

# Expression and Action of Transforming Growth Factor Beta (TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3) during Embryonic Rat Testis Development<sup>1</sup>

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## ABSTRACT

The objective of the current study was to determine the role of transforming growth factor beta (TGF $\beta$ ) during seminiferous cord formation and embryonic testis development. The expression pattern of mRNA for TGF $\beta$  isoforms was evaluated during testis development through a quantitative reverse transcription-polymerase chain reaction (QRT-PCR) procedure. Expression of mRNA for TGF $\beta$ 1 was highest at postnatal day 0 (P0) and P10. In contrast, TGF $\beta$ 2 was high at embryonic day 15 (E15), declined at E16, and showed a transient increase at P0 through P3 of testis development. Interestingly, expression of mRNA for TGF $\beta$ 3 was high during embryonic development and then declined after P3. Immunohistochemical localization of TGF $\beta$ 1 and TGF $\beta$ 2 demonstrated expression in Sertoli cells at E14 and in the seminiferous cords at P0. Selective interstitial cells expressed high concentrations of TGF $\beta$ 1 and TGF $\beta$ 2 in P0 testis. TGF $\beta$ 3 was expressed in selective cells at the junction of the E14 testis and mesonephros. The cells expressing TGF $\beta$ 3 in the testis appeared to be preperitubular cells that resided around the seminiferous cords. TGF $\beta$ 3 was localized to gonocytes in P0 testis. TGF $\beta$ 1 was found to have no influence on seminiferous cord formation in embryonic organ cultures of E13 testis. In contrast, growth of both E13 and E14 embryonic organ cultures was inhibited by TGF $\beta$ 1 and resulted in reduced testis size (40% of controls) with fewer cords present. A P0 testis cell culture and thymidine incorporation assay were used to directly examine the effects of recombinant TGF $\beta$ 1. TGF $\beta$ 1 alone had no influence on thymidine incorporation in P0 testis cell cultures when compared to controls. Interestingly, TGF $\beta$ 1 inhibited epidermal growth factor (EGF), and 10% calf serum stimulated P0 testis cell growth but not FSH-stimulated growth. Therefore, TGF $\beta$ 1 appears to inhibit testis growth in both the embryonic and early postnatal periods. The hormonal regulation of TGF $\beta$  expression was measured using P0 testis cell cultures and a QRT-PCR procedure for each TGF $\beta$  isoform. High concentrations of EGF stimulated expression of mRNA for TGF $\beta$ 1 after 24 h but suppressed expression of TGF $\beta$ 3. In contrast, there was no effect of FSH on TGF $\beta$  isoform expression. In summary, TGF $\beta$  regulates embryonic and P0 testis growth through inhibiting the actions of positive growth factors such as EGF. In addition, EGF but not FSH appears to regulate TGF $\beta$  isoform expression. Combined observations from the present study demonstrate that TGF $\beta$  isoforms are differentially expressed and appear to be regulators of testis growth during the embryonic and early postnatal periods.

## INTRODUCTION

Seminiferous cord formation is one of the first critical events in testis development, occurring at embryonic day 13.5 (E13.5; E0 is the date a vaginal copulation plug was detected) of gestation in the rat [1]. Both aggregation of

pre-Sertoli and germ cells within the differentiating gonad and cellular migration of pre-peritubular cells from the adjoining mesonephros [1–4] must occur in order for seminiferous cords to form. After seminiferous cord formation, all cell populations within the testis proliferate, and by E15 the testis is twice the size of the ovary from animals of the same age [5]. Growth and proliferation of cells within the testis are necessary to allow for adequate numbers of somatic cells to support adult germ cell maturation and function. [6]. All somatic cell populations proliferate during embryonic testis development. In contrast, the germ cell population undergoes mitotic arrest around E17–E18 and by postnatal day 5 (P5) resumes cellular proliferation [7]. Early growth of the embryonic testis is presumed to be independent of gonadotropins. Specific binding of gonadotropin receptors has been detected around E16, but it is unknown if these receptors have the ability to elicit a response at this time [8]. Therefore, much of the growth associated with the testis during early embryonic testis development must be due to locally produced paracrine growth factors.

Transforming growth factor betas (TGF $\beta$ s) are critical for growth regulation and development of many different cell types within an organism. Of the five TGF $\beta$  isoforms identified, three [9–11] are present in mammals (TGF $\beta$ 1, TGF $\beta$ 2, TGF $\beta$ 3). Each of the TGF $\beta$  isoforms is encoded by a unique gene, each on a different chromosome. The primary functions of the TGF $\beta$  isoforms are to enhance formation of the extracellular matrix and inhibit proliferation of most cells (for reviews see [9, 12]). Inhibition of growth by TGF $\beta$  occurs through an arrest of the cell cycle in late G1 phase and may require interactions with retinoblastoma and cyclin or cyclin-dependent kinases. The effects of TGF $\beta$ s are elicited by activation of two types of membrane receptors containing serine/threonine kinase activity [12, 13], but all TGF $\beta$  isoforms bind and signal primarily through the TGF $\beta$  receptor II.

Gene knockout and overexpression experiments with TGF $\beta$  have demonstrated that precise regulation of each isoform is essential for survival. TGF $\beta$ 1 knockouts are phenotypically normal until approximately 3 wk after birth and then develop a severe wasting syndrome [14, 15]. Reproductive traits and organs within TGF $\beta$ 1 isoform knockout mice have not been extensively studied. However, there are significant deviations from normal Mendelian ratios, resulting in decreased offspring for both heterozygotes and homozygotes carrying the allele with the TGF $\beta$ 1 gene disruption. Thus, TGF $\beta$ 1 may be important in reproductive function or embryonic development.

Both TGF $\beta$ 1 and TGF $\beta$ 2 have been localized to the somatic cells in early embryonic testis [16–18], with receptor localization within the germ cells [19]. Before birth, the TGF $\beta$ 2 isoform is also detected within the germ cells [18]. The primary functions of TGF $\beta$  isoforms during embryonic testis development are regulation of steroidogenesis within Leydig cells [20] and potential regulation of germ cell ap-

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optosis [19]. Since TGF $\beta$  isoforms are present in somatic cells of the testis during early embryonic development, their presence may be necessary for cell-cell interactions that occur during the morphological process of cord formation or embryonic testis growth.

In the current study, the expression of TGF $\beta$  isoforms during embryonic testis development was examined. In addition, two critical time points were evaluated to determine the actions of TGF $\beta$  during testis development. The first was E13-E14, when seminiferous cord formation occurs. The second time was P0, when cells of the testis are actively proliferating. The hypothesis tested was that TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3 have critical roles in testis development and are necessary for normal cell-cell interactions during the process of seminiferous cord formation and embryonic testis growth.

## MATERIALS AND METHODS

### *Organ Cultures*

Timed pregnant Sprague-Dawley rats were obtained from Charles River (Wilmington, MA). For E13 dissections, gonads were dissected out with the mesonephros, and for later-stage dissections testes alone were dissected. The organs were cultured in drops of medium on Millicell CM filters (Millipore, Bedford, MA) floating on the surface of 0.4 ml of CMRL 1066 medium (Gibco BRL, Gaithersburg, MD) supplemented with penicillin-streptomycin, insulin (10  $\mu$ g/ml), and transferrin (10  $\mu$ g/ml). Antibodies and factors were added directly to the culture medium. The medium was changed every day. E13 gonad + mesonephros cultures were typically kept for 3 days, by which time point cords are well developed. E14 testes were kept for 3 days, and cords were formed before dissection and organ culture.

### *Genomic DNA Isolation and Polymerase Chain Reaction (PCR) for SRY*

To determine the sex of E13 gonads, PCR for SRY was examined. Embryonic tails were collected to make genomic DNA by standard procedures. Briefly, the tissue was homogenized through a 25-gauge needle in digestion buffer (100 mM NaCl, 10 mM Tris pH 8, 25 mM EDTA, 0.5% SDS) and digested with proteinase K (0.15 mg/ml) for at least 4 h at 60°C. The samples were then extracted twice with an equal volume of phenol:chloroform:isoamyl alcohol (25:24:1), and once with chloroform:isoamyl alcohol. The DNA was then precipitated by adding a 1/10 volume of 7.5 M NH<sub>4</sub>Ac and 3 volumes cold ethanol, and incubating at -80°C for 1 h before centrifugation at 4°C for 30 min. Pellets were dried and resuspended in 10  $\mu$ l dH<sub>2</sub>O. PCR was performed using 1  $\mu$ l of genomic DNA with primers to SRY. The sequences of the SRY primers are: 5' CGGGATCCATGTCAAGCGCCCATGAATGCATTATG 3' and 5' GCGGAATTCACCTTAGCCCTCCGATGAGGCTGATAT 3'. PCR was performed using an annealing temperature of 55°C for 30 cycles to yield a product of 240 base pairs (bp) [21].

### *P0 Testis Culture and Growth Assay*

To generate a testicular culture from P0 testis, the tunica was removed, and the testis was digested with 0.125% trypsin, 0.1% EDTA, and 0.02 mg/ml deoxyribonuclease (DNase) in Hanks' Balanced Salt Solution (HBSS) for 15 min at 37°C. The trypsin was inactivated with 10% calf serum. The samples were triturated with a pipette tip and washed

twice in 1 ml HBSS by resuspending, spinning for 2 min, and removing the supernatant. The remaining cell pellet was resuspended and used immediately in growth assays or plated in 100-mm plates in F12 medium supplemented with 10% bovine calf serum until confluent (approximately two days). Cells were plated at a 25% confluency in 24-well plates and allowed to settle overnight in Dulbecco's Modified Eagle's medium (DMEM) without thymidine. Medium was replaced the next day, and cells were treated for 24 h with different hormones or growth factors. Media were removed after the 24-h treatment period, and medium containing tritiated thymidine (10  $\mu$ Ci/ml) was placed on cells and allowed to remain for 6 h. After 6 h, media were discarded, and cells were either frozen or processed using the following tritiated thymidine assay. A solution of 0.5 M NaH<sub>2</sub>PO<sub>4</sub> (pH 7.3; 500  $\mu$ l) was added to each well, and cells were sonicated. Half of the sonicated cells were placed on DE-81 filters on a manifold, and a vacuum was applied. After three washes with the NaH<sub>2</sub>PO<sub>4</sub> buffer (vacuum applied after each wash) the filters were dried, placed in counting vials with 5 ml of scintillation fluid, and counted. The remaining sonicate was then used for DNA assays to normalize number of cells (DNA) per well [22].

### *DNA Assay*

To assay the DNA content of organs, each organ was sonicated in 100  $\mu$ l ethidium bromide buffer (EBB; 20 mM NaCl, 5 mM EDTA, 10 mM Tris pH 7.5) and stored at -20°C. DNA content then was determined fluorometrically with ethidium bromide as previously described [22]. Briefly, 0.25 nM ethidium bromide and 100 U/ml heparin in EBB were added to each sample, vortexed, and incubated for 15 min at room temperature. Fluorescent emission was measured and quantified by using a standard curve with calf thymus DNA from 0.5  $\mu$ g to 6  $\mu$ g DNA. For growth assays, the above procedure was used on remaining sonicate from the tritiated thymidine procedure [22].

### *Imaging and Area Analysis*

Images of whole organs were obtained by using an image analysis system (Pixera; Pixera Corp., Los Gatos, CA; [22]). Areas were quantified using the NIH image program. Previous data correlated DNA concentrations of testis organ cultures with the area imaged by the NIH image program [23]. Each testis (without mesonephros) was outlined three times, and the areas of these outlines were averaged to obtain accurate area measurements. The averages for the control testis organ cultures were set to 100%, and the area of a treated testis was calculated as a percentage of its paired control. Approximately 18 testis pairs for the E14 testis organ cultures (three experiments with 6 testis pairs per experiment) and 36 testis pairs for the E13 testis organ cultures (4 experiments with 6 testis pairs per experiment) were imaged for area quantifications. Areas for each age were averaged and presented as a percentage of their respective controls.

### *RNA Isolation and Quantitative Reverse Transcription (RT)-Polymerase Chain Reaction (PCR)*

RNA for RT-PCR was extracted from tissue using Tri Reagent (Sigma, St. Louis, MO) for RNA isolation. RT and quantitative RT-PCR (QRT-PCR) procedures were utilized as previously published [22]. Briefly, for QRT-PCR, total RNA (1  $\mu$ g) was reverse-transcribed using the specific 3'-

primers of interest. Carrier DNA (Bluescript plasmid; Stratagene, La Jolla, CA) was added to a final concentration of 10 ng/ $\mu$ l. Plasmid DNAs containing standard subclones of interest were used to generate standard curves from 1 ng/ $\mu$ l ( $10^{-15}$  g/ $\mu$ l) to 10 pg/ $\mu$ l ( $10 \times 10^{-9}$  g/ $\mu$ l), each containing 10 ng/ $\mu$ l Bluescript carrier DNA. Identical 10- $\mu$ l aliquots of each sample and standard were used for PCR amplification. By this design it was possible to simultaneously assay 5 known standard concentrations and 40 unknown samples for each gene. At least 0.25  $\mu$ Ci of  $^{32}$ P-labeled dCTP was included in each sample during amplification. Specific PCR products were quantitated by electrophoresing all samples on 4–5% polyacrylamide gels, simultaneously exposing the gels to a phosphor screen for 8–24 h, and then quantifying specific bands on a PhosphorImager (Molecular Dynamics, Sunnyvale, CA). Each gene was assayed in separate PCR reactions from the same RT samples. Equivalent steady-state mRNA levels for each gene were determined by comparing each sample to the appropriate standard curve. All gene expression data were normalized for 1B15 (cyclophilin) mRNA. Cyclophilin is constitutively expressed in the testis until the pachytene spermatocytes are present [24]. Since pachytene spermatocytes first appear around P17–18 of age, measurements at any age after this point should be evaluated with this limitation considered. The optimal cycle number for amplification was determined for each assay in order to achieve maximum sensitivity while maintaining linearity (i.e., logarithmic phase of PCR reactions). The sensitivity of each quantitative PCR assay is below 1 fg, with intra-assay variabilities of 6.0–15%. Primers used for the QRT-PCR are as follows: TGF $\beta$ 1, 5' prime: 5'-TCG ATT TTG ACG TCA CTG GAG TTG T-3', 3' prime: 5'-GGG GTG GCC ATG AGG AGC AGG-3'; TGF $\beta$ 2, 5' prime: 5'-CCG CCC ACT TTC TAC AGA CCC-3', 3' prime: 5'-GCG CTG GGT GGG AGA TGT TAA-3'; TGF $\beta$ 3, 5' prime: 5' TGC CCA ACC CGA GCT CTA AGC G-3', 3' prime: 5' CCT TTG AAT TTG ATC TCC A-3'; cyclophilin, 5' prime: 5' ACA CGC CAT AAT GGC ACT GG-3', 3' prime: 5'-ATT TGC CAT GGA CAA GAT GCC-3' [22].

#### *Embedding, Histology, and Immunohistochemistry*

Tissues were fixed in Histochoice (Amresco, Solon, OH) and embedded in paraffin according to standard procedures [25, 26]. Sections were stained with hematoxylin and eosin according to standard procedures [25, 26]. Briefly, 3- $\mu$ m sections were deparaffinized and rehydrated, microwaved (15 min), and blocked in 10% serum for 30 min at room temperature. Immunocytochemistry was performed as previously described [22, 25]. The TGF $\beta$ 1 primary antibody was an anti-TGF $\beta$ 1 peptide antibody (Santa Cruz Biotechnology [SCB], Santa Cruz, CA) raised against amino acids 328–353 of human TGF $\beta$ 1 (which is 100% homologous to mouse TGF $\beta$ 1). The TGF $\beta$ 2 primary antibody was an anti-TGF $\beta$ 2 peptide antibody (SCB) raised against amino acids 352–377 of human TGF $\beta$ 2. The TGF $\beta$ 3 primary antibody was an anti-TGF $\beta$ 3 peptide antibody (SCB) raised against amino acids 350–375 of human TGF $\beta$ 3. The TGF $\beta$ 1 and TGF $\beta$ 3 antibodies were diluted 1:50 in 10% goat serum; the TGF $\beta$ 2 primary antibody was diluted 1:1200 in 10% goat serum. The biotinylated goat anti-rabbit secondary antibody (Vector Laboratories, Burlington, CA) was diluted 1:300. Two negative controls were conducted for each TGF $\beta$  isoform. The first negative control involved a serial section of testis tissue treated as described above, but with

no primary TGF $\beta$  antibody. The second negative control involved incubation of each primary antibody with 50- to 100-fold excess of each respective TGF $\beta$  protein before application to the tissue; then these tissues were treated as described above. The secondary antibody was detected by using the histo stain-sp kit (Zymed Laboratories, South San Francisco, CA), and immunohistochemical images were digitized with a slide scanner (Sprint Scan, Polaroid, Cambridge, MA).

#### *Statistical Analysis*

All data were analyzed by a JMP 3.1 statistical analysis program (SAS Institute, Cary, NC). All values are expressed as the mean  $\pm$  SEM. Statistical analysis was performed using one-way ANOVA. Significant differences were determined using Dunnett's test for comparison to controls and using the Tukey-Kramer honestly significant difference test for multiple comparisons. Statistical difference was confirmed at  $p < 0.05$ .

## RESULTS

### *Characterization of the QRT-PCR Procedure for TGF $\beta$*

Preliminary studies were performed to establish a reproducible and accurate QRT-PCR procedure [22]. The linearity of generating a PCR product relative to cycle number was determined [22]. Thirty cycles was selected as an appropriate cycle number for TGF $\beta$ 1, 33 cycles for TGF $\beta$ 2, 35 cycles for TGF $\beta$ 3, and 25 cycles for cyclophilin [22]. Comparison of standard DNA with unknown samples was conducted to determine parallel displacement. Plasmid DNA with subcloned PCR product and cDNA produced from unknown RNA samples were run in parallel. PCR products of diluted plasmid DNA and diluted unknown cDNA were compared. These two curves were parallel with each growth factor, indicating that the QRT-PCR assay could be used to quantitate mRNA levels. Minimal variability of this assay was demonstrated previously [22].

### *Developmental Regulation of TGF $\beta$ Expression during Testis Development*

Experiments were designed to investigate the changes in expression of TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3 from E15 through postnatal day 30 (P30) of testis development. Whole testes were removed from rats aged E15, E16, E18, P0, P3, P4, P5, P10, P20, and P30, and the mRNA expression of TGF $\beta$  was measured by QRT-PCR [22]. The expression of TGF $\beta$  isoforms was quantitated using a standard curve for each isoform and was normalized by the expression of the gene cyclophilin, which is constitutively expressed through P10 of testis development [22], for each sample. The amount of mRNA for TGF $\beta$ 1 was low early in embryonic development (E15,  $p < 0.05$ ); then increased at E16 ( $p < 0.05$ ), birth (P0,  $p < 0.05$ ), and prepuberty (P10,  $p < 0.05$ ); and decreased after puberty and into adulthood (P20-P30,  $p < 0.05$ ) (Fig. 1A). In contrast to TGF $\beta$ 1 expression, mRNA for TGF $\beta$ 2 was elevated early in embryonic development (E15,  $p < 0.05$ ) and then decreased during the late embryonic period (E16, E18). TGF $\beta$ 2 transiently increased during the early postnatal period (P0-P4) and decreased during the pubertal and adult stages of testis development (P5-P30,  $p < 0.05$ ) (Fig. 1B). Expression patterns for TGF $\beta$ 3 were the most dramatic, with higher concentrations of TGF $\beta$ 3 during embryonic testis development (E16-P0) and significantly lower concentrations during the



postnatal, pubertal, and adult periods (P3-P30,  $p < 0.05$ ) (Fig. 1C). In a subsequent study, E14 mRNA was analyzed, and levels of TGF $\beta$  isoforms were consistent with those of E15 (data not shown). Each of the TGF $\beta$  isoforms had a different pattern of expression during embryonic testis development. This suggests that these TGF $\beta$  isoforms are differentially regulated. The reduction in message for all TGF $\beta$  isoforms after puberty (P20–30) may be a dilution effect of increased number of germ cells in the testis due to the onset of spermatogenesis, or due to the increased amount of cyclophilin produced by pachytene spermatocytes at these developmental stages [24].

#### Localization of TGF $\beta$ during Embryonic Testis Development

Immunohistochemistry was conducted on testis sections from E14 and P0 rats to determine expression of TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3 (Fig. 2, A–H). Sections were evaluated and cell types were determined by staining of serial sections for cell-specific antibodies. Negative controls for each antibody were used to determine positively stained cells. Excess TGF $\beta$  protein abolished staining for TGF $\beta$ s 1, 2, and 3 antibodies for the sections evaluated (data not shown). At E14 there appeared to be more widespread staining of TGF $\beta$ 1. Positive staining for TGF $\beta$ 1 was present in Sertoli cells and surrounding gonocytes. However, even at higher magnification it was not conclusive whether gonocytes themselves were stained or the Sertoli cells surrounding the gonocytes were positive for TGF $\beta$ 1 (Fig. 2C). At P0, TGF $\beta$ 1 was expressed in Sertoli cells surrounding gonocytes, in gonocytes, and in some interstitial cells (Fig. 2D). Staining for TGF $\beta$ 2 was observed to be specific for Sertoli cells at E14 (Fig. 2E). At P0, TGF $\beta$ 2 was expressed at low levels in Sertoli cells, and high levels of expression were observed in selective interstitial cells (Fig. 2F). In contrast, TGF $\beta$ 3 was expressed in cells bordering the E14 mesonephros and testis (Fig. 2G). The intensely stained cells in E14 testis appeared to be pre-peritubular and to reside around seminiferous cords. Single cells of the testis interstitium also stained for TGF $\beta$ 3 at E14. Lower-intensity staining was observed both in mesonephric ducts of the mesonephros and in specific cells of the testis (Fig. 3, A–D). This pattern of TGF $\beta$ 3 may provide a marker for migrating cells from the mesonephros. In contrast to TGF $\beta$ 3 expression at E14, TGF $\beta$ 3 was expressed in gonocytes in the P0 testis (Fig. 2H). Cellular localization of TGF $\beta$  isoforms appeared to be distinct, with changing cellular localization during embryonic and early postnatal testis development. These data complement the QRT-PCR data and confirm the expression of the TGF $\beta$  proteins.

#### TGF $\beta$ 1 Regulation of Embryonic Seminiferous Cord Formation and Growth

The effects of TGF $\beta$ 1 on seminiferous cord formation were investigated in E13 testis organ cultures. E13 testes with mesonephroi were cultured on floating filters in the presence or absence of 40 ng/ml recombinant TGF $\beta$ 1 for a 3-day period. The testis organ cultures were routinely treated each day with daily changes of media. The control organ cultures formed seminiferous cords by the third day of culture. The dose of 40 ng/ml of TGF $\beta$ 1 was used because it had been determined previously [22, 23] to be the most effective dose to inhibit cellular growth in cell culture. Others have demonstrated that 10 ng/ml of TGF $\beta$ 1 can also inhibit cell growth in embryonic testis germ cells [19]. In

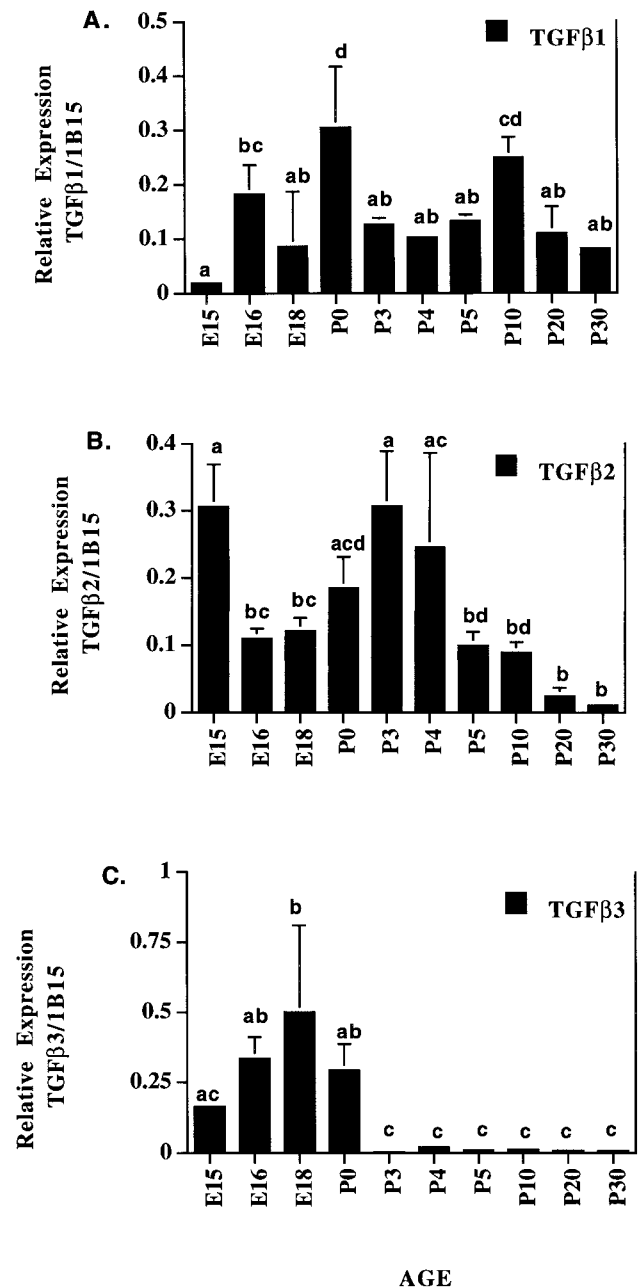


FIG. 1. Relative expression of mRNA for A) TGF $\beta$ 1, B) TGF $\beta$ 2, and C) TGF $\beta$ 3 during E15 through P30 of testis development. Expression of TGF $\beta$  isoforms is normalized for amount of cyclophilin. The mean  $\pm$  SEM are presented for each time period during which RNA was evaluated. Three to six pooled tissue samples were assayed in duplicate for each developmental time period in a minimum of three pooled different experiments. Different letters for each developmental time represent statistical differences at  $p < 0.05$ .

the current study, TGF $\beta$ 1 did not inhibit seminiferous cord formation (Fig. 4, A and B) but did inhibit growth of the E13 testis organ cultures. The number of seminiferous cords formed in the TGF $\beta$ 1-treated testis was reduced, but this was due to the overall reduced size of the testis organ culture.

To determine the effects of TGF $\beta$  on growth of testis organ cultures, the embryonic testes were cultured in the presence or absence of 40 ng/ml of TGF $\beta$ 1. TGF $\beta$ 1 inhibited growth of the E14 testis organ cultures in a manner similar to that of the E13 testis organ cultures (Fig. 4, C

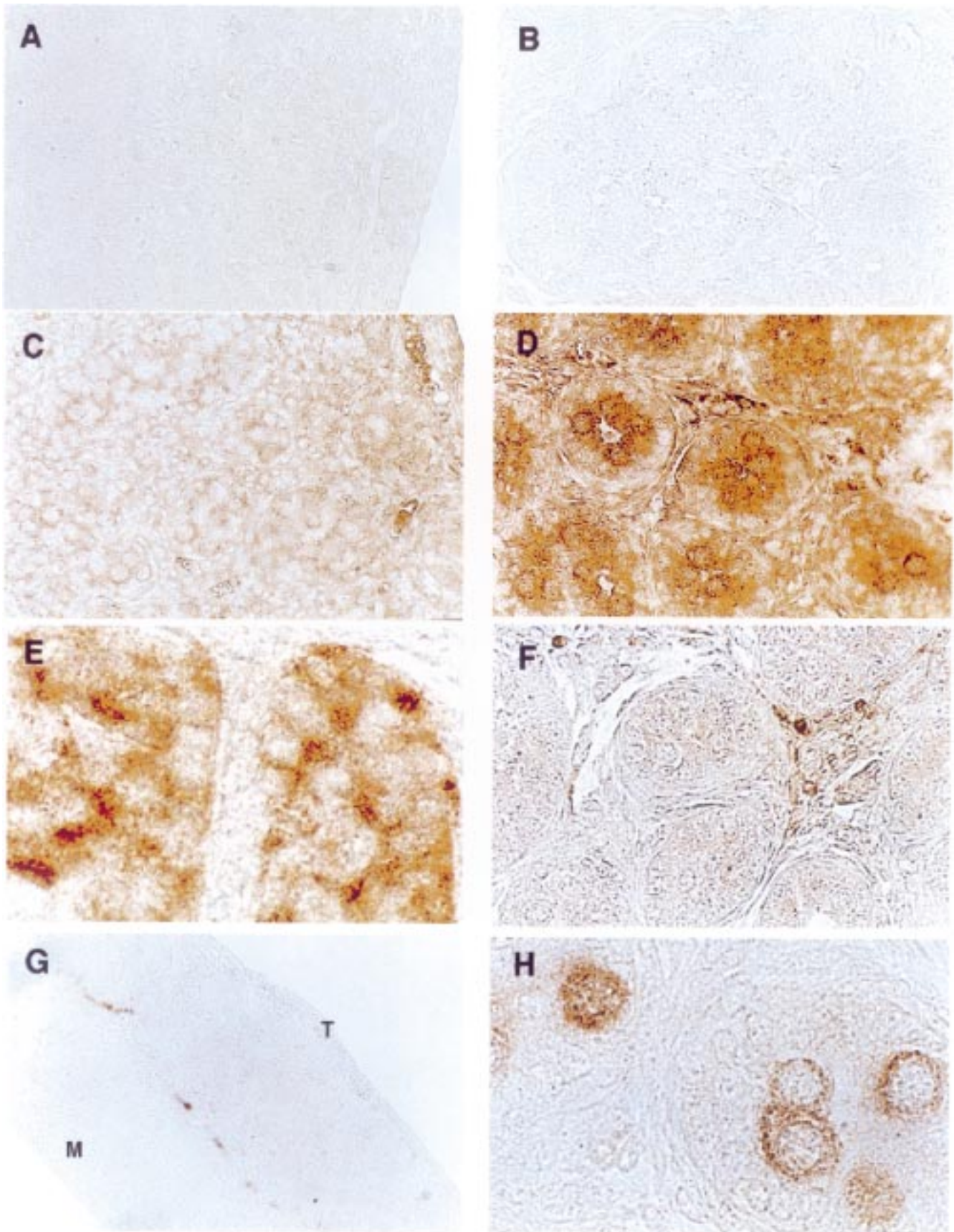


FIG. 2. Immunohistochemistry for control sections at **A**) E14 and **B**) P0; TGF $\beta$ 1 at **C**) E14 and **D**) P0; TGF $\beta$  2 at **E**) E14 and **F**) P0; and TGF $\beta$ 3 at **G**) E14 and **H**) P0. Immunohistochemistry was conducted three separate times for each developmental time period. Controls were samples not treated with primary antibody (**A**, **B**) and incubation of excess (50–100 $\times$ ) TGF $\beta$  protein to suppress signal.  $\times$ 400: **A**, **B**, **E**, **F**;  $\times$ 200: **G**, **C**, **H**;  $\times$ 1000. Reproduced at 93%. M, Mesonephros; T, testis.



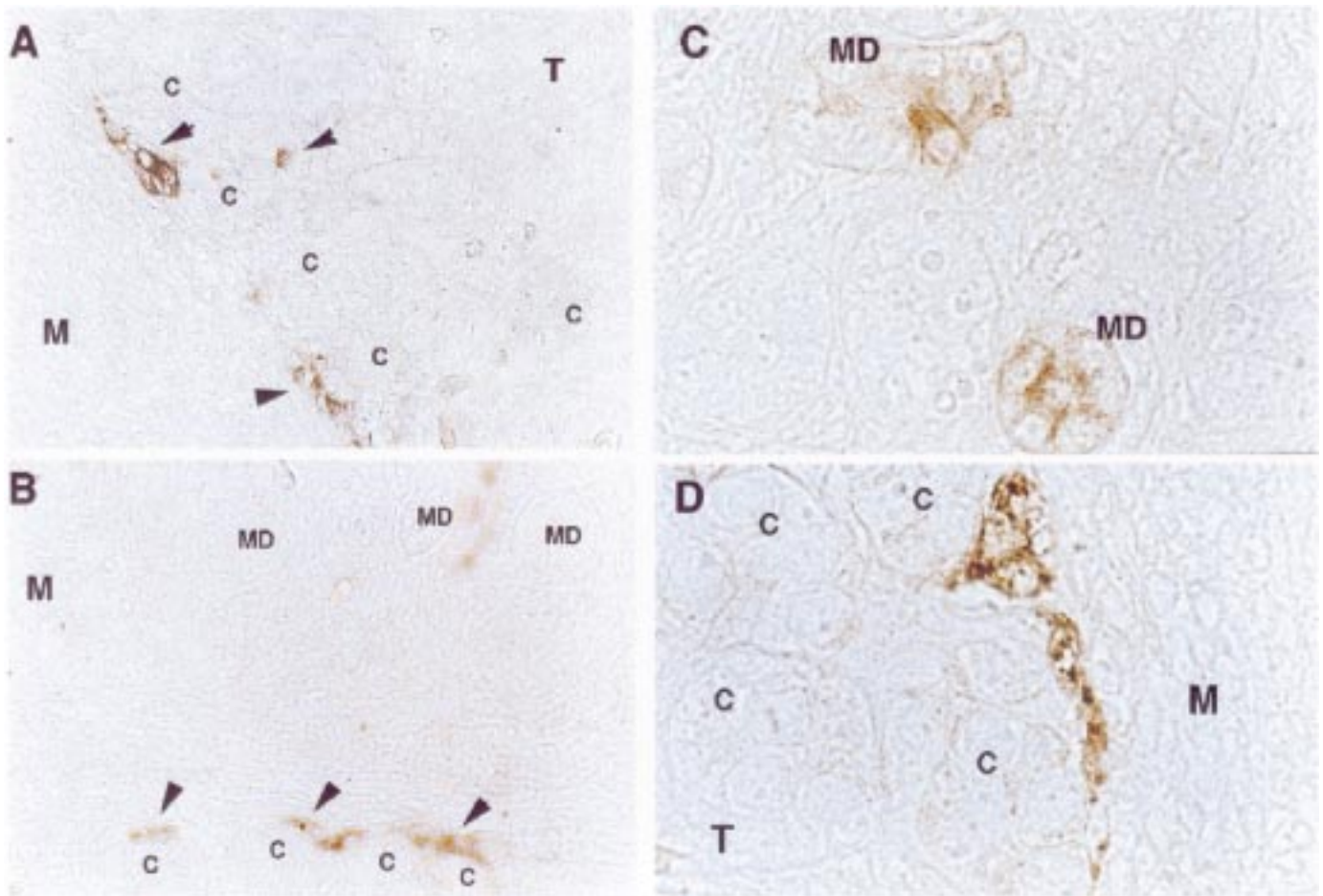


FIG. 3. Immunohistochemistry for TGF $\beta$ 3 in E14 testis sections. **A–B** represent two different testis sections ( $\times 400$ ). Arrows point to positive stained cells for TGF $\beta$ 3 surrounding seminiferous cords. **C–D** Higher magnification of mesonephros (**C**) and testis (**D**) at  $\times 1000$ . Reproduced at 93%. M, Mesonephros; T, testis; MD, mesonephric duct; C, seminiferous cord.

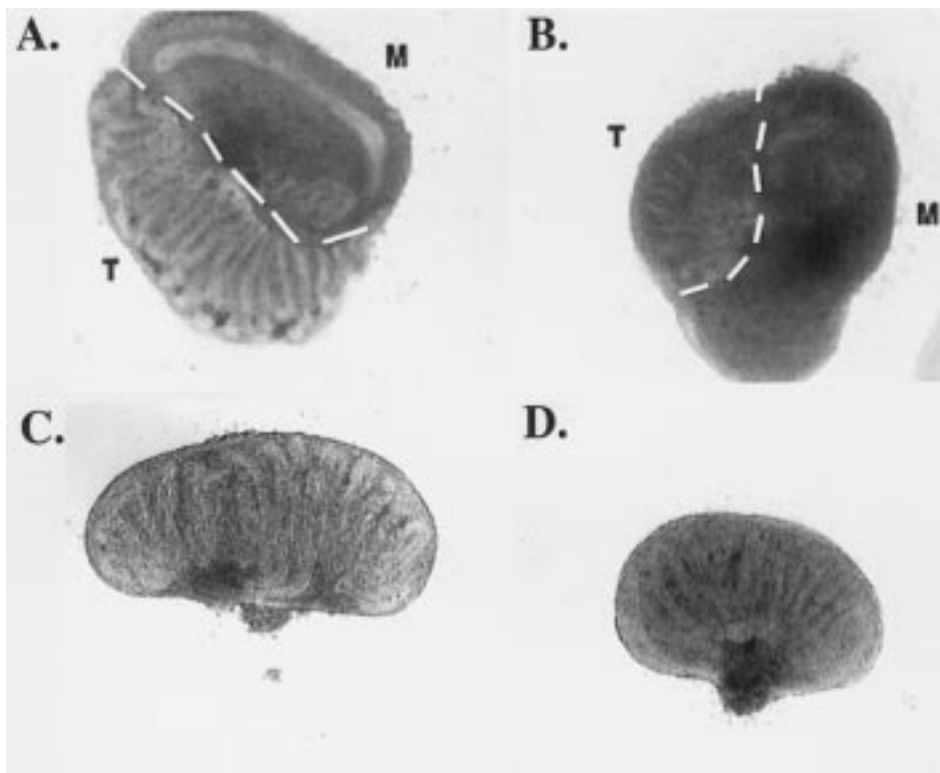


FIG. 4. **A)** Control E13 testis organ cultures plus mesonephros, **B)** E13 testis organ cultures plus mesonephros treated with 40 ng/ml TGF $\beta$ 1, **C)** control E14 testis organ culture, **D)** E14 testis organ culture treated with 40 ng/ml of TGF $\beta$ 1. Organ cultures were either not treated (controls) or treated daily with 40 ng/ml of TGF $\beta$ 1 at the time of the daily change in medium for a 3-day period. These are representative of E13 organ cultures from 36 pairs of testes treated ( $n = 36$ ), and E14 testis organ cultures from 18 pairs of testes treated ( $n = 18$ ; one control and one treated per pair). T, Testis; M, mesonephros. Dashed lines separate testis and mesonephros.  $\times 80$  (reproduced at 88%).

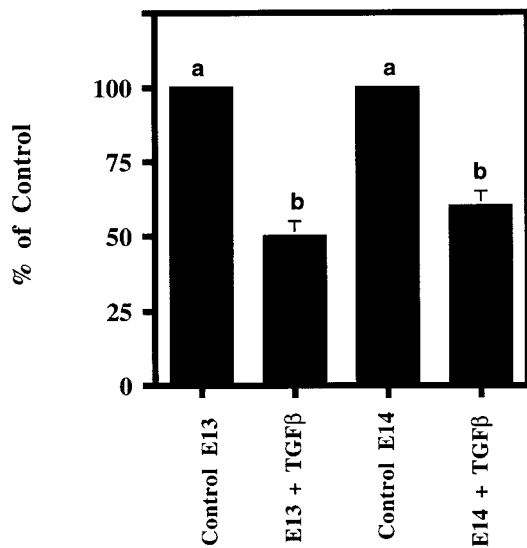


FIG. 5. Area of testis expressed as percentage of control for E13 and E14 testis organ cultures either treated with TGFβ or controls. The mean + SEM are presented for each developmental age for E13 ( $n = 36$ ; 4 replicates with 6 testis pairs per experiment) and E14 testis ( $n = 18$ ; 3 replicates with 6 testis pairs per experiment). Different letters for each mean represent statistical differences at  $p < 0.05$ .

and D). The areas of the cultured testes were analyzed, and a significant reduction in testis size was observed in E13 and E14 cultured testes when compared to matched controls (approximately 40–50% reduction,  $p < 0.05$ ; Fig. 5). Previously, the reduced area has been shown to correlate to a reduced DNA content in the organ (data not shown). Therefore, TGFβ1 does not alter seminiferous cord formation but can inhibit testis growth, as demonstrated by the decreased testis area in TGFβ1-treated E13 and E14 testis organ cultures.

#### TGFβ1 Regulation of P0 Testis Cell Growth

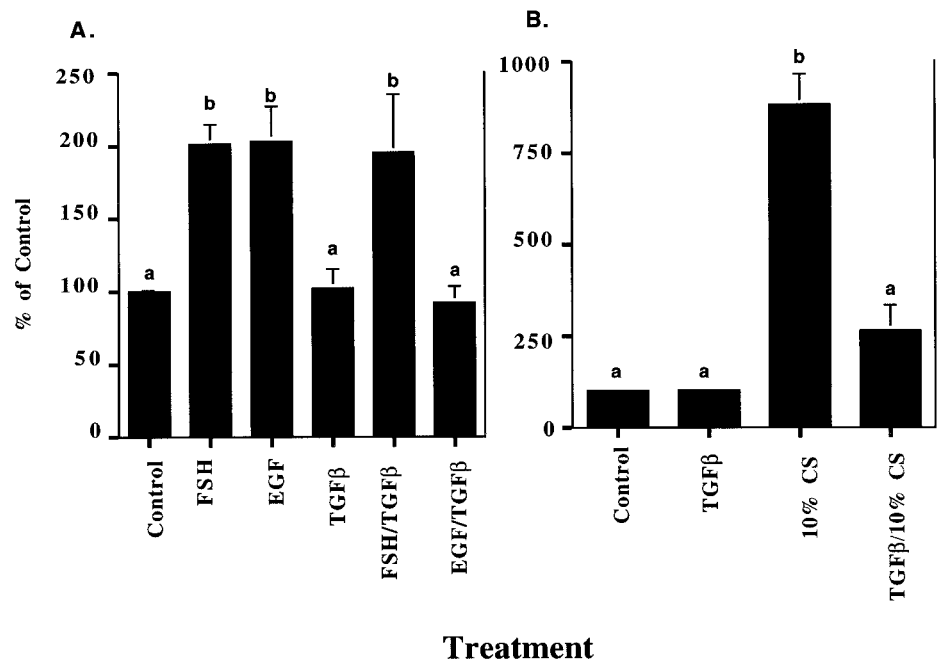
The effects of TGFβ1 on P0 testis growth were investigated through a tritiated thymidine incorporation assay to

access cellular growth. Data were normalized to the amount of DNA for each sample. Mixed populations of P0 testis cultures were treated with the most effective dose of the growth factors FSH (25 ng/ml), EGF (50 ng/ml), and 10% calf serum. All treatments stimulated tritiated thymidine incorporation in growth assays conducted on P0 testis cultures (Fig. 6). P0 testis cell cultures were treated with TGFβ alone or with positive regulators of P0 testis growth—FSH, EGF, and 10% calf serum. TGFβ1 (40 ng/ml) treatment alone at the most effective dose for growth inhibition did not significantly alter thymidine incorporation into P0 testis cultures when compared to controls. However, TGFβ1 inhibited ( $p < 0.05$ ) EGF- and 10% calf serum-stimulated thymidine incorporation into P0 testis cultures ( $p < 0.05$ ; Fig. 5). Interestingly, TGFβ1 did not modulate FSH-stimulated growth in P0 testis cultures. Therefore, TGFβ1 can inhibit growth factor-stimulated growth in P0 testis cultures (i.e., EGF and 10% calf serum) and may be a potential regulator of testis growth during this perinatal period.

#### Hormonal Regulation of TGFβ Expression

The effects of positive stimulators of growth (i.e., EGF and FSH) on expression of TGFβ1, TGFβ2, and TGFβ3 were examined (Fig. 7) in P0 testis cultures using QRT-PCR. All values were normalized with cyclophilin and expressed as relative expression compared with that in control cultures. P0 testis cultures were treated with FSH (25 ng/ml) and EGF (100 ng/ml), and RNA was collected after 24 h of treatment. EGF significantly stimulated expression of TGFβ1 ( $p < 0.05$ ) and reduced expression of TGFβ3 ( $p < 0.05$ ) after a 24-h period relative to controls (Fig. 7). There was no effect of treatment of P0 testis cultures with FSH (25–50 ng/ml) on expression of TGFβ isoforms 24 h after stimulation. Therefore, these data demonstrate that EGF may directly regulate expression of mRNA for TGFβ1 and TGFβ3 in P0 testis cultures. This regulation may be part of a negative feedback loop between EGF and TGFβ to modulate testis cell growth and differentiation.

FIG. 6. Effect of TGFβ1 on cell growth in P0 testis suspensions. P0 testes were stimulated with FSH (25 ng/ml), EGF (50 ng/ml), or 10% calf serum alone or with TGFβ1 (40 ng/ml). Data are the combined results of four independent experiments conducted in triplicate. Values have been normalized for DNA/well and are expressed as percentage of controls with controls set to 100%. Different letters for each mean represent statistical differences at  $p < 0.05$ .



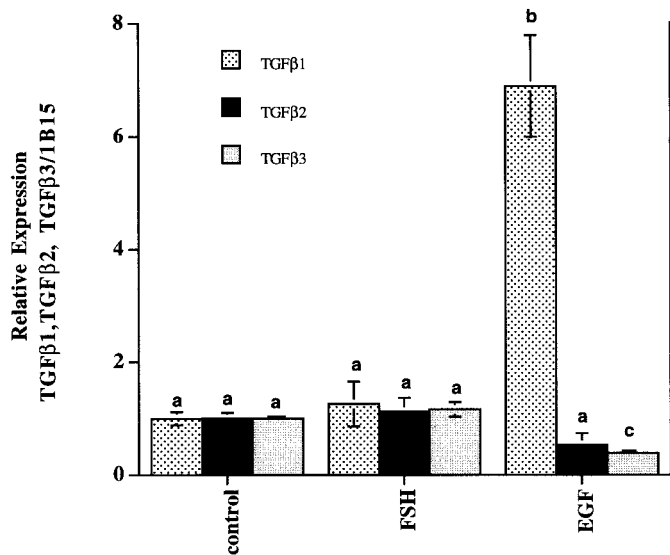


FIG. 7. Relative amounts of mRNA for TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3 after 24 h of P0 testis cultures with no treatment (control) or treatment with FSH (25 ng/ml) or EGF (100 ng/ml). Data are combined results of three different experiments conducted in duplicate. Messenger RNA levels for each isoform have been normalized to cyclophilin and are relative to controls for each experiment. Different superscript letters for each represent statistical differences at  $p < 0.05$ .

## DISCUSSION

The current study was designed to investigate the action and expression of TGF $\beta$  during embryonic testis development. Previously, three isoforms of TGF $\beta$  (TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3) have been determined to be present in the postnatal testis [9–12]. In addition, TGF $\beta$ 1 and TGF $\beta$ 2 have been identified in the embryonic testis by immunohistochemistry [16–18]. Localization of TGF $\beta$ 1 and TGF $\beta$ 2 in the current study was similar to that in data previously reported. In previous studies, TGF $\beta$ 1 was found to be positive in Sertoli cells, but not in gonocytes, in E14.5 testis. In the current study, E14 testis sections also stained positive for TGF $\beta$ 1 in Sertoli cells. There was also staining that surrounded gonocytes at a higher magnification of these testis sections, but it was unclear as to whether TGF $\beta$ 1 was present in the gonocytes. At P0, TGF $\beta$ 1 positive staining was present in Sertoli cells, surrounding gonocytes, and in selected interstitial cells. No previous reports have described TGF $\beta$ 1 staining in P0 testis. Previously, TGF $\beta$ 1 has been demonstrated to be present in Leydig cells at E16.5, P4, and P20. The antibodies used in the present study for TGF $\beta$ 1 were different from those used in previous studies. Antibody differences may explain these slight localization differences for TGF $\beta$ 1. Positive staining for TGF $\beta$ 2 was present at E14 in Sertoli cells, a finding that agrees with previously published data. In addition, at P0 there were faint staining for TGF $\beta$ 2 in Sertoli cells and high levels of staining in selected cells of the interstitium. In addition, the current study also localized expression of TGF $\beta$ 3 during embryonic testis development, which previously has not been reported. TGF $\beta$ 3 was expressed in cells surrounding seminiferous cords at the testis-mesonephros interface at E14. Mesonephric ducts within the mesonephros and individual interstitial cells within the gonad also expressed TGF $\beta$ 3 at E14. This pattern of expression of TGF $\beta$ 3 suggests potential cellular interactions between mesonephric and testicular cells. Previously, it had been shown that cells migrate from the mesonephros into the testis to participate

in seminiferous cord formation. It appears that pre-peritubular cells and selected interstitial cells stain for TGF $\beta$ 3 at E14. Therefore, pre-peritubular cells may express TGF $\beta$ 3 to induce migration or differentiation resulting in seminiferous cord formation. Interestingly, only cells surrounding cords adjacent to the mesonephros stained for TGF $\beta$ 3. Further investigation is necessary to determine the potential role of TGF $\beta$ 3 in mesonephric cell migration into the testis. Expression of TGF $\beta$ 3 in the P0 testis appeared to be in Sertoli cells with high concentrations localized in gonocytes. Therefore, TGF $\beta$ 3 may regulate two distinct developmental processes at different times during testis development.

To extend these data, expression of mRNA for TGF $\beta$  isoforms were also evaluated in the current study. Expression patterns of TGF $\beta$ 1, TGF $\beta$ 2, and TGF $\beta$ 3 are unique during testis development and do not appear to have overlapping expression patterns. Early in embryonic testis development (i.e., E15), only TGF $\beta$ 2 expression was high while the concentrations of mRNA for TGF $\beta$ 1 and TGF $\beta$ 3 were relatively low. There were similar results with E14 testis (data not shown). In addition, expression of TGF $\beta$ 1 was significantly higher at P0 and P10 while expression of TGF $\beta$ 2 was highest at E15 and P3. Interestingly, TGF $\beta$ 3 has the most distinctive expression pattern, with highest concentrations observed during embryonic testis development. This pattern may indicate an important role of TGF $\beta$ 3 during embryonic testis development, or it may have been due to the dilution effect of spermatogenesis during the postnatal period. TGF $\beta$ 1 has been reported to be present in germ cells and Sertoli cells during the postnatal period, and there was no dramatic change in expression of mRNA between the embryonic and postnatal periods. It is not known what the expression pattern of TGF $\beta$ 3 is during the postnatal period; therefore, if it is present in the somatic cells, a decrease in expression of this gene would be observed.

Actions of TGF $\beta$  during embryonic testis development are thought to be primarily on gonocytes (E14), and by E16.5 on both Leydig cells and gonocytes [19]. Receptors for TGF $\beta$  have been localized to gonocytes and Leydig cells at these developmental time periods. TGF $\beta$ 1 has been identified as a regulator of Leydig cell steroidogenesis, and it can inhibit LH-stimulated testosterone production [20] in E16.5 testis cultures. Both TGF $\beta$ 1 and TGF $\beta$ 2 have been demonstrated to induce gonocyte apoptosis around E14 of embryonic testis development [19]. Therefore, these results suggest that paracrine and/or autocrine interactions occur between cells that produce TGF $\beta$ 1 and TGF $\beta$ 2, to regulate both Leydig and gonocyte functions in the embryonic testis.

The potential action of TGF $\beta$  on seminiferous cord formation has not been previously reported and is addressed in the current study. Treatment of E13 testis organ cultures did not affect seminiferous cord formation in the present study. However, growth of the embryonic testis organ cultures was inhibited as measured by testis area. A reduction in seminiferous cord numbers was observed in E13 testis organ cultures, but this was determined to occur because of a reduced overall size of the testis. This inhibition of growth was further demonstrated in E14 testis organ cultures treated with TGF $\beta$ 1, in which a 40% reduction in testis size compared to that of controls was observed. Previous reports have demonstrated a similar effect on gonocyte numbers with TGF $\beta$ 1 and TGF $\beta$ 2 treatment of E13.5 testis organ cultures. This reduction was demonstrated to occur through an increase in gonocyte apoptosis [19], and



no data were included on effects of TGF $\beta$  on overall testis size. In the current study, a 40% reduction in testis size in both E13 and E14 testis organ cultures was observed with TGF $\beta$ 1. A similar effect would be hypothesized with TGF $\beta$ 2. It seems unlikely that a 40% reduction in the size of the testis would occur because of the inhibition of one cell population alone. The dose of TGF $\beta$ 1 used in these experiments (40 ng/ml) was greater than in the experiments previously reported (10 ng/ml) [19]. Additionally, our experiments were conducted for 3 days, with TGF $\beta$ 1 treatments each day. Thus, by the last day of treatment, the Leydig cells may have obtained receptors for TGF $\beta$ , causing a reduction in cellular proliferation within this cell type. This may explain the dramatic reduction in testis size within the testis organ cultures in the current study. Therefore, regulation of expression of TGF $\beta$ 1 may be important during embryonic testis development to initially regulate germ cell numbers and later to potentially regulate somatic cell growth.

TGF $\beta$ 1 is capable of inhibiting early postnatal testis growth as well as embryonic testis growth. In the current study, TGF $\beta$ 1 inhibited EGF- and 10% calf serum-stimulated growth in P0 testis cultures. The P0 testis cultures have a mixed population of cells, and these data must be interpreted carefully. Both gonocytes and Leydig cells, but not Sertoli cells, have receptors for TGF $\beta$  at this time during testis development. Treatment of P0 testis cultures with FSH stimulates tritiated thymidine incorporation, presumably through stimulation of growth of Sertoli cells, which contain FSH receptors. TGF $\beta$ 1 did not inhibit FSH-stimulated growth but did inhibit EGF- and 10% calf serum-stimulated growth. Therefore, most of the effects of TGF $\beta$ 1 on inhibition of P0 testis may be elicited through inhibition of interstitial and/or gonocyte cell growth.

The TGF $\beta$ s have been reported to stop the cell cycle in numerous cell types [13, 27] late in G1 when the cell becomes committed to enter S phase. Previous literature has demonstrated that gonocytes undergo mitotic arrest around E17-E18 and resume mitosis after P5 [28]. TGF $\beta$ 1 and TGF $\beta$ 2 may contribute to the regulation of this mitotic arrest since they are both highly expressed around P0. Growth stimulators such as EGF and FSH must either stimulate the expression of genes that promote progression to the S phase of the cell cycle, or inhibit expression of genes that halt cell cycle progression. Therefore, in the present study we hypothesized that EGF and FSH may inhibit mRNA expression of the TGF $\beta$  isoforms. EGF did suppress expression of TGF $\beta$ 3 in P0 testis 24 h after stimulation. However, most of the data collected in the present study did not support our hypothesis. FSH stimulation had no effect on expression of TGF $\beta$  isoforms. EGF stimulated expression of TGF $\beta$ 1 and suppressed expression of mRNA for TGF $\beta$ 3. These observations are interesting since FSH does not appear to regulate TGF $\beta$  isoforms while EGF appears to regulate them differentially. Previous data suggest overlapping roles for the TGF $\beta$  isoforms in the regulation of cell growth and proliferation; however, the current study suggests a unique regulation of each TGF $\beta$  isoform by growth factors.

Interestingly, FSH stimulation of P0 testis was not inhibited by TGF $\beta$ . In addition, FSH treatment did not influence expression of TGF $\beta$  isoforms. Potential interactions have been reported between TGF $\beta$ 1 and LH in the fetal rat testis. TGF $\beta$ 1 has been demonstrated to inhibit LH-induced cAMP production and LH-induced testosterone production in dispersed fetal testis (E16.5) [20]. However, no studies

have demonstrated interactions between FSH and TGF $\beta$  isoforms. The results of the current study suggest that there is no direct regulation of FSH on expression of TGF $\beta$  isoforms in cultures of P0 testis. This may be due to the fact that Sertoli cells do not appear to contain receptors for TGF $\beta$  isoforms. Therefore, TGF $\beta$  isoforms are incapable of directly regulating Sertoli cell specific growth. FSH may also stimulate the expression of factors that stimulate growth such as TGF $\alpha$ .

It is also interesting that the growth factor EGF can stimulate expression of a growth-inhibitory factor such as TGF $\beta$ 1 while suppressing TGF $\beta$ 3. This differential regulation of the two isoforms of TGF $\beta$  may be due to the different cell types that produce each factor. At P0, TGF $\beta$ 1 is localized to three different cell types while TGF $\beta$ 3 is in gonocytes. EGF may differentially regulate these cell types. Increased expression of TGF $\beta$ 1 in response to EGF would demonstrate a feedback loop between these growth factors. High concentrations of EGF may act to stimulate TGF $\beta$ 1, which in turn suppresses EGF-stimulated growth.

The novel results of the current study demonstrate that TGF $\beta$  isoforms effect embryonic testis growth through the regulation of locally produced growth factors. The unique expression patterns and cellular localization of the TGF $\beta$  isoforms during embryonic testis development support a role for each isoform in the regulation of cellular growth and differentiation. TGF $\beta$  regulates embryonic testis growth through inhibition of growth stimulators such as EGF. In contrast, EGF regulates expression of mRNA for TGF $\beta$  isoforms. Combined observations suggest that the interactions of paracrine factors such as TGF $\beta$ s and EGF allow for optimal cellular growth and differentiation during embryonic testis development.

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## REFERENCES

- Magre S, Jost A. The initial phases of testicular organogenesis in the rat. An electron microscopy study. *Arch Anat Microsc Morphol Exp* 1980; 69:297-318.
- Magre S, Jost A. Sertoli cells and testicular differentiation in the rat fetus. *J Electron Microsc Tech* 1991; 19:172-188.
- Merchant-Larios H, Moreno-Mendoza N, Buehr M. The role of the mesonephros in cell differentiation and morphogenesis of the mouse fetal testis. *Int J Dev Biol* 1993; 37:407-415.
- Buehr M, Gu S, McLaren A. Mesonephric contribution to testis differentiation in the fetal mouse (published erratum appears in *Development* 1993 Aug; 118(4);following 1384). *Development* 1993; 117: 273-281.
- Mittwoch U, Delhanty JD, Beck F. Growth of differentiating testes and ovaries. *Nature* 1969; 224:1323-1325.
- Orth JM, Gunsalus GL, Lamperti AA. Evidence from Sertoli cell-depleted rats indicates that spermatid number in adults depends on numbers of Sertoli cells produced during perinatal development. *Endocrinology* 1988; 122:787-794.
- McGuinness MP, Orth JM. Reinitiation of gonocyte mitosis and movement of gonocytes to the basement membrane in testes of newborn rats in vivo and in vitro. *Anat Rec* 1992; 233:527-537.
- Tsutsui K, Kawashima S. Properties of the binding of follicle-stimulating hormone to the fetal rat testis. *Endocrinol Jpn* 1987; 34:717-725.
- Sporn MB, Roberts AB. Peptide growth factors: current status and therapeutic opportunities. *Important Adv Oncol* 1987; 75-86.

10. Roberts AB, Sporn MB. Transforming growth factor beta. *Adv Cancer Res* 1988; 51:107–145.
11. Roberts AB, Sporn MB. The transforming growth factor- $\beta$ s. In: Sporn MB, Roberts AB (eds.), *Handbook of Experimental Pharmacology*. Heidelberg: Springer; 1990:419–472.
12. Lawrence DA. Transforming growth factor-beta: a general review. *Eur Cytokine Netw* 1996; 7:363–374.
13. Howe PH, Draetta G, Leof EB. Transforming growth factor  $\beta$ 1 inhibition of p34cdc2 phosphorylation and histone H1 kinase activity is associated with G1/S-phase growth arrest. *Mol Cell Biol* 1991; 11: 1185–1194.
14. Shull MM, Ormsby I, Kier AB, Pawlowski S, Diebold RJ, Yin M, Allen R, Sidman C, Proetzel G, Calvin D, Annunziata N, Doetschman T. Targeted disruption of the mouse transforming growth factor- $\beta$ 1 gene results in multifocal inflammatory disease. *Nature* 1992; 359: 693–699.
15. Shull MM, Doetschman T. Transforming growth factor-beta 1 in reproduction and development. *Mol Reprod Dev* 1994; 39:239–246.
16. Gautier C, Levacher C, Avallet O, Vigier M, Rouiller-Fabre V, Lecerf L, Saez J, Habert R. Immunohistochemical localization of transforming growth factor-beta 1 in the fetal and neonatal rat testis. *Mol Cell Endocrinol* 1994; 99:55–61.
17. Teerds KJ, Dorrington JH. Localization of transforming growth factor beta 1 and beta 2 during testicular development in the rat. *Biol Reprod* 1993; 48:40–45.
18. Olaso R, Gautier C, Levacher C, Duran P, Saez J, Habert R. The immunohistochemical localization of transforming growth factor-beta 2 in the fetal and neonatal rat testis. *Mol Cell Endocrinol* 1997; 126: 165–172.
19. Olaso R, Pairault C, Boulogne B, Durand P, Habert R. Transforming growth factor  $\beta$ 1 and reduce the number of gonocytes by increasing apoptosis. *Endocrinology* 1998; 139:733–740.
20. Gautier C, Levacher C, Saez JM, Habert R. Transforming growth factor  $\beta$ 1 inhibits steroidogenesis in dispersed fetal testicular cells in culture. *Mol Cell Endocrinol* 1997; 131:21–30.
21. Giese K, Pagel J, Grosschedl R. Distinct DNA-binding properties of the high mobility group domain of murine and human SRY sex-determining factors. *Proc Natl Acad Sci USA* 1994; 91:3368–3372.
22. Itoh N, Patel U, Cupp AS, Skinner MK. Developmental and hormonal regulation of transforming growth factor- $\beta$ 1 (TGF $\beta$ 1), -2 and -3 gene expression in isolated prostatic epithelial and stromal cells: epidermal growth factor and TGF $\beta$  interactions. *Endocrinology* 1988; 139:1378–1388.
23. Levine E, Miyashiro L, Skinner MK. Role of transforming growth factor-alpha related ligands and the epidermal growth factor receptor in embryonic testis development. *Endocrinology* 1999; (in press).
24. Wine RN, Ku WW, Li Ling-Hong, Chapin RE. Cyclophilin A is present in rat germ cells and is associated with spermatocyte apoptosis. *Biol Reprod* 1997; 56:439–446.
25. Akmal KM, Dufour JM, Kim KH. Region-specific localization of retinoic acid receptor-alpha expression in the rat epididymis. *Biol Reprod* 1996; 54:1111–1119.
26. Akmal KM, Dufour JM, Kim KH. Retinoic acid receptor alpha gene expression in the rat testis: potential role during the prophase of meiosis and in the transition from round to elongating spermatids. *Biol Reprod* 1997; 56:549–556.
27. Massague J, Weis-Garcia F. Serine/threonine kinase receptors mediators of transforming growth factor beta family signals. *Cancer Surv* 1996; 27:41–63.
28. Orth JM. Proliferation of Sertoli cells in fetal and postnatal rats: a quantitative autoradiographic study. *Anat Rec* 1982; 203:485–492.