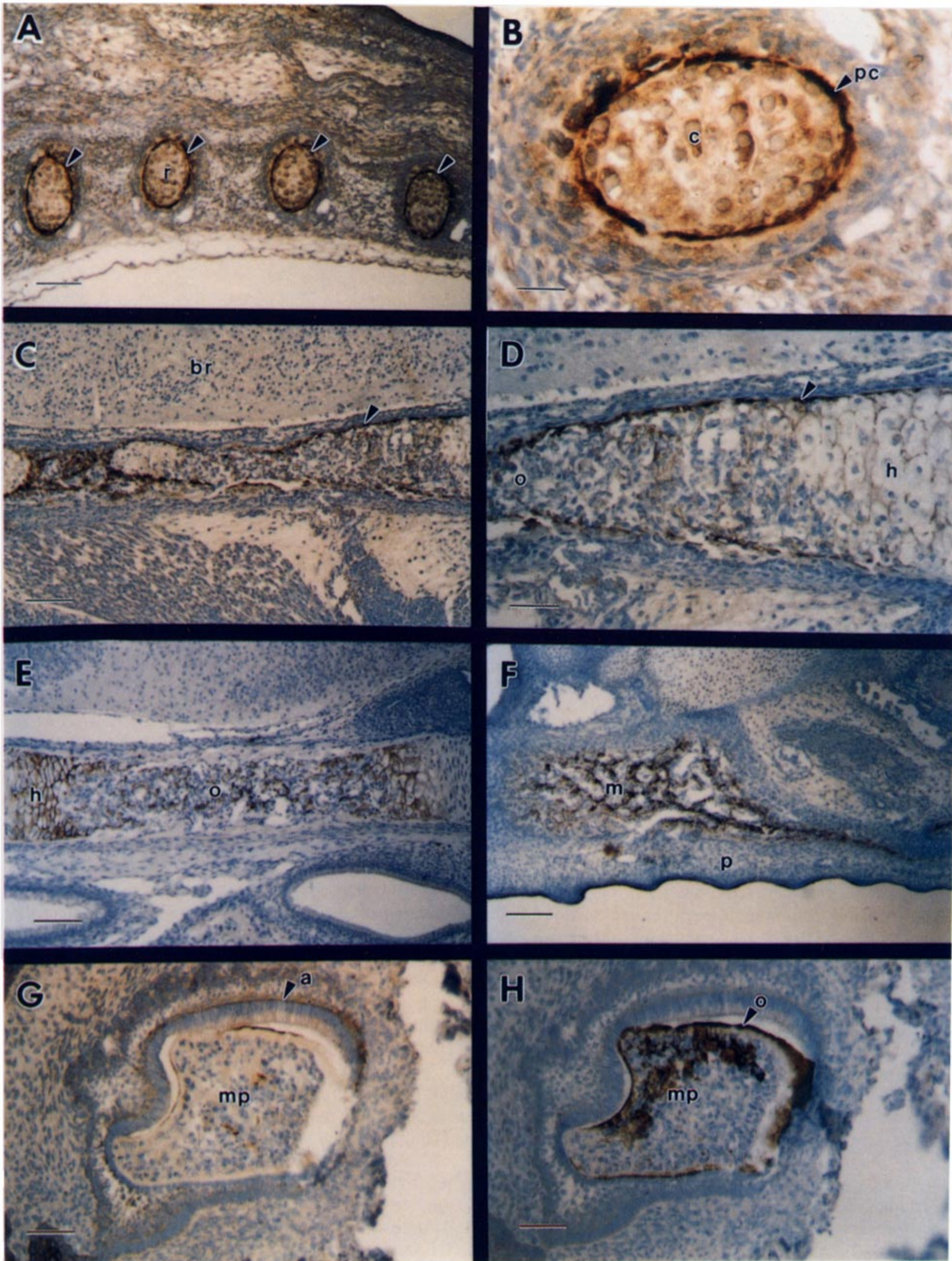
The results of the immunohistochemical localization of TGFβs 1–3 are summarized in Table I. Data not shown in Figs. 2–11 are referred to in Table I.

The Embryonic Skeletal System. Chondrification centers for most bones are first seen in the embryo at ~13–14 d.p.c. with centers of ossification usually appearing 2–3 d later (Rugh, 1990). At 12.5 d.p.c., chondrocytes in the ribs and vertebrae showed strong TGFβ3 staining but only very weak staining for TGFβ1 or TGFβ2. The cartilage rudiments in other bones at 12.5 d.p.c. showed little TGFβ3 staining. From 13.5 to 15.5 d.p.c., TGFβ3 staining in the chondrocytes remained high and as the maturing chondrocytes became hypertrophic, TGFβ1 (Fig. 3, *A* and *B*) and TGFβ2 expression was seen. TGFβ1 levels were especially high in the perichondrium (Fig. 3, *A* and *B*). By 16.5 d.p.c., high levels of TGFβ1 were localized to the periosteum of several bones (Fig. 3, *C* and *D*) as well as in the maturing chondrocytes of various cartilage rudiments. Although little TGFβ2 or TGFβ3 was detected in the periosteum, both were found in osteocytes of bone and maturing chondrocytes such as those of the tracheal cartilage. The TGFβ3 staining in bone was found in the cytoplasm of osteocytes, while the TGFβ2 staining was found predominantly in the extracellular matrix surrounding the osteocytes (Fig. 3 *E*). TGFβ1 immunoreactivity in the 17.5 d.p.c. embryo was found in the developing maxilla (Fig. 3 *F*), an intramembranous bone, as well as in the periosteum of endochondral bones (Fig. 3, *C* and *D*). Whereas TGFβ1 and TGFβ2 were both still present at high levels in osteogenic bone and hypertrophic cartilage at this stage, TGFβ3 staining had diminished (Fig. 3, *C–F*).

It has been previously demonstrated that at 16.5 d.p.c., very high levels of TGFβ mRNAs are found in the embryonic tooth, primarily in the odontoblast and mesenchymal pulp cells (Pelton et al., 1990*a*). However, TGFβ proteins in the 17.5 d.p.c. tooth were localized to additional structures. For example, although TGFβ1 mRNA was very abundant in the pulp cells, TGFβ1 antibody staining was seen at highest levels in the ameloblast layer (Fig. 3 *G*). In addition, while TGFβ2 mRNA was found at high levels in the odontoblast layer and to a lesser extent in the pulp cells, TGFβ2 protein was observed at high levels in both the odontoblast and pulp cells (Fig. 3 *H*). TGFβ3 immunostaining was found at low levels in both the pulp cells and the ameloblasts but was not seen in the odontoblast layer.

The Embryonic Circulatory System. Previous reports have shown that at 7 d.p.c., TGFβ1 mRNA was observed in cardiac mesoderm cells; however, TGFβ1 protein could not be detected (Akhurst et al., 1990). Transcripts for TGFβ3 are restricted to the atrioventricular cushions of the 11.5 d.p.c. heart and are not found in the ventricles (Pelton et al., 1990*a*). Although immunostaining for TGFβ3 protein, and to a lesser extent for TGFβ1 and TGFβ2, was also present in the embryonic heart from 12.5 through 16.5 d.p.c., as seen in the tooth, there were differences in the TGFβ mRNA and

Figure 3. Localization of TGFβ proteins in the murine embryonic skeletal system. (*A*) Cross section through the ribs of a 14.5 d.p.c. embryo stained with TGFβ1 antibodies. Staining is seen primarily in the perichondrium surrounding the hypertrophic cartilage in the ribs. (*B*) Higher power magnification of *A*, illustrating high TGFβ1 expression in the perichondrium of a rib. Lower levels were seen in the hypertrophic cartilage. (*C*) Longitudinal section of a bone at the base of the skull in a 17.5 d.p.c. embryo stained with TGFβ1 antibodies. TGFβ1



is seen in the periosteum (*arrow*) and osteogenic zone of the bone. (*D*) Higher power of *C* showing the TGFβ1 expression in the periosteum of the bone (*arrow*). (*E*) Same bone as in *C* stained with TGFβ2 antibodies. Staining is seen in the hypertrophic cartilage and osteogenic zone of the bone. (*F*) Staining with TGFβ1 antibodies in osteoblasts in the maxilla of a 17.5 d.p.c. embryo. (*G*) Section through a tooth in a 17.5 d.p.c. embryo incubated with TGFβ1 antibodies. Staining is seen in the basal region of the ameloblasts (*arrow*). (*H*) Same section as in *G* incubated with TGFβ2 antibodies. Staining is seen in the odontoblasts (*arrow*) and in the mesenchymal primordium of the pulp. r, ribs; c, cartilage; pc, perichondrium; br, brain; o, osteogenic zone (*D* and *E*); h, hypertrophic cartilage; m, maxilla; p, palate; a, ameloblasts; mp, mesenchymal primordium of the pulp; o, odontoblasts (*H*). Bars: (*A*) 110 μm; (*B*) 30 μm; (*C*) 120 μm; (*D*) 65 μm; (*E*) 115 μm; (*F*) 145 μm; (*G*) 80 μm; (*H*) 80 μm.

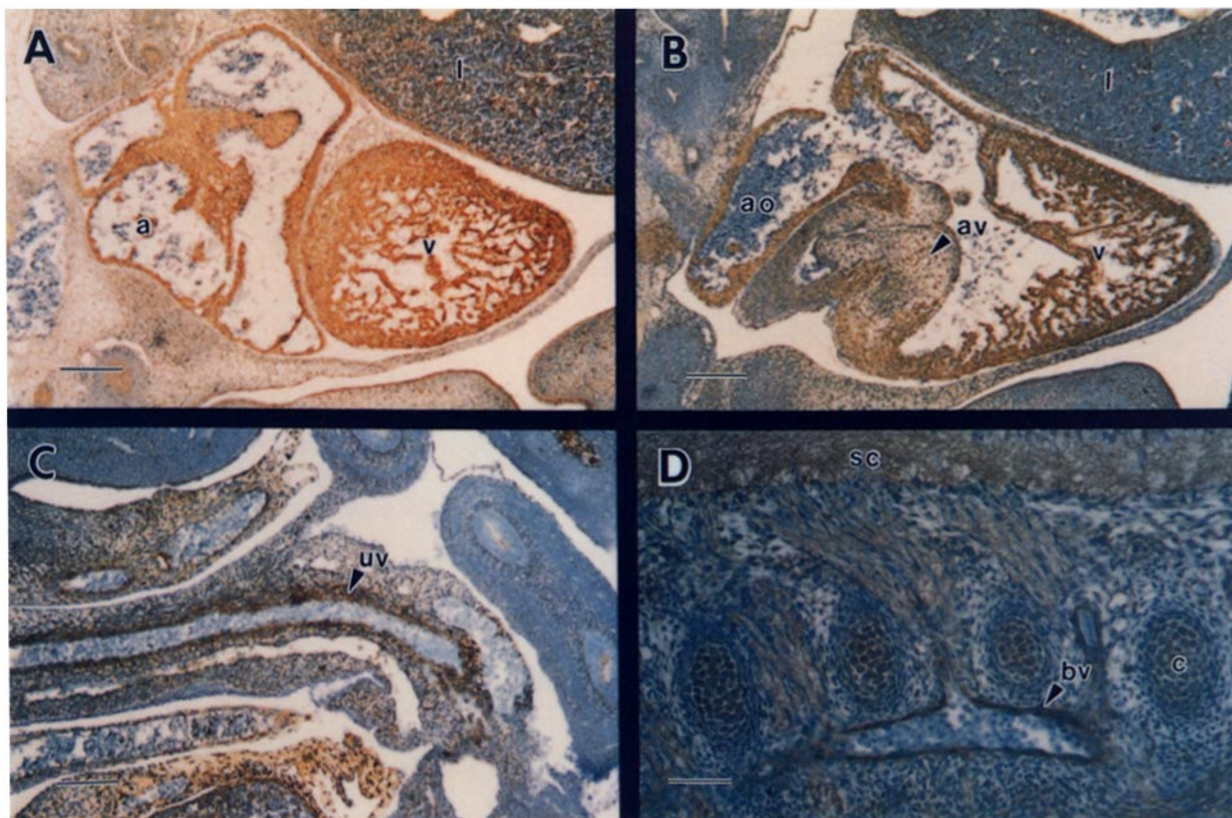


Figure 4. Expression of TGFβ3 in the 12.5 d.p.c. embryonic circulatory system. (*A*) Parasagittal section through a 12.5 d.p.c. heart stained with TGFβ3 antibodies. Staining is seen in the atria and ventricles. (*B*) Sagittal section through same heart as in *A* illustrating TGFβ3 in the walls of the aorta and at low levels in the atrioventricular cushions (*arrow*). (*C*) Section showing TGFβ3 localization in an umbilical vessel (*arrow*). (*D*) TGFβ3 staining in an embryonic blood vessel (*arrow*) near the spinal cord. a, atria; v, ventricle; l, liver; ao, aorta; av, atrioventricular valve; uv, umbilical vessel; sc, spinal cord; bv, blood vessel; c, cartilage. Bars (*A*) 175 μm; (*B*) 175 μm; (*C*) 115 μm; (*D*) 60 μm.

protein expression patterns in this tissue. For example, while TGFβ3 mRNA signal was high in the atrioventricular cushions and low in the ventricles of the 11.5 d.p.c. mouse heart, TGFβ3 protein in the 12.5 d.p.c. heart was high in the ventricles and atria and low in the atrioventricular cushions (Fig. 4, *A* and *B*). By 17.5 d.p.c., the staining for TGFβ1 and TGFβ2 proteins was barely detectable above background while TGFβ3 staining remained strong. TGFβ 1-3 staining was also found in blood vessels throughout the body. For example, TGFβ3 immunoreactivity was found in small vessels such as those entering the spinal cord (Fig. 4 *D*) as well as in large arteries and veins, such as the umbilical and pulmonary vessels (Fig. 4 *C* and 8, *A* and *B*).

The Embryonic Internal Organs. Thompson et al. (1989) have shown that TGFβ1 is localized to a subset of tubule cells in the cortex of the adult kidney and in the present study, TGFβ proteins were also found in the embryonic kidney (Fig. 5, *A–D*). In the 12.5 d.p.c. embryo, the developing kidney consists of metanephric tubules lined by a cuboidal epithelium (Rugh, 1990). At 12.5 d.p.c., TGFβ2 staining was present in a very restricted pattern in the basement membrane of the cuboidal epithelium. Neither TGFβ1 nor TGFβ3 was detected in the kidney at this stage. From 13.5 to 14.5 d.p.c., the TGFβ2 expression in the basement membrane of the cuboidal epithelium increased in intensity and became more extensive (compare Fig. 5, *A* and *B*). In contrast, during this stage TGFβ1 and TGFβ3 were found in the cuboidal epithelial lining of the tubules, but not in the basement membranes. The expression of TGFβ1 and β3 remained high in the tubule epithelium throughout development. TGFβ2 staining was found in the basement membrane surrounding the tubules throughout development, but was also detectable in the tubule epithelium beginning at 15.5 d.p.c. (Fig. 5, *C* and *D*) in a pattern similar to TGFβ1 and TGFβ3. Although the staining intensity for all three TGFβs in the tubular epithelium of the kidney began to decrease at 17.5 d.p.c., immunoreactivity for TGFβ1s 1–3 in the mesenchymal cells that support the tubules could be seen at this stage.

TGFβ1 has been previously localized to the zona fasiculata and zona reticularis in the cortex of the adult murine adrenal gland (Thompson et al., 1989). Similarly, in our studies, the embryonic adrenal gland also shows very strong TGFβ immunoreactivity. Adrenal blastemas are present in the 11 d.p.c. embryo, but these do not consolidate into cortex and medulla until 14 d.p.c. (Rugh, 1990). Antibodies to TGFβ1 and TGFβ2 showed only slight reactivity in the 13.5 d.p.c. embryos; however by 15.5 d.p.c., very strong staining for TGFβ2 (Fig. 5, *C*, *E*, and *F*) and TGFβ1 was present in the cortex (presumptive zona fasiculata and zona reticularis) of the adrenal gland. This high level of expression for TGFβ1 and TGFβ2 persisted through 17.5 d.p.c.. Antibody staining was confined to the cortex since the medulla was negative for

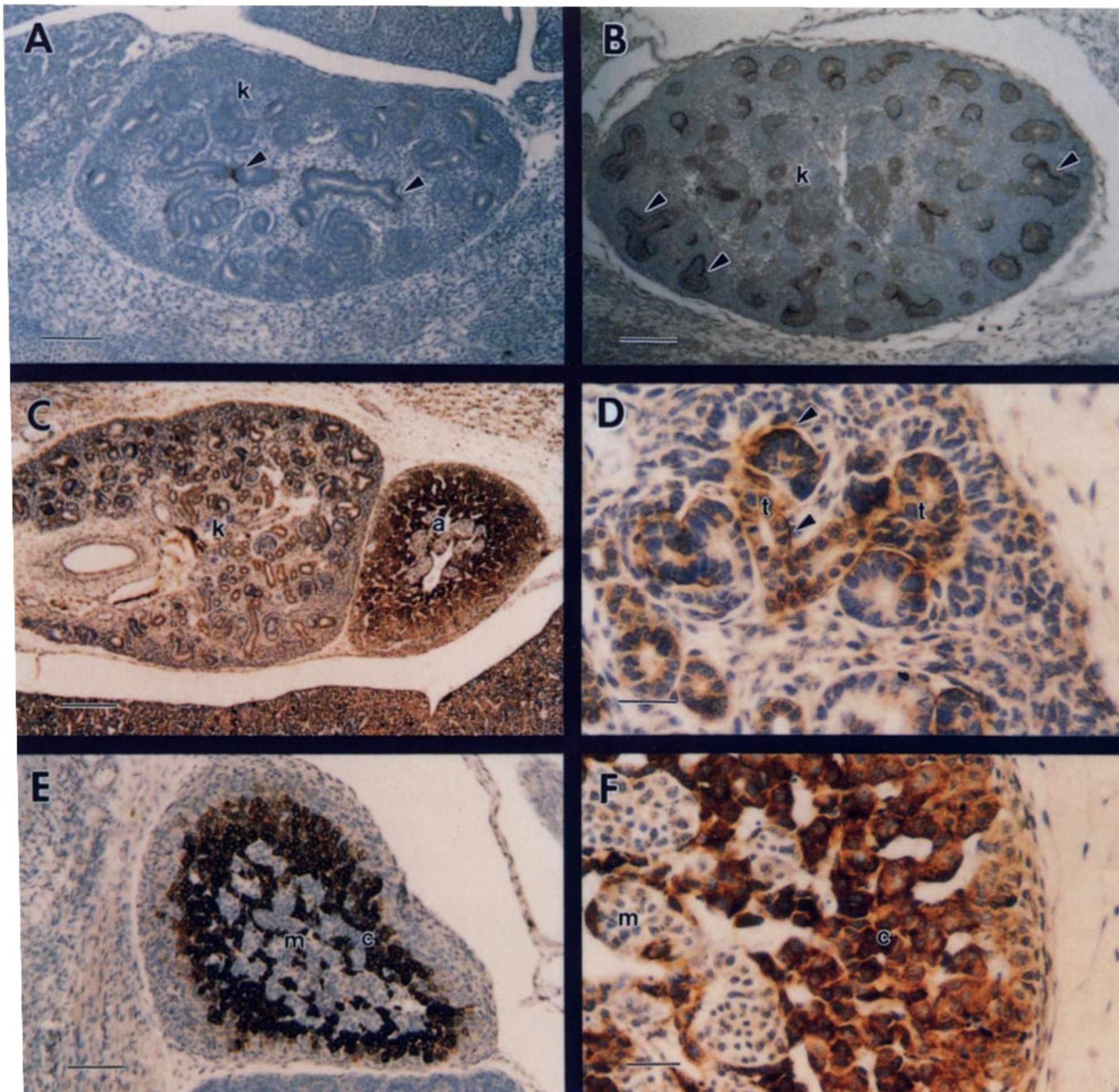


Figure 5. TGFβ2 localization in the embryonic kidney and adrenal gland. (*A*) 13.5 d.p.c. kidney showing TGFβ2 at the base of the epithelium in a subpopulation of tubules (*arrows*). (*B*) 14.5 d.p.c. kidney demonstrating TGFβ2 staining similar to that in (*A*). At 14.5 d.p.c., the staining is stronger and in almost all tubules of the kidney cortex (*arrows*). (*C*) Section through a 15.5 d.p.c. kidney and adrenal gland showing TGFβ2 localization in kidney tubules and cells of the adrenal cortex. (*D*) Higher power of the kidney in *C* showing TGFβ2 staining in the epithelium of the kidney tubules as well as in the supporting cells at the base of the epithelium (*arrows*). (*E*) TGFβ2 expression in the cortex of a 15.5 d.p.c. adrenal gland. The medullary cells show no TGFβ2 staining. (*F*) Higher power of the section in *E* showing TGFβ2 staining in the cells of the adrenal cortex but not the adrenal medulla. k, kidney; a, adrenal gland; t, kidney tubule; m, adrenal medulla; c, adrenal cortex. Bars: (*A*) 120 μm; (*B*) 125 μm; (*C*) 200 μm; (*D*) 35 μm; (*E*) 125 μm; (*F*) 40 μm.

TGFβ1 and β2 immunoreactivity (Fig. 5, *E* and *F*). TGFβ3 did not appear to be present in the adrenal gland during these stages of development (13.5–17.5 d.p.c.).

Using sequential elution of intestinal villus cells and Northern blot analysis, Barnard et al. (1989) have demonstrated that TGFβ1 mRNA is present in a gradient along the villi epithelium in the adult rat intestine with highest levels evident at the tip of the intestinal villus. Immunohistochemistry reflects a similar gradient of TGFβ proteins in the embryonic gut. Slight reactivity was seen at 14.5 d.p.c. in the intestinal epithelium with all three TGFβ antibodies, but by 15.5 d.p.c. significantly stronger staining in these cells was observed (Fig. 6 *A*). Similar to the TGFβ1 mRNA localization, staining appeared in a gradient fashion with the highest levels of TGFβ proteins at the villus tip; lowest levels were in the intestinal crypts. Although TGFβ1 staining remained high at 17.5 d.p.c. (Fig. 6 *B*), TGFβ2 and TGFβ3 staining was not as intense as seen during earlier stages. In addition, the stratified squamous epithelium of the esophagus and forestomach in the 17.5 d.p.c. embryo showed intense TGFβ1

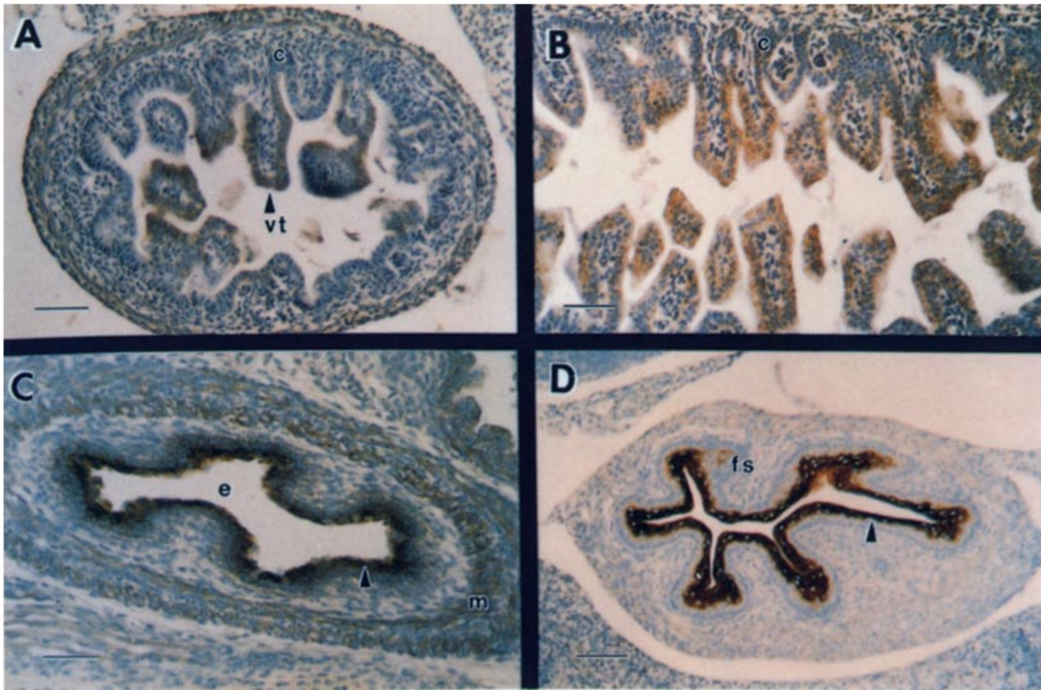


Figure 6. Expression of TGFβ1 and TGFβ2 in epithelia of the embryonic digestive tract. (*A*) TGFβ1 expression in the villi of the 15.5 d.p.c. intestine. Staining is highest at the villus tip (*arrow*) and lowest in the crypts. (*B*) Section through the 17.5 d.p.c. intestine showing TGFβ1 staining in the villi. Staining is similar to that in *A*. (*C*) Localization of TGFβ1 in the squamous epithelium (*arrow*) of the 17.5 d.p.c. esophagus. (*D*) TGFβ1 expression in the squamous epithelium of the forestomach of a 17.5 d.p.c. embryo. g, gut; vt, villus tip; c, crypt; e, esophagus; m, muscle; fs, forestomach. Bars: (*A*) 80 μm; (*B*) 75 μm; (*C*) 50 μm; (*D*) 95 μm.

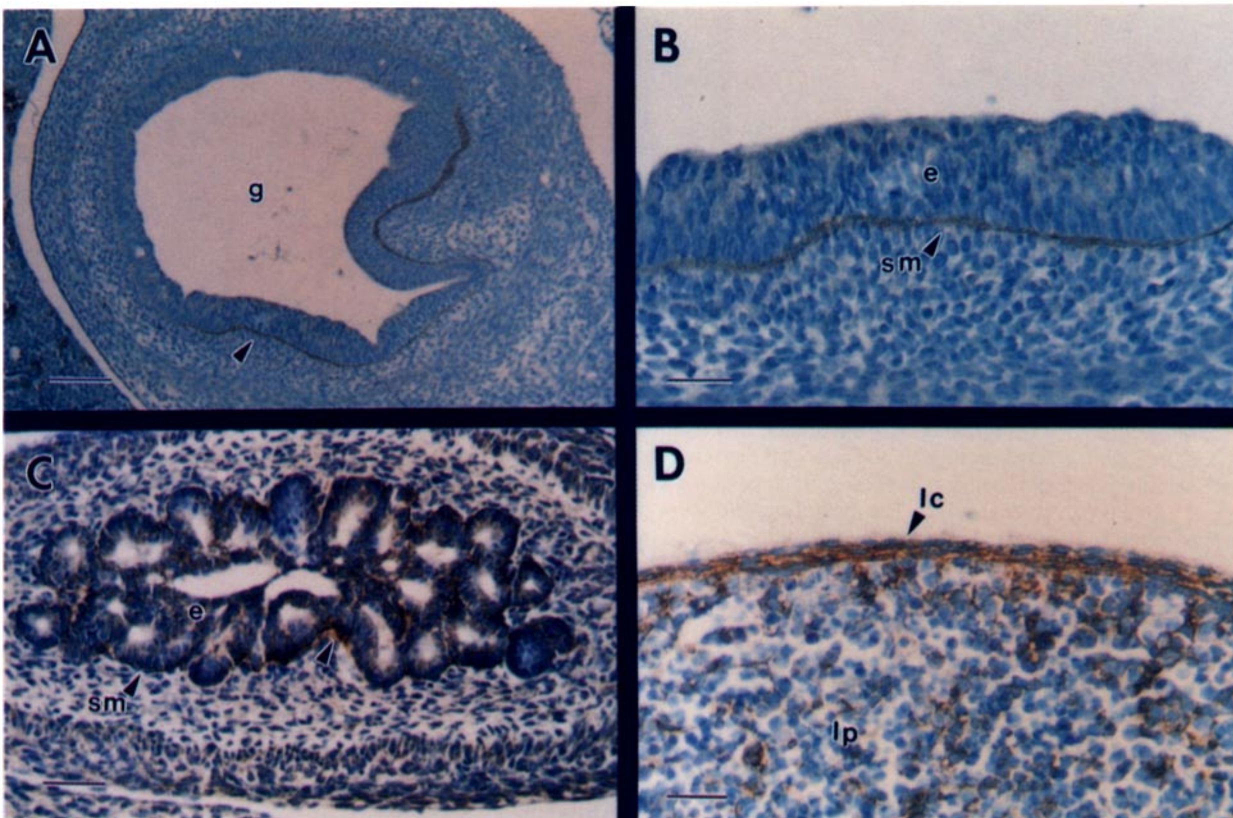


Figure 7. Localization of TGFβ proteins in the submucosa of the embryonic stomach, intestines and in the liver capsule. (*A*) Section through a 13.5 stomach showing TGFβ2 expression in the submucosal region just basal to the epithelium (*arrow*). (*B*) Higher power of the section in *A* showing TGFβ2 staining in the submucosa (*arrow*). (*C*) Section demonstrating TGFβ2 localization in the submucosa of the 15.5 d.p.c. intestine (*arrows*). (*D*) Expression of TGFβ3 in the capsule (*arrow*) of a 13.5 d.p.c. liver. Low levels of TGFβ3 staining were also seen in the mesenchymal cells supporting the liver parenchyma. g, gut; e, epithelium; sm, submucosa; lc, liver capsule; lp, liver parenchyma. Bars: (*A*) 90 μm; (*B*) 25 μm; (*C*) 35 μm; (*D*) 35 μm.

staining (Fig. 6, *C* and *D*), but immunoreactivity for TGFβ2 or β3 was not observed. Moderate staining for TGFβ1 (Fig. 6, *A* and *C*), β2, and β3 was also seen in the smooth muscle of the esophagus and intestine.

Earlier studies have reported that TGFβ2 mRNA is localized to the submucosal layer of the embryonic gut (Pelton et al., 1989). TGFβ2 protein staining was also found in the basement membrane of this layer (Fig. 7, *A* and *B*). At 13.5 d.p.c., a well demarcated line of staining for TGFβ2 was evident just basal to the mucosal (epithelial) layer of the developing stomach and intestines (Fig. 7, *A–C*). TGFβ2 immunoreactivity was not seen in the muscosal layer of the stomach nor in the surrounding mesenchymal layers, although staining was observed in the epithelial cells of the intestine (Fig. 7 *C*).

Previous reports have demonstrated the presence of TGFβ1 mRNA in megakaryocytes in the embryonic liver (Wilcox and Derynck, 1988; Lehnert and Akhurst, 1988) and although no TGFβ mRNA has been found in liver hepatocytes, transcripts for TGFβ2 and β3 have been localized to the capsule surrounding the liver of the 11.5 d.p.c. embryo (Pelton et al., 1990*a*). Similarly, light staining for TGFβ1 and β3 was evident in megakaryocytes of the 12.5 d.p.c. liver and TGFβ3 immunostaining was observed in the liver capsule at 13.5 d.p.c. (Fig. 7 *D*). Although light staining for TGFβ3 was observed in the mesenchymal cells supporting the liver parenchyma (Fig. 7 *D*), TGFβ 1–3 staining of the hepatocytes was not detected.

Heine et al. (1990) have used immunohistochemical analysis to demonstrate that TGFβ1 colocalizes in the embryonic lung with a number of important ECM proteins. In addition, earlier reports have shown that TGFβ1, β2, and β3 mRNAs can be detected in the embryonic lung (Pelton et al., 1989, 1990*a*; Lehnert and Akhurst, 1988; Millan et al., 1991; Schmid et al., 1991). In the adult murine lung, the protein localization patterns in the proximal airways for all three TGFβs are essentially identical (Pelton et al., 1991). Correspondingly, TGFβ proteins in the embryonic mouse lung, showed strikingly similar patterns of expression (Fig. 8, *A–D*). Although slight TGFβ 1–3 immunoreactivity was seen in the epithelium of 17.5 d.p.c. bronchioles, staining for the TGFβs in the airways was seen primarily just basal to the respiratory epithelium (Fig. 8, *A–D*). Moreover, staining for TGFβ 1–3 proteins was present in the smooth muscle cells in the walls of large blood vessels of the lung in a pattern similar to that seen in other large vessels of the embryo (compare Figs. 8, *B* and *C* and 4, *C* and *D*). The highest levels of TGFβ expression in the embryonic lung were seen in late gestation at 17.5–18.5 d.p.c..

The Embryonic Sense Organs. The lens of the eye is derived from the surface embryonic ectoderm and by 12.5 d.p.c. becomes separate from the epidermis. Distinct layers

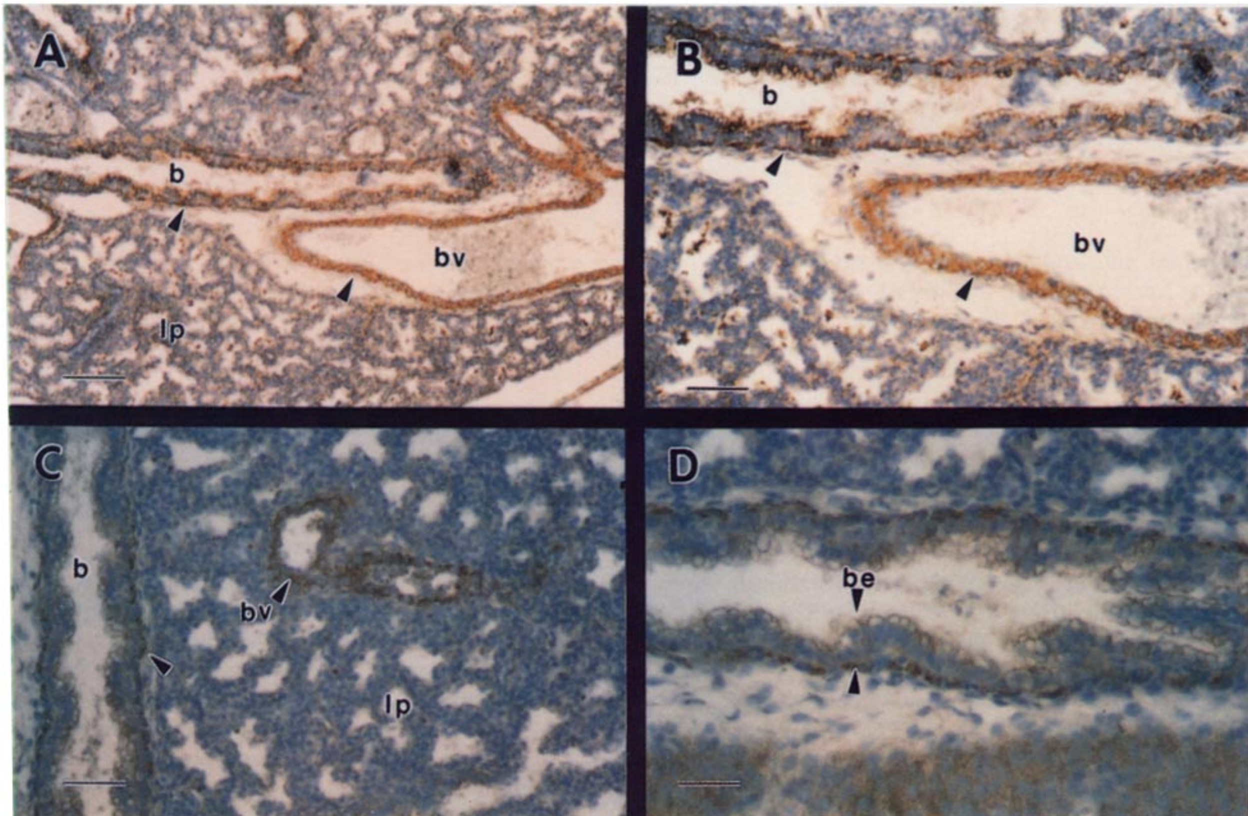


Figure 8. Expression of TGFβs in the 17.5 d.p.c. embryonic lung. (*A*) Section of a lung in a 17.5 d.p.c. embryo stained with TGFβ3 antibodies. Strong staining is seen in the bronchioles and large blood vessels (*arrows*). (*B*) Higher power of the section seen in *A* to show the TGFβ3 staining in the subepithelial region of the bronchioles and in the smooth muscle cells of the blood vessel. (*C*) Similar section to that in *A* incubated with TGFβ2 antibodies. Staining is seen just basal to the epithelium in the bronchiole as well as in the small blood vessel (*arrows*). (*D*) High power photomicrograph of a lung section stained with TGFβ1 antibodies. Low levels of TGFβ1 were localized to the epithelium but higher levels were seen in the subepithelium at the base of the epithelial cells (*arrows*). b, bronchiole; bv, blood vessel; lp, lung parenchyma; be, bronchiolar epithelium. Bars: (*A*) 115 μm; (*B*) 60 μm; (*C*) 55 μm; (*D*) 35 μm.

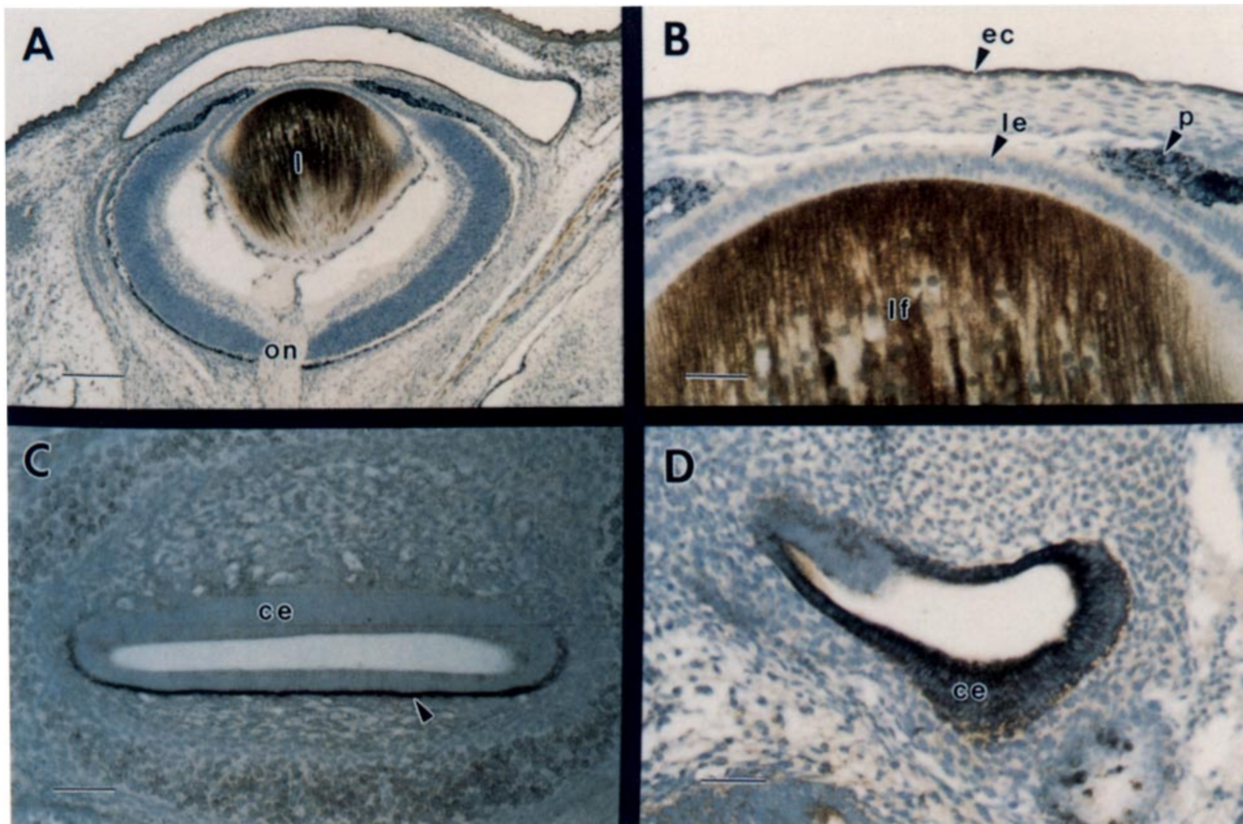


Figure 9. Localization of TGFβs in the sensory organs. (*A*) Expression of TGFβ1 in the lens fibers (but not the lens epithelium) of the 17.5 d.p.c. embryonic eye. (*B*) Higher power of *A* to illustrate the lack of staining at the border between the lens fibers and the lens epithelium. (*C*) Section through the 14.5 d.p.c. cochlea of the inner ear showing staining for TGFβ2 in the basement membrane just basal to the cochlear epithelium (*arrow*). (*D*) Section through the inner ear of a 13.5 d.p.c. embryo showing TGFβ3 staining throughout the cochlear epithelium. l, lens; on, optic nerve; ec, epithelium of cornea; p, retinal pigment; le, lens epithelium; lf, lens fibers; ce, cochlear epithelium. Bars: (*A*) 175 μm; (*B*) 45 μm; (*C*) 60 μm; (*D*) 45 μm.

of lens epithelium and lens fibers have formed by 13 d.p.c. (Rugh, 1990). Intense staining for TGFβ1 was seen in the lens fibers as early as 14.5 d.p.c. and remained strong through 17.5 d.p.c. (Fig. 9, *A* and *B*). However, neither the lens epithelium nor the equatorial region of lens fiber elongation showed TGFβ1 expression (Fig. 9, *A* and *B*). TGFβ2 and β3 staining was also observed in the lens fibers but was much weaker than that for TGFβ1. Previous studies have found the presence of TGFβ2 mRNA in the embryonic eye although not in the lens fibers (Millan et al., 1991). Moreover, recent reports have found TGFβ protein activity (predominantly TGFβ2) in the aqueous and vitreous humors of adult eyes (Connor et al., 1991; Jampel et al., 1991) indicating that TGFβ expression in the eye continues from the embryo into adulthood.

TGFβ2 mRNA is present in the ciliated cochlear epithelium of the inner ear (Pelton et al., 1990*a*; Millan et al., 1991; Schmid et al., 1991). Immunostaining demonstrated that TGFβ2 protein was also found in the inner ear; however, in contrast to the TGFβ2 mRNA, it was localized in the basement membrane just basal to the cochlear epithelium (Fig. 9 *C*). This staining pattern was seen as early as 12.5 d.p.c. and was consistently high through 17.5 d.p.c.. Although TGFβ1 staining in the cochlea was not detected, TGFβ3 was localized throughout the cochlear epithelium in the 13.5 d.p.c. embryo with the highest levels of immunoreactivity found in the apical region (Fig. 9 *D*). Therefore, one of the most striking differences in immunostaining for TGFβ isoforms was found in the ear. By 17.5 d.p.c., TGFβ3 staining was no longer present in this epithelium.

The Embryonic Central Nervous System. The central nervous system (CNS) is unique in that it is one of the first embryonic systems to arise, yet one of the last to complete development (Rugh, 1990). In general, the highest levels of TGFβ immunoreactivity in the embryonic CNS were found with antibodies to TGFβ2 and TGFβ3; very little staining in the CNS was observed with TGFβ1 antibodies. By 12.5 d.p.c., the brain and spinal cord are well developed in the embryo and at this stage, TGFβ2 staining was already apparent in the meninges which envelop the CNS. The TGFβ2 staining in the meninges remained strong in the embryo from 13.5 until 17.5 d.p.c. (Fig. 10, *A–E*). This is in agreement with our in situ hybridization data which also shows TGFβ2 mRNA expression in the meninges of the embryonic brain (Pelton et al., 1989). In the 17.5 d.p.c. embryo, TGFβ2 staining was also found in glia surrounding neurons in the brain and in spinal cord astrocytes (Fig. 10, *F* and *G*). Although little TGFβ1 immunoreactivity was seen in the CNS, TGFβ3 staining was very strong in the brain, choroid plexus, and spinal cord (Fig. 10 *H*). Both TGFβ2 and β3 were localized

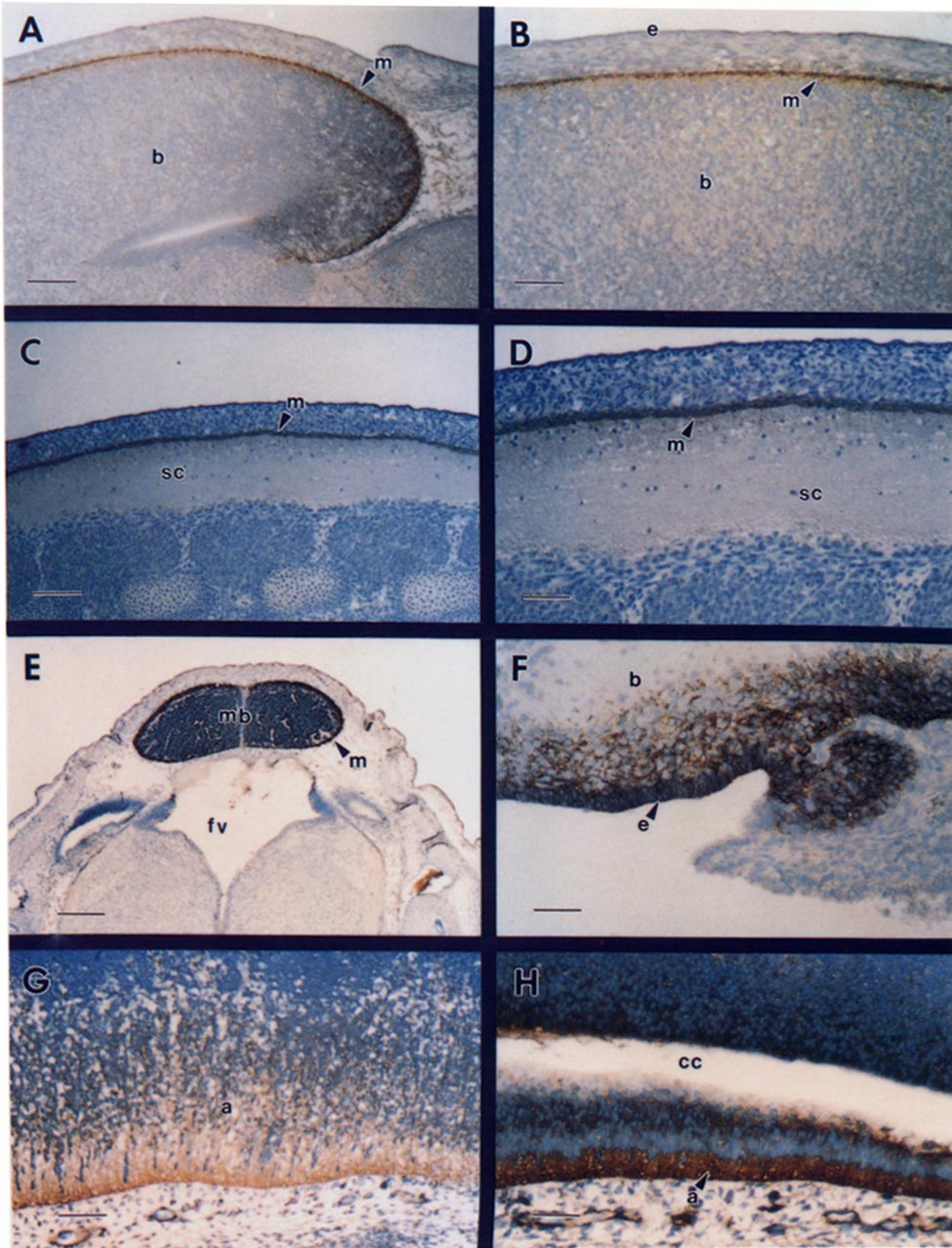


Figure 10. Expression of TGFβ proteins in the embryonic central nervous system. Sagittal section through the midbrain region of a 14.5 d.p.c. embryo demonstrating TGFβ2 staining in the meninges surrounding the brain. (*b*) Higher power of the section in *A* to show staining in a thin layer of meningeal cells surrounding the brain. (*C*) Section showing TGFβ2 expression in the meninges surrounding the dorsal spinal cord in a 13.5 d.p.c. embryo. (*D*) Higher power of section in *C* to show strong TGFβ2 staining in the thin layered meninges and only weak staining in the neurons. (*E*) Frontal section through the midbrain region of a 14.5 d.p.c. embryo to demonstrate TGFβ2 staining in the meninges. (*F*) High power micrograph of a midbrain region of a 17.5 d.p.c. embryo to show TGFβ2 expression in the glial tissue surrounding the neurons. (*G*) Section through the 12.5 d.p.c. ventral spinal cord demonstrating TGFβ2 in astrocytes. (*H*) Section similar to *G* showing strong TGFβ3 staining in the astrocytes of the ventral spinal cord. b, brain; m, meninges; e, epidermis (*B*); sc, spinal cord; mb, midbrain; fv, fourth ventricle; a, astrocytes; cc, central canal of spinal cord. Bars: (*A*) 100 μm; (*B*) 85 μm; (*C*) 115 μm; (*D*) 65 μm; (*E*) 220 μm; (*F*) 30 μm; (*G*) 30 μm; (*H*) 30 μm.

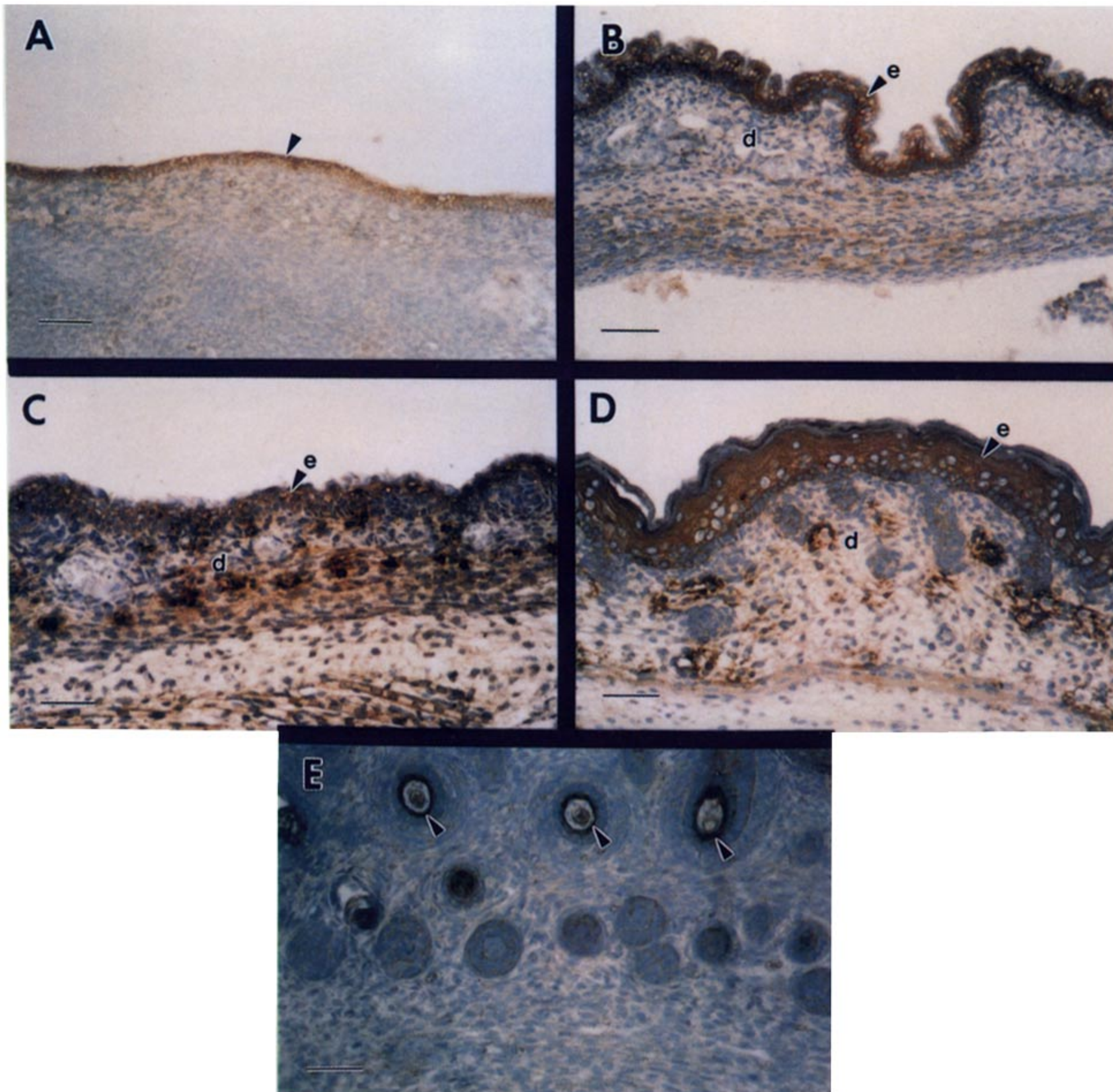


Figure 11. Localization of TGFβs in the embryonic skin. (*A*) TGFβ1 staining in epidermis (*arrow*) of the 14.5 d.p.c. skin but not the dermis. (*B*) TGFβ1 expression in the epidermis (*arrow*) of the 17.5 d.p.c. skin. The dermis is also negative at this stage. (*C*) Expression of TGFβ2 in the 15.5 d.p.c. embryonic skin. Staining is seen in both the dermis and epidermis. (*D*) Section through skin of a 17.5 d.p.c. embryo illustrating TGFβ2 staining primarily in the epidermis at this stage; only low levels were seen in the dermis. (*E*) Staining of 17.5 d.p.c. whisker follicles (*arrows*) with TGFβ1 antibodies. e, epidermis; d, dermis. Bars: (*A*) 80 μm; (*B*) 50 μm; (*C*) 35 μm; (*D*) 35 μm; (*E*) 50 μm.

to spinal cord astrocytes as early as 12.5 d.p.c. (Fig. 10, *G* and *H*). Whereas, TGFβ2 staining in the astrocytes was absent after 13.5 d.p.c., TGFβ3 expression remained consistently high in these cells until late in gestation at 17.5–18.5 d.p.c.

The Embryonic Skin. The skin is formed first as a single cell layer, the periderm, and begins to differentiate into multiple layers at ∼14 d.p.c. (Rugh, 1990). Significant staining for the TGFβs was first seen at this stage. At 14.5 d.p.c., intense staining for TGFβ1 and TGFβ3 was seen in the epithelial layer of the skin over the entire body, while only low levels of TGFβ2 could be detected at this stage (Fig. 11 *A*). TGFβ1 and TGFβ3 were still localized to the epidermis and hair follicles through 17.5 d.p.c. (Fig. 2, *A* and *B* and 11, *B* and *E*). In the 17.5 d.p.c. embryo, TGFβ1 was also expressed at very high levels in the keratinized squamous epithelium of the mouth (Fig. 2, *C* and *D*). Earlier, we reported that TGFβ2 mRNA is localized to the dermis of 15.5 d.p.c. mouse embryo skin and showed that by 18.5 d.p.c., the expression had switched from the dermis to the epidermis (Pelton et al., 1989). In contrast, TGFβ2 protein in the 15.5 d.p.c. embryo was present in the dermis, epidermis and hair follicles of the skin (Fig. 11 *C*). By 17.5 d.p.c., most of the TGFβ2 staining in the dermis had faded but the staining in the epidermis remained strong (compare Fig. 11 *C* with *D*). The highest levels of TGFβ2 immunostaining at this stage were seen in the

epidermis of the skin, although the hair follicles were also positive for TGFβ2 staining.

Discussion

The data presented in these studies demonstrate that TGFβ1, TGFβ2, and TGFβ3 proteins are expressed during murine embryogenesis in a temporally and spatially regulated fashion. TGFβ proteins are differentially expressed in the embryo and show isoform-specific and overlapping localization patterns. Moreover, in many tissues, the restriction of TGFβ proteins corresponds with morphogenetic events in the embryo. Comparison of TGFβ protein and mRNA localizations is consistent with an intricate pattern of gene transcription, translation, secretion, storage, and degradation of TGFβ1, β2, and β3 during embryogenesis of the mouse. The disparate localization of TGFβ mRNAs and proteins in some tissues and colocalization in others suggests that TGFβ1-3 act through both paracrine and autocrine mechanisms in the morphogenesis of many organs.

In many tissues, TGFβ proteins are found in the same cells as the TGFβ mRNA. For example, in situ hybridization analysis demonstrates TGFβ 1-3 mRNA expression in the periosteum and osteocytes of developing skeletal tissue (Pelton et al., 1990*a*) in a pattern very similar to the TGFβ immunostaining presented here. All three TGFβ mRNAs (Pelton et al., 1990*a*) and proteins colocalized in the osteocytes of the intramembranous bones of the head and TGFβ1 immunostaining in the perichondrium of developing cartilage was strikingly similar to the TGFβ1 mRNA pattern (Pelton et al., 1990*a*) in this tissue. TGFβ2 and β3 also showed examples of colocalization of mRNA and protein including TGFβ2 in the submucosal layer of the gut, the pulp and odontoblasts of the tooth, the meninges of the CNS, and the skin; and TGFβ3 in the capsule of the liver, the choroid plexus, and the large blood vessels of the embryo. Thus, for the cells in these tissues, the TGFβs may be working in an autocrine fashion.

In contrast to this, in many instances, TGFβ mRNA and proteins were expressed in the same organ and yet were localized to different, but adjacent, cell types. For example, in the inner ear, transcripts for TGFβ2 are found in the cochlear epithelium (Pelton et al., 1990*a*; Schmid et al., 1991; Millan et al., 1991), while TGFβ2 protein was restricted to the basement membrane just basal to the cochlear epithelium (Fig. 9 *C*). Other examples of differential localization of TGFβ mRNAs and proteins were seen in the cartilage, brain, heart, teeth, and skin. It is well established that the TGFβs are secreted proteins, thus, certain cells may synthesize and release TGFβ proteins into the extracellular matrix of adjacent cells which have the potential to respond to these factors. Thus, our TGFβ immunolocalization data, in conjunction with previous TGFβ in situ hybridization studies, suggest that in many tissues, the TGFβs act in a paracrine mode. In support of this model, it has recently been shown that TGFβ1 bound to type IV collagen remains biologically active (Vishwas et al., 1990) and the ability of latent TGFβ1 to bind to heparin-Sepharose suggests that it contains a specific heparin binding site (Wakefield et al., 1989). Moreover, the latent forms of all TGFβs (except TGFβ2) contain the RGD integrin cellular recognition sequence (Ruoslahti and Pierschbacher, 1986). Thus, the extracellular matrix may act as a repository for TGFβ proteins. Indeed, at least one study has demonstrated that both freshly isolated and commercially available fibronectins can be contaminated with TGFβ activity (Fava and McClure, 1987).

Secretion and subsequent storage of TGFβs in the extracellular matrix may be a primary regulatory step in the production of mature, biologically active TGFβ protein in vivo. Experiments by Sato et al. (1990) demonstrate that homotypic cultures of both endothelial cells and smooth muscle cells secrete TGFβ only in a latent form. However, if these two cell types are cocultured, a portion of the total TGFβ secreted into the culture medium is activated. This suggests that in vivo, latent TGFβs may be produced and secreted by one cell type and activated in conjunction with an adjacent cell type. Activation of latent TGFβ may be through serine proteases (e.g., plasmin; Lyons et al., 1989) released locally by cells. This idea is supported by the observation that specific inhibitors of plasmin block the activation of TGFβ in heterotypic cultures of endothelial cells and pericytes (Sato and Rifkin, 1989). Furthermore, Saksela and Rifkin (1990) have proposed a model whereby TGFβ regulates the synthesis of plasminogen activator which in turn regulates the release of bFGF from extracellular matrix. Interestingly, a comparison of TGFβ2 and bFGF staining during embryogenesis demonstrates that both of these proteins are often found in the basement membrane next to an epithelial cell type (Figs. 5, *A* and *B*; 7, *A-C*; 8 *C*; 9 *C*; and Gonzalez et al., 1990), indicating that these molecules may interact in vivo.

In some of the tissues we examined that express high levels of TGFβ mRNA, very little TGFβ protein was observed; the converse is also true. Other groups have also observed this phenomenon of TGFβ expression (Lehnert and Akhurst, 1988; Akhurst et al., 1991). This may suggest that some of the reported mRNA or protein localization is nonspecific; however, the controls on our experiments have consistently shown that the TGFβ probes used for the in situ hybridization analysis as well as the TGFβ antibodies used in the immunohistochemistry are specific for their respective molecules. An alternative explanation that is consistent with this data is suggested by the work of Madisen et al. (1988) who found that although a prostatic adenocarcinoma cell line produced more TGFβ1 mRNA than TGFβ2, there was significantly more TGFβ2 protein than TGFβ1 present in these cells. Hence, it is possible that some cells transcribe but never translate a given TGFβ gene. It is known, for example, that TGFβ2 has at least five different transcripts in the mouse, but it is not known how many are translated into functional proteins (Miller et al., 1990).

To date there have been no reports concerning the embryonic expression of TGFβ2 and TGFβ3 proteins in mammals; however, several papers studying the distribution of TGFβ1 have been published (Heine et al., 1987, 1990; Thompson et al., 1989; Flanders et al., 1989). Comparison of our results of TGFβ1 staining with these previous data shows that in some tissues the staining patterns were very similar, while in others they differ. For example, immunostaining for TGFβ1 has been reported in adult murine adrenocortical and kidney tubule cells (Thompson et al., 1989) as well as in murine embryonic chondrocytes (Flanders et al., 1989) and osteocytes (Heine et al., 1988); these tissues showed very strong staining for TGFβ1 in our study as well.

Similarly, Jakowlew et al. (1991) observed staining for TGFβ2, β3, and β4 (and to a lesser extent β1) in avian embryonic chondrocytes and cardiac myocytes in patterns much like those seen in the data presented here. Thus, in general, our results are consistent with the expression of TGFβ1 as reported by others (Thompson et al., 1989; Heine et al., 1988; Flanders, et al., 1988; Jakowlew et al., 1991), however, we do find some differences between our studies and those reported by Heine et al. (1988). For example, the intense TGFβ1 staining in the epidermis of the embryonic skin (Figs. 2 *B* and 11, *A–E*) and in the epithelium of the gut (Figs. 6, *A–D*) was not reported by Heine et al. (1988). In contrast, Heine and colleagues found very strong TGFβ1 staining in the atrioventricular valves of the heart which was not seen in our studies. There are several possible reasons for these discrepancies between our results and those of Heine et al. (1988). The TGFβ1 antipeptide antibodies used in their experiments were raised against the first 30 amino acids in the mature region of TGFβ1 (Heine et al., 1988), while those used in our studies were raised against residues 4–19 of the TGFβ1 amino acid sequence. Thus, while the anti-TGFβ1 antibodies used in both studies react with β1, they may recognize different conformations of the protein. For example, Heine et al. (1988) found that embryos fixed in paraformaldehyde did not show immunoreactivity with their antibodies, while embryos fixed in Bouin's fixative reacted strongly. In contrast, all embryos used for our immunohistochemistry were paraformaldehyde fixed. Alternatively, the possibility that some antibodies may cross-react with epitopes on other proteins should also be entertained; however, Western blot analysis indicates that specific staining is achieved with each of the TGFβ antibodies used in this study (Fig. 1).

Yang and Moses (1990) have demonstrated a range of in vivo cellular events (migration, proliferation, inhibition, angiogenesis, etc.) in the chick embryo chorioallantoic membrane in response to exogenously added TGFβ1. A large body of in vitro evidence also strongly suggests that many cellular activities critical to morphogenesis (cell proliferation, cell migration, cell differentiation, extracellular matrix production, etc.) are mediated by the TGFβs (reviewed in Pelton and Moses, 1990*a*). The expression of TGFβ1, β2, and β3 during mouse embryogenesis, as presented in our results, correlates well with these in vivo and in vitro observations. For example, TGFβ1 and β2 are found in the adrenal cortex of the mouse embryo (Fig. 5, *E* and *F*) and human fetal adrenocortical cell differentiation is inhibited by TGFβ1 (Riopel et al., 1989). TGFβ proteins also inhibit the growth of mesangial and proximal tubular cells in the kidney (Avner, 1990), regulate differentiation, proliferation and extracellular matrix deposition in bone and cartilage cells (Centrella et al., 1988) as well as in lung cells (Pelton and Moses, 1990*b*), mediate transdifferentiation of cells in the embryonic heart (Potts and Runyan, 1989), control the growth and differentiation of skin cells (Pittelkow et al., 1988), and appear to regulate morphogenesis, proliferation, and differentiation in astroglial cells of the central nervous system (Toru-Delbauffe et al., 1990). These are all cell types which we show to express TGFβs 1–3 during embryogenesis. A major challenge is to now provide evidence that the localization of TGFβ1, β2, and β3 proteins in specific tissues and cells in the embryo has biological relevance for murine embryonic development. The most direct in vivo method to achieve this end may be to construct transgenic and/or chimeric animals which either mis-express or do not express TGFβ genes. Nonetheless, the temporal and spatial expression of TGFβs 1–3 at crucial steps in the morphogenesis of specific organs in the mouse undoubtedly implicates a role for these factors in the development of the mammalian embryo.

In conclusion, we have generated isoform-specific antibodies which recognize TGFβ1, β2, or β3 and have used them to study the distribution of these three proteins during murine embryogenesis. We have observed that the expression patterns for each protein are both temporally and spatially unique. Similarly, these distinct but overlapping patterns of expression are seen for TGFβ1, β2, and β3 mRNAs as well (Pelton et al., 1990*a*). While the mRNA and protein expression patterns do not always strictly coincide, TGFβ protein is often found in cells or extracellular matrix positioned next to a cell type in which the mRNA is found in many tissues. This is consistent with the premise that during embryonic development, TGFβ1, β2, and β3 may act through both autocrine and paracrine mechanisms. Currently, there is little evidence ascribing unique functions for these three closely related isoforms of TGFβ. The expression patterns shown in this study of different isoforms of TGFβ in dissimilar cell types, for example, in the eye and ear, may imply separate cell-specific functions for each of the TGFβs in vivo. Together with the known biological activities of the β-TGFs, these data support the hypothesis that TGFβ1, β2, and β3 are important mediators of cell–cell interaction during embryonic development and may offer insight into an explanation for the evolutionary persistence of these very closely related proteins.

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References

Akhurst, R. J., S. A. Lehnert, A. Faissner, and E. Duffie. 1990. TGF beta in murine morphogenetic processes: the early embryo and cardiogenesis. *Development (Camb.).* 108:645–656.

Akhurst, R. J., D. R. Fitzpatrick, D. Gatherer, S. A. Lehnert, and F. A. Millan. 1991. Transforming growth factor betas in mammalian embryogenesis. *Proc. Growth Factor Res.* 2:153–168.

Avner, E. D. 1990. Polypeptide growth factors and the kidney: a developmental perspective. *Ped. Nephrol.* 4:345–353.

Barnard, J. A., R. D. Beauchamp, R. J. Coffey, Jr., and H. L. Moses. 1989. Regulation of intestinal epithelial cell growth by transforming growth factor type beta. *Proc. Natl. Acad. Sci. USA.* 86:1578–1582.

Centrella, M., T. L. McCarthy, and E. Canalis. 1988. Skeletal tissue and transforming growth factor β. *FASEB (Fed. Am. Soc. Exp. Biol.) J.* 2:3066–3073.

Connor, T. B., Jr., A. B. Roberts, M. B. Sporn, D. Danielpour, L. L. Dart, R. G. Michels, S. de Bustros, C. Enger, H. Kato, M. Lansing, H. Hayashi, and B. M. Glaser. 1989. Correlation of fibrosis and transforming growth factor-β type 2 levels in the eye. *J. Clin. Invest.* 83:1661–1666.

Derynck, R., J. A. Jarret, E. Y. Chen, D. H. Eaton, J. R. Bell, R. K. Assoian, A. B. Roberts, M. B. Sporn, and D. V. Goeddel. 1985. Human transforming growth factor-β complementary DNA sequence and expression in normal and transformed cells. *Nature (Lond.).* 316:701–705.

Derynck, R., P. B. Lindquist, A. Lee, D. Wen, J. Tamm, J. L. Graycar, L. Rhee, A. J. Mason, D. A. Miller, R. J. Coffey, H. L. Moses, and E. Y.

Chen. 1988. A new type of transforming growth factor-β, TGF-β3. *EMBO (Eur. Mol. Biol. Organ.) J.* 7:3737–3743.

Fava, R. A., and D. B. McClure. 1987. Fibronectin-associated transforming growth factor. *J. Cell. Physiol.* 131:184–189.

Fitzpatrick, D. R., F. Denhez, P. Kondaiah, and R. J. Akhurst. 1990. Differential expression of TGFβ isoforms in murine palatogenesis. *Development (Camb.).* 109:585–595.

Flanders, K. C., N. L. Thompson, D. S. Cissel, L. R. Ellingsworth, A. B. Roberts, and M. B. Sporn. 1989. Transforming growth factor β1: histochemical localization with antibodies to different epitopes. *J. Cell Biol.* 108:653–660.

Gatherer, D., P ten Dijke, D. T. Baird, and R. J. Akhurst. 1990. Expression of TGFβ isoforms during first trimester human embryogenesis. *Development (Camb.).* 110:445–460.

Gonzalez, A.-M., M. Buscaglia, M. Ong, and A. Baird. 1990. Distribution of basic fibroblast growth factor in the 18-day rat fetus: localization in the basement membrane of diverse tissues. *J. Cell Biol.* 110:753–765.

Graycar, J. L., D. A. Miller, B. A. Arrick, R. M. Lyons, H. L. Moses, and R. Derynck. 1989. Human transforming growth factor-β3: recombinant expression, purification and biological activities in comparison with transforming growth factors-β1 and β2. *Mol. Endocrinol.* 7:1977–1986.

Heine, U. I., E. F. Munoz, K. C. Flankers, L. R. Ellingsworth, H.-Y. P. Lam, N. L. Thompson, A. B. Roberts, and M. B. Sporn. 1987. Role of transforming growth factor-β in the development of the mouse embryo. *J. Cell Biol.* 105:2861–2876.

Heine, U. I., E. F. Munoz, K. C. Flanders, A. B. Roberts, and M. B. Sporn. 1990. Colocalization of TGFβ1 and collagen I and III, fibronectin and glycosaminoglycans during lung branching and morphogenesis. *Development (Camb.).* 109:29–36.

Jakowlew, S. B., P. Dillard, M. B. Sporn, and A. B. Roberts. 1988. Complementary deoxyribonucleic acid cloning of a messenger ribonucleic acid encoding transforming growth factor β4 from chicken embryo chondrocytes. *Mol. Endocrinol.* 2:1186–1195.

Jakowlew, S. B., P. J. Dillard, T. S. Winokur, K. C. Flanders, M. B. Sporn, and A. B. Roberts. 1991. Expression of transforming growth factor-βs 1–4 in chicken embryo chondrocytes and myocytes. *Dev. Biol.* 143:135–148.

Jampel, H. D., N. Roche, W. J. Stark, and A. B. Roberts. 1990. Transforming growth factor-β in human aqueous humor. *Current Eye Res.* 9:963–969.

Jennings, J. C., S. Mohan, T. A. Linkhart, R. Widstrom, and D. J. Baylink. 1988. Comparison of the biological actions of TGF beta-1 and TGF beta-2: differential activity in endothelial cells. *J. Cell. Physiol.* 137:167–172.

Kimelman, D., and M. Kirschner. 1987. Synergistic induction of mesoderm by FGF and TGF-β and the identification of an mRNA coding for FGF in the early *Xenopus* embryo. *Cell.* 51:869–877.

Lehnert, S. A., and R. J. Akhurst. 1988. Embryonic expression pattern of TGF beta type-1 RNA suggests both paracrine and autocrine mechanisms of action. *Development (Camb.).* 104:263–273.

Lyons, K. M., R. W. Pelton, and B. L. M. Hogan. 1990. Organogenesis and pattern formation in the mouse: RNA distribution patterns suggest a role for *Bone Morphogenetic Protein-2A (BMP-2A). Development (Camb.).* 109: 833–844.

Lyons, R. M., and H,. L. Moses. 1990. Transforming growth factors and the regulation of cell proliferation. *Eur. J. Biochem.* 187:467–473.

Lyons, R. M., L. E. Gentry, A. F. Purchio, and H. L. Moses. 1989. Mechanism of activation of latent recombinant transforming growth factor β1 by plasmin. *J. Cell Biol.* 110:1361–1367.

Madisen, L., N. R. Webb, T. M. Rose, H. Marquardt, T. Ikeda, D. Twardzik, S. Seyedin, and A. F. Purchio. 1988. Transforming growth factor-β2: cDNA cloning and sequence analysis. *DNA.* 7:1–8.

Mercola, M., and C. D. Stiles. 1988. Growth factor superfamilies and mammalian embryogenesis. *Development (Camb.).* 102:451–460.

Merwin, J. R., W. Newman, L. D. Beall, A. Tucker, and J. Madri. 1991. Vascular cells respond differentially to transforming growth factors beta1 and beta2 in vitro. *Am. J. Pathol.* 138:37–51.

Millan, F. A., F. Denhez, P. Konaiah, and R. J. Akhurst. 1991. Embryonic gene expression patterns of TGFβ1, β2 and β3 suggest differential development functions *in vivo. Development (Camb.).* 111:131–144.

Miller, D. A., R. W. Pelton, R. Derynck, and H. L. Moses. 1990. Transforming growth factor β: A family of growth regulatory peptides. *Ann. N.Y. Acad. Sci.* 593:208–217.

Nilsen-Hamilton, M. 1990. Growth factors and development. Current Topics in Developmental Biology. Vol. 24. Academic Press, Inc., San Diego. 347 pp.

Ohta, M., J. S. Greenberger, P. Anklesaria, A. Bassols, and J. Massague. 1987. Two forms of transforming growth factor-beta distinguished by multipotential hematopoietic progenitor cells. *Nature (Lond.).* 329:539–541.

Pelton, R. W., S. Nomura, H. L. Moses, and B. L. M. Hogan. 1989. Expression of transforming growth factor beta-2 RNA during murine embryogenesis. *Development (Camb.).* 106:759–767.

Pelton, R. W., and H. L. Moses. 1990*a*. The transforming growth factor β family of growth regulatory peptides. *In* Contributions to Oncology: Oncogenes in Cancer Diagnostics. Vol. 39. C. R. Bartram, K. Munk, and M. Schwab, editors. Karger, Basel. 94–114.

Pelton, R. W., and H. L. Moses. 1990*b*. The beta-type transforming growth factors: mediators of cell regulation in the lung. *Am. Rev. Respir. Dis.* 142:S31–S35.

Pelton, R. W., M. E. Dickinson, H. L. Moses, and B. L. M. Hogan. 1990*a*. In situ hybridization analysis of TGFβ3 RNA expression during mouse development: comparative studies with TGFβ1 and β2. *Development (Camb.).* 110:609–620.

Pelton, R. W., B. L. M. Hogan, D. A. Miller, and H. L. Moses. 1990*b*. Differential expression of genes encoding TGFs β1, β2 and β3 during murine palate formation. *Dev. Biol.* 141:456–460.

Pelton, R. W., M. D. Johnson, E. A. Perkett, L. I. Gold, and H. L. Moses. 1991. Expression of Transforming growth factor (TGF)-β1, TGFβ2 and TGFβ3 mRNA and protein in the murine lung. *Am. J. Respir. Cell Mol. Biol.* In press.

Pittelkow, M. R., R. J. Coffey, and H. L. Moses. 1988. Keratinocytes produce and are regulated by transforming growth factors. *Ann. N.Y. Acad. Sci.* 548:211–224.

Potts, J. D., and R. Runyan. 1989. Epithelial-mesenchymal cell transformation in the embryonic heart can be mediated in part by transforming growth factor beta. *Dev. Biol.* 134:392–401.

Riopel, L., C. L. Branchaud, C. G. Goodyer, V. Adkar, and Y. Lefebvre. 1989. Growth-inhibitory effects of TGF beta on human fetal adrenal cells in primary monolayer culture. *J. Cell Physiol.* 140:233–238.

Rosa, F., A. B. Roberts, D. Danielpour, L. L. Dart, M. B. Sporn, and I. B. Dawid. 1988. Mesoderm induction in amphibians: the role of TGF-β2-like factors. *Science (Wash. DC).* 239:783–785.

Rugh, R. 1990. The mouse: Its Reproduction and Development. Oxford University Press, England. 430 pp.

Ruoslahti, E., and M. D. Pierschbacher. 1986. Arg-Gly-Asp: a versatile cell recognition signal. *Cell.* 44:517–518.

Saksela, O., and D. B. Rifkin. 1990. Release of basic fibroblast growth factor-heparan sulfate complexes from endothelial cells by plasminogen activator-mediated proteolytic activity. *J. Cell Biol.* 110:767–775.

Sandberg, M., H. Autio-Harmainen, and E. Vuorio. 1988*a*. Localization of the expression of types I, III, and IV collagen, TGF-β1 and c-fos genes in developing human calvarial bones. *Dev. Biol.* 130:324–334.

Sandberg, M., T. Vuorio, H. Hirrovan, K. Alitalo, and E. Vuorio. 1988*b*. Enhanced expression of TGF-B and c-*fos* mRNAs in the growth plates of developing human long bones. *Development (Camb.).* 102:461–470.

Sato, Y., and D. B. Rifkin. 1989. Inhibition of endothelial cell movement by pericytes and smooth muscle cells: activation of a latent transforming growth factor β1-like molecule by plasmin during co-culture. *J. Cell Biol.* 109:309–315.

Sato, Y., R. Tsuboi, R. Lyons, H. L. Moses, and D. B. Rifkin. 1990. Characterization of the activation of latent TGFβ by co-cultures of endothelial cells and pericytes or smooth muscle cells: a self-regulating system. *J. Cell Biol.* 111:757–763.

Schmid, P., D. Cox, G. Bilbe, R. Maier, and G. K. McMaster. 1991. Differential expression of TGFβ1, β2 and β3 genes during mouse embryogenesis. *Development (Camb.).* 111:117–130.

Segarini, P. R. 1990. Cell type specificity of TGFβ binding. *Ann. N.Y. Acad. Sci.* 548:73–90.

ten Dijke, P., P. Hansen, K. K. Iwata, C. Pieler, and J. G. Foulkes. 1988a. Identification of another member of the transforming growth factor type β gene family. *Proc. Natl. Acad. Sci. USA.* 85:4715–4719.

Theiler, K. 1989. The House Mouse. Springer-Verlag, New York. 178 pp.

Thompson, N. L., K. C. Flanders, J. M. Smith, L. R. Ellingsworth, A. B. Roberts, and M. B. Sporn. 1989. Expression of transforming growth factor-β1 in specific cells and tissues of adult and neonatal mice. *J. Cell Biol.* 108:661–669.

Toru-Belauffe, D., D. Baghdassarian-Chalaye, J. M. Gavaret, F. Courtin, and M. Pomerance. 1990. Effects of TGFβ1 on astroglial cells in culture. *Ann. N.Y. Acad. Sci.* 593:367–370.

Vishwas, M. P., S. Vukicevic, and A. H. Reddi. 1990. Transforming growth factor β type 1 binds to collagen IV of basement membrane matrix: implications for development. *Dev. Biol.* 143:303–308.

Wakefield, L. M., D. M. Smith, S. Broz, M. Jackson, A. D. Levinson, and M. B. Sporn. 1989. Recombinant TGFβ1 is synthesized as a two component latent complex that shares some structural features with the native latent TGFβ1 complex. *Growth Factors.* 1:203–218.

Whitman, M., and D. A. Melton. 1989. Growth factors in early embryogenesis. *Annu. Rev. Cell Biol.* 5:93–117.

Wilcox, J. N., and R. Derynck. 1988. Developmental expression of transforming growth factors alpha and beta in mouse fetus. *Mol. Cell. Biol.* 8:3415–3422.

Yang, E. Y., and H. L. Moses. 1990. Transforming growth factor β1-induced changes in cell migration, proliferation, and angiogenesis in the chicken chorioallantoic membrane. *J. Cell Biol.* 111:731–741.