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The Spectrum of Mutations in *TBX3:* Genotype/Phenotype Relationship in Ulnar-Mammary Syndrome

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Summary

Ulnar-mammary syndrome (UMS) is a pleiotropic disorder affecting limb, apocrine-gland, tooth, hair, and genital development. Mutations that disrupt the DNA-binding domain of the *T-box* gene, *TBX3*, have been demonstrated to cause UMS. However, the 3′ terminus of the open reading frame (ORF) of *TBX3* was not identified, and mutations were detected in only two families with UMS. Furthermore, no substantial homology outside the T-box was found among *TBX3* and its orthologues. The subsequent cloning of new *TBX3* cDNAs allowed us to complete the characterization of *TBX3* and to identify alternatively transcribed *TBX3* transcripts, including one that interrupts the T-box. The complete ORF of *TBX3* is predicted to encode a 723-residue protein, of which 255 amino acids are encoded by newly identified exons. Comparison of other *T-box* genes to *TBX3* indicates regions of substantial homology outside the DNA-binding domain. Novel mutations have been found in all of eight newly reported families with UMS, including five mutations downstream of the region encoding the T-box. This suggests that a domain(s) outside the T-box is highly conserved and important for the function of *TBX3*. We found no obvious phenotypic differences between those who have missense mutations and those who have deletions or frameshifts.

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Introduction

T-box genes are members of a rapidly growing and highly conserved family of transcription factors that share a region of homology to the DNA-binding domain (T-box) of the mouse *Brachyury* (or *T*) gene product (Herrmann et al. 1990; Bollag et al. 1994; Papaioannou and Silver 1998). Most *T-box* genes have been found through experiments designed to identify genes that have specific activities in embryonic development or that cause developmental defects (Bollag et al. 1994). During embryogenesis the spatial and temporal expression patterns of *T-box* genes are unique although overlapping. This indicates that they are differentially regulated during development (Chapman et al. 1996). Phylogenetic analyses suggest that the origin of the *T-box* gene family predates the divergence of arthropods and chordates from a common ancestor >600 million years ago (Agulnik et al. 1996; Ruvinsky and Silver 1997; Wattler et al. 1998). Thus, *T-box* genes are likely to play critical roles in the development of all animal species.

The *T* gene and its orthologues are immediate-early-response genes (i.e., transcription is directly activated by a signal-transduction pathway) that appear to control the specification and differentiation of mesoderm subpopulations in the developing embryo (Smith et al. 1991). Consequently, many of the early studies of *T-box* genes concentrated on understanding their role in the promotion of mesoderm formation (O'Reilly et al. 1995; Schulte-Merker and Smith 1995). Recently, more effort has shifted toward explaining how *T-box* genes act to control morphogenesis and organogenesis. For example, *Tbx5* and *Tbx4* are exclusively expressed in the vertebrate forelimb and hindlimb, respectively (Gibson-Brown et al. 1996, 1998; Simon et al. 1997). This suggests that *T-box* genes may specify limb identity in tet-

Table 1

***TBX3* Mutations and Clinical Findings in Families with Ulnar-Mammary Syndrome**

TBX3 Mutation and Individual[a]	Clinical Finding(s)[b]						
		Apocrine		Breast			
	Limb[c]	Axillary Hair	Perspiration	Lactation[d]	Breasts	Endocrine (Puberty)	Other
S343ter:							
1	Stiff digit (B 5)	Absent	Reduced	Reduced	Hypoplasia (B)	Normal	Anteposition of the anus
2	Stiff digit (B 5)	Prepubertal	Prepubertal	N/A	Normal	Normal	Cryptorchidism, imperforate anus
1301G…G1302:							
1	Extra digit (B 5)	Reduced	Reduced	N/A	Deceased	Deceased	
2	Extra digit (B 5)	Absent	Reduced	N/A	Normal	Delayed	Extra digit (L foot)
3	Absent digit (L 5)	Absent	Reduced	Normal	Hypoplasia (U)	Normal	Small uterus
4	Absent ulna (B), absent digits (L 3–5, R 5), fused digits (R 3–4)	Prepubertal	Prepubertal	Nulliparous	Normal	Prepubertal	
IVS2+1G→C:							
1	Extra digit (B 5)	Absent	Absent	Normal	Hypoplasia (U)	Normal	
2	Extra digit (U 5)	Prepubertal	Prepubertal	Nulliparous	Normal	Prepubertal	Kyphosis, scoliosis, recto-perineal fistula
Y149S:							
1	Duplicated nail (B 5), tapered digit (B 5)	Reduced	Reduced	N/A	Hypoplasia (B)	Delayed	Short stature
1857delC:							
1	Extra digit (B 5), stiff digit (R 5)	Normal	Normal	N/A	Normal	Normal	
2	Extra digit (B 5), stiff digit (5)	Absent	Reduced	None	Hypoplasia (B), absent areola (B)	Normal	
3	Stiff digit (R 5)	Absent	Absent	Normal	Absent areola (B)	Normal	Single kidney, septate uterus
4	Normal	Absent	Reduced	None	Absent areola (B)	Normal	
5	Extra digit (L 5)	Normal	Normal	Normal	Normal	Normal	
6	Normal	Absent	Absent	Nulliparous	Absent areola (B)	Normal	
7	Absent digits (L 4–5), stiff digit (R 5)	Absent	Reduced	N/A	Normal	Normal	Cryptorchidism
8	Extra digit (L 5)	Absent	Absent	None	Hypoplasia (B), absent areola (B)	Normal	
9	Normal	Absent	Absent	None	Absent areola (B)	Normal	
10	Normal	Absent	Absent	None	Absent areola (B)	Normal	
11	Extra digit (L 5)	Prepubertal	Prepubertal	Nulliparous	Absent areola (B)	Prepubertal	Absent teeth (incisors)
12	Absent ulna (L), absent digits (L 3–5), fused digit (R 5)	Prepubertal	Prepubertal	N/A	Absent areola (B)	Prepubertal	Anteposition of the anus
227delT:							
1	Deceased	Absent	Absent	N/A	Normal	Normal	Ectopic canine (R)
2	Stiff digit (L 5)	Absent	Absent	None	Hypoplastic areola (B)	Normal	Obesity, ectopic canine (R)
3	Stiff digit (B 5)	Absent	Absent	Nulliparous	Normal	Normal	Ectopic canine (B)
4	Absent digit (R 4), fused digits (R 2–3), stiff digit (R 5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Ectopic canine (B), obesity, inguinal hernia, micro-penis, hypoplastic testis (R), shawl scrotum

IVS6+2T→A:							
1	Reduced digit (B 5)	Reduced	Absent	N/A	Hypoplastic areola (B)	Delayed	Anal stenosis, subglottic cartilaginous webs, cryptorchidism (L), micropenis, hypoplastic testis (B)
2	Absent digits (L 5, R 4–5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Pyloric stenosis, anal stenosis, obesity, cryptorchidism, micropenis
3	Reduced digit (B 5)	Reduced	Reduced	N/A	Hypoplastic areola (B)	Delayed	Cryptorchidism (B), micropenis
4	Reduced digit (B 5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Inguinal hernia (B), scoliosis, obesity, absent testis (R), micropenis
L143P:							
1	Deceased	Absent	Absent	N/A	Deceased	Delayed	Delayed growth
2	Reduced humerus (B), absent ulna (B), absent digits (L 4–5, R 3–5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Delayed growth, cryptorchidism (B)
3	Stiff digit (B 5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Scoliosis, delayed growth, cryptorchidism (B)
4	Reduced humerus (B), absent ulna (B), absent digits (L 4–5, R 3–5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Cryptorchidism (B)
5	Reduced humerus (L), absent ulna (L), absent digits (L 3–5, R 5)	Prepubertal	Prepubertal	Nulliparous	Hypoplastic areola (B)	Prepubertal	
465T…T466:							
1	Stiff digit (R 5), reduced digit (L 5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Pectus carinatum
2	Normal	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Pectus carinatum
3	Reduced digit (B 5)	Absent	Absent	N/A	Hypoplastic areola (B)	Delayed	Pectus carinatum, duplicated teeth, hypospadias
4	Stiff digit (B 5)	Prepubertal	Prepubertal	N/A	Hypoplastic areola (B)	Prepubertal	
5	Stiff digit (U 5)	Prepubertal	Prepubertal	N/A	Hypoplastic areola (B)	Prepubertal	
6	Stiff digit (R 5)	Prepubertal	Prepubertal	Nulliparous	Hypoplastic areola (B)	Prepubertal	Anteposition of the anus

[a] The clinical findings in families with Q360ter, 227delC, and IVS6+2T→A have been published elsewhere (Schinzel et al. 1987; Franceschini et al. 1992; Bamshad et al. 1996).
[b] U = unilateral; B = bilateral; L = left; R = right.
[c] Digits are numbered "1"–"5" from anterior (thumb) to posterior (little finger).
[d] N/A = not applicable.

rapods (Logan et al. 1998; Ohuchi et al. 1998; Logan and Tabin 1999).

Mutations in *T-box* genes have been associated with defects of development in *Drosophila melanogaster* (Kispert et al. 1994), *D. rerio* (Schulte-Merker et al. 1994), and *Mus musculus* (Herrmann et al. 1990). In humans, mutations in *TBX3* cause limb, apocrine-gland, hair, genital, and dental defects in ulnar-mammary syndrome (UMS [MIM 181450]; Bamshad et al. 1997), and mutations in *TBX5* cause limb and heart defects in Holt-Oram syndrome (HOS [MIM 142900]; Basson et al. 1997, 1999; Li et al. 1997; Bamshad et al. 1999). Thus, the medical importance of *T-box* gene mutations as causes of human birth defects is well established (Bamshad et al. 1999).

Direct evidence of a role for *TBX3* and *TBX5* in control of the anterior/posterior axis of the tetrapod forelimb comes from the analysis of human birth defects of the limb. Defects of the anterior elements of the upper limb are the most common abnormalities observed in individuals with *TBX5* mutations (Basson et al. 1994, 1997; Li et al. 1997), whereas mutations in *TBX3* cause deficiencies or duplications of the posterior elements of the upper limb (Bamshad et al. 1996, 1997; see fig. 1*A*). The pattern of limb defects observed in UMS is concordant with the finding that *Tbx3* is expressed by cells of the posterior region of the chick wing that are fated to become posterior skeletal elements (Gibson-Brown et al. 1998). Thus, analogous to the role of *T* in the specification of axial mesodermal subpopulations, *TBX3* may specify posterior mesodermal subpopulations in the tetrapod forelimb.

TBX3 may also play a role in the specification of the dorsal/ventral axis of the forelimb. This inference is based on the observation that the ventral surface of the posterior digits of the upper limb are dorsalized in some individuals with UMS, as manifested by both the presence of a nail and the lack of normal dermatoglyphic patterning (fig. 1*B*). Thus, mutations in *TBX3* can disturb the development of all three axes (i.e., proximal/distal, anterior/posterior, and dorsal/ventral) of the limb.

Here we report the characterization of *TBX3* mutations in 75 individuals with UMS who are members of eight newly identified families and two families reported previously (Bamshad et al. 1997). We emphasize that half the mutations are found downstream of exons encoding the T-box domain, suggesting the existence of an additional functional domain(s) in *TBX3*. Relationships between the types of mutations in *TBX3* and the distribution and severity of developmental defects observed in patients with UMS are examined. Defining these relationships is necessary to allow us to further understand both the role of *TBX3* in human development and the phenotypic consequences of specific *TBX3* mutations. Furthermore, a clear understanding of the mutation spectrum and the genotype/phenotype relationship will permit molecular testing and will facilitate genetic counseling of families with limb defects.

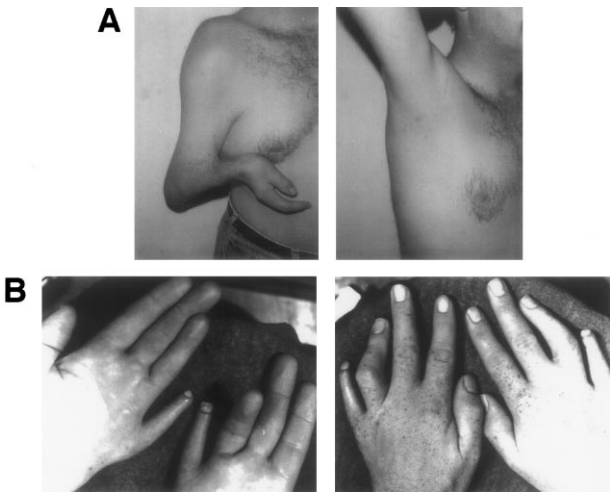

Figure 1 Limb defects observed in individuals with a *TBX3* (L143P) mutation causing UMS. *A*, Photograph of right upper limb and chest (*left*) and axilla (*right*) of an adult male with UMS. Note the shortened forearm and absence of the 3d–5th digits. Axillary hair is absent, and the amount of hair on the anterior-lateral chest is reduced. Additionally, the right areola is hypoplastic. *B*, View of ventral surface of right and left hands of an adult male with UMS. Note the dorsalized ventral surface of the right and left 5th digits, including a duplication of the nailbed of these digits.

Patients and Methods

Clinical Evaluation

All studies were performed with the approval of the Institutional Review Board of the University of Utah and the General Counsel of the Shriners Hospitals for Children. After informed consent was obtained, each participant was evaluated by history and physical examination and/or review of medical records. Radiography was performed on selected individuals. The diagnosis of UMS was based on criteria described elsewhere (Bamshad et al. 1996). At least one affected individual in each family had limb, apocrine-gland, dental, and/or axillary-hair defects (table 1). Affected individuals in 10 unrelated families with UMS were selected for mutation analysis of *TBX3*. Vertical transmission of UMS, with affected individuals in two or more generations, was documented in 9 of 10 families.

Analysis of TBX3

Isolation and analysis of a P1 clone containing *TBX3* has been reported previously (Bamshad et al. 1997). *TBX3* cDNAs were isolated from a 15-wk-old human fetal kidney cDNA library, a human placental cDNA

library, and an adult pancreatic cDNA library. The *TBX3* exon 1/7 and exon 2a alternative transcripts were obtained from a Soares human senescent fibroblast NbHSF DNA library and a Soares human infant brain 1NIB cDNA library, respectively. Exon/intron boundaries corresponding to the *TBX3* cDNA sequence were defined by comparison of cDNA and genomic sequences (table 2 and fig. 2). The BLAST algorithm (Altschul et al. 1990) was used to search the expressed sequence tag (EST) database of the National Center for Biotechnology Information, for sequences homologous to *TBX3*.To extend the *TBX3* contig, EST sequences were grouped into overlapping sets.

To isolate *Tbx3,* murine cDNA was synthesized by means of a Superscript Preamplification System (GIBCOBRL) and ~2 μg of total RNA from adult mouse kidney. Since we wished to extend the partial sequence for *Tbx3* available from GenBank to include the entire T-box domain, a number of primer combinations were tested. The primers that gave us the desired murine *Tbx3* product were derived from the 5′ end of the human *TBX3* DNA-binding domain (5′-CCTGACGCTGCCTCCCAACGG-3′) and from the 3′ end of murine *Tbx2* (5′-AGGCAGTGACAGCGATGAA-3′). The PCR product was cloned into pCRII-topo (Invitrogen) and was sequenced on an ABI 377 automated sequencer (Applied Biosystems). The sequence agreed with the partial *Tbx3* sequence found in GenBank and extended this sequence as shown in figure 2.

Northern Blot Analysis

A human Multi-Tissue northern blot (Clontech) was screened with [^{32}P]-labeled PCR products that included either exon 1 or exon 7. The filter was hybridized and washed under high-stringency conditions, in accordance with the manufacturer's recommendations. The quantity of RNA from each tissue was normalized against the expression of eight housekeeping genes. Volume-based pixel densities for each dot were quantified by means of a BioRad imager and MULTIANALYST software (BioRad).

RNAse Protection Assay

A PCR product containing part of exon 1 through to exon 5, including the 60-nt alternative exon (exon 2a), was cloned into pCRII-topo (Invitrogen). The template DNA was linearized at a *Bsr*GI site within exon 2, and an ~460-nt riboprobe was synthesized by means of T7 polymerase. The riboprobe includes 428 nt of *TBX3* sequence and ~40 nt of sequence derived from the vector. Six micrograms of total RNA from normal mammary epithelial cells, fetal kidney, or three breast carcinoma–derived cell lines were hybridized with 500,000 cpm of *TBX3* plus 5,000 cpm of β-actin probe synthesized at 1/100 the specific activity of the *TBX3* probe.

Table 2

DNA Sequence of *TBX3* Exon Boundaries

Exon/ Intron	Sequence[a]
1	ATGAGCCTCT....AGTCGGGAAGgtaagcagtg
2	cgttttatagGCGAATGTTT....ACATGGATTTgtaagtttca
3	gcccctgcagACTATATTGA....GAATGATAAGgtcanctcaa
4	cttccaatagATAACCCAGT....GAGAAAAAAGgtgagttgaa
5	tctgccacagAAAACAGCTC....AACCTCAAAGgtaaaccatg
6	cctgtggtagATTTATGTCC....GGCCTCTCAGgtatggatcc
7	ctcaccccagGGCCTGGCCA....GTCCCCGTAG

[a] Exonic regions are shown as uppercase, and intronic regions are shown as lowercase.

After hybridization, the reactions were processed according to the instructions provided by Ambion's RNase protection kit and were subjected to electrophoresis on 5% denaturing polyacrylamide gels.

Mutation Analysis of TBX3

Genomic DNA was prepared from peripheral lymphocytes and/or Epstein-Barr virus–transformed lymphoblastoid cell lines derived as previously described. Exons 1–5 of *TBX3* were PCR-amplified by means of previously published exon-flanking primers (Bamshad et al. 1997). Exons 6 and 7 were PCR-amplified by means of 5′-GGAGATAACGCCCTTCTGCCTTGG-3′ (forward)/5′-TTACAGCTACTAGGCCAAAGGGATC-3′ (reverse) and 5′-AGAGGAGAGGGATGAGATAAGCTC-3′ (forward) and 5′-CAACTGCAAAAGGAAGGGCTAACG-3′ (reverse), respectively. Genomic DNA sequences were amplified in 1 × buffer (10 mM Tris pH 8.3, 50 mM KCl, 1.5 mM $MgCl_2$, 10% dimethylsulfoxide) by 20 ng of template genomic DNA, 50 μM of each dNTP, 20 pmol of each primer, and 1 unit of *Taq* polymerase, in a total reaction volume of 25 μl. Samples were cycled 30 times in a Perkin-Elmer 9600 PCR machine using a standard three-step PCR profile with an annealing temperature of 60°C. PCR products were purified on a 2% NuSieve gel and were sequenced by means of either ABI Dye-primer or dRhodamine sequencing reagents. Sequenced products were loaded on an ABI 377 automated sequencer and were analyzed by SEQUENCHER software (Genecodes). The forward and reverse strand of every exon, including flanking splice-recognition sequences, was PCR-amplified and sequenced twice in each direction. For all missense and nonsense mutations, the presence of a mutation was confirmed by restriction digestion, and genomic DNA samples from 100 individuals representing 200 control chromosomes were screened.

To confirm the presence of mutations that did not alter a restriction site, PCR-amplified products from individuals with insertion mutations were ligated into a pAMP1 plasmid (BRL), according to the manufacturer's rec-

Figure 2 Deduced amino acid sequence of partial Tbx3 protein, in mouse and chicken, and of complete TBX3 protein, in human. The conserved T-box region is shaded. Asterisks (*) denote identical amino acids, and dots (.) denote conserved amino acid changes. Locations of intron/exon boundaries in TBX3 protein are indicated by arrows (↓). The deduced amino acid residues encoded by exon 2a (TLAFPSDHA-TWQGNYSFGTQ) are not shown.

ommendations. Ligation mixes were used to transform DH5α cells (Stratagene), and transformants were selected on ampicillin plates. From each individual, 10 transformed colonies were picked, and DNA was prepared by means of an alkaline/SDS miniprep protocol. DNA from each clone was bidirectionally sequenced by previously described methods using ABI dRhodamine sequencing reagents.

Results

Construction of the Full-Length Open Reading Frame (ORF) of TBX3

We previously have reported the partial cDNA sequence of *TBX3* (Bamshad et al. 1997). However, the 3′ boundary of the ORF of *TBX3* was not determined, and, as a result, mutations were identified in only two of three families studied. We characterized both the 3′ boundary of the ORF of *TBX3* and the 3′ UTR, to help us to identify additional disease-causing mutations in *TBX3*. The 3′ UTR of *TBX3* extends 1,587 bp beyond the termination codon in exon 7. The transcription-termination site is demarcated by a consensus polyadenylation sequence (AATAAA) and a poly-A tail (data not shown).

TBX3 is composed of at least seven exons (fig. 3) with an ORF of 2,172 bp that is predicted to encode a protein containing 723 amino acid residues. The predicted DNA-binding domain of TBX3 protein is 98% identical to that of murine and chick Tbx3 protein (fig. 2). The regions 5′ and 3′ of the T-box in human TBX3 protein also exhibit a high degree of homology to the human TBX2 protein (fig. 4). Compared with TBX2 protein, there are two domains of ~75–100 amino acid residues, encoded by portions of exons 6 and 7, that exhibit nearly 70% identity to TBX3 protein.

Expression Studies and Identification of Alternatively Spliced TBX3 *Transcripts*

Northern blot analyses reveal a major *TBX3* transcript of ~5.2 kb in adult human tissues (Bamshad et al. 1997). At least three additional transcripts can be observed (fig. 5*A*). Alternative transcription-start sites, polyadenylation sites, or splicing could generate these *TBX3* transcripts of different lengths. Quantification of *TBX3* RNA from human fetal and adult tissues (fig. 5*B*) reveals abundant signal in placenta, adrenal gland, thyroid, prostate, breast, bladder, uterus, and liver. A weaker signal is detected in RNA isolated from ovary, lung, salivary gland, kidney, small bowel, and skeletal muscle. In fetal tissue, a signal is detected in lung, kidney, heart, liver, and spleen. In the adult brain, the pituitary gland is the only tissue in which a signal is observed. *TBX3* expression was not detected in mRNA isolated from lymphoblastoid cell lines (data not shown).

An alternative transcript of *TBX3* contains an additional 60 bp inserted between exons 2 and 3 (fig. 5*C*). Examination of the intronic region between exons 2 and 3 reveals a 60-bp exon (exon 2a in fig. 3) bracketed by consensus splice-acceptor/-donor (ag/gt) sequences. The region of *TBX3* into which exon 2a is spliced encodes the highly conserved DNA-binding domain of TBX3 protein. Insertion of a novel 20 amino acid residues into the middle of the T-box is likely to alter its DNA-binding

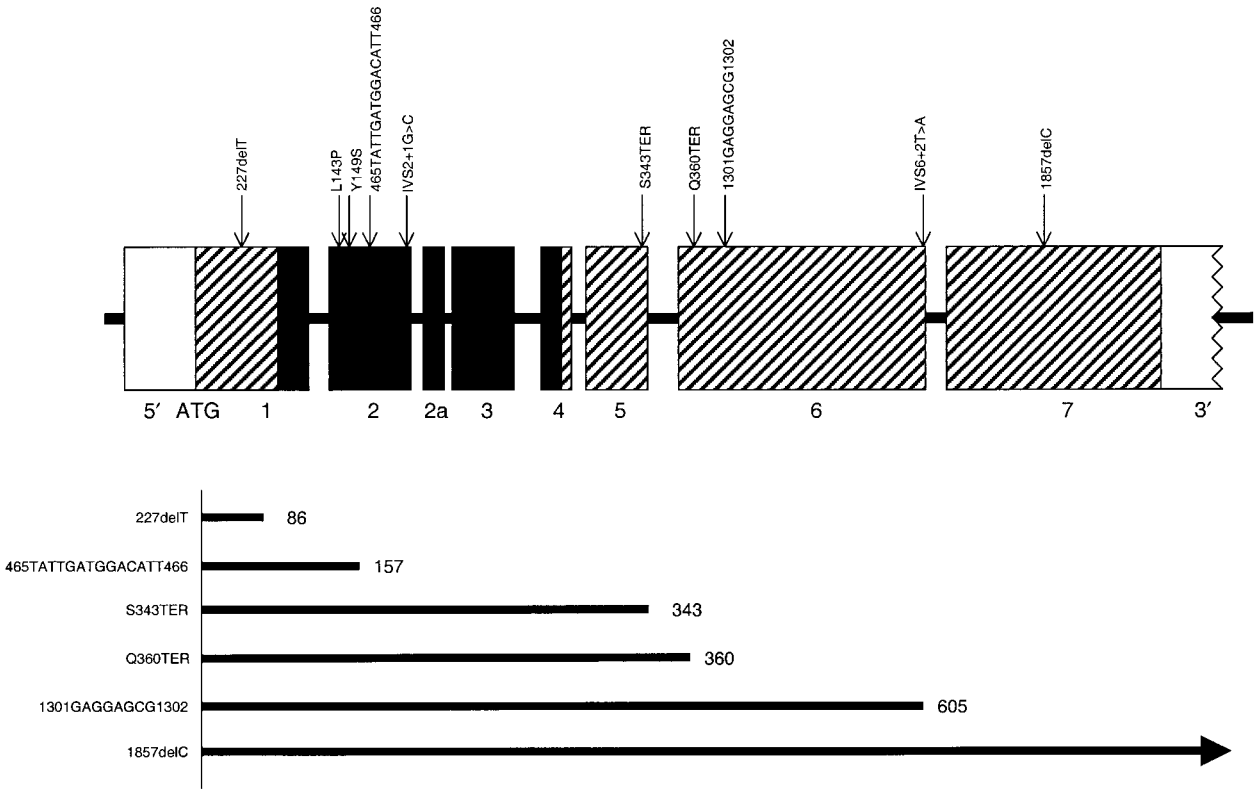

Figure 3 Genomic structure of exons encoding the ORF of *TBX3*. *TBX3* is composed of at least seven exons (Bamshad et al. 1997) that contain untranslated sequence (*unblackened boxes*), highly conserved T-box sequences (*blackened boxes*), and protein-encoding sequence (*striped boxes*). Exon 2a is alternatively transcribed. Locations of *TBX3* mutations found in 10 families with UMS are indicated by arrows (↓). Predicted polypeptides encoded by mutant *TBX3* alleles are shown below the genomic structure of *TBX3*.

properties. Another alternative transcript of *TBX3* splices the 5′ sequence of exon 1 to exon 7 in frame and eliminates the T-box. This is analogous to the few transcripts lacking a homeobox that have been reported for several *Hox* genes (Chariot et al. 1995). Furthermore, if this *TBX3* transcript is translated, the predicted isoform would include only the highly homologous regions conserved with *TBX2* protein.

Identified Mutations

Mutation analysis was conducted on at least two affected individuals in each multiplex family. DNA sequence changes were found in the affected individuals of all 10 families (fig. 6). Two individuals were found to have single-base deletions (227delT and 1857delC) that produced frameshift mutations. Three individuals had a 1-bp change that produced either a missense (L143P and Y149S) or nonsense (Q360TER) mutation. One individual had a 2-bp change (S343TER) resulting in a nonsense mutation. Presumably, this was produced by an initial silent substitution, G→A, followed by a pathogenic mutation, C→A. Two individuals had splice-site mutations (IVS2+1G→C and IVS6+2T→A) that are predicted to produce a truncated protein product. Frameshift mutations caused by insertions of small duplications (465TATTGATGGACATT466 and 1301GAGGAGCG1302) were identified in two individuals. Each specific mutation was identified in only one kindred. Sequence and/or restriction analysis confirmed that each mutation segregated only with affected individuals. None of the changes predicted to cause missense or nonsense mutations were found in 200 control chromosomes. Additional sequence variants were identified within the intronic regions of affected and unaffected individuals and were classified as nonpathogenic polymorphisms (data not shown).

Discussion

Structure and Expression Pattern of TBX3

Here we have reported the characterization of the complete ORF of *TBX3*, its 3′ UTR with a transcription termination site, and a *TBX3* cDNA containing a partial ORF that, we suggest, encodes a novel isoform of TBX3 protein. Because the Northern blots indicate that the predominant *TBX3* transcript is ~5.2 kb in length (fig.

Figure 4 Amino acid alignment of human TBX3 and TBX2 proteins. Asterisks (*) denote identical amino acids, and dots (.) denote conserved amino acid changes. The conserved T-box region is shaded.

5A), the full-length transcript of *TBX3* is likely to include a long 5′ UTR that remains to be characterized. Comparisons with chick and mouse *Tbx3* reveal that the nucleotide and amino acid identity of *TBX3* and TBX3 protein, respectively, are highly conserved (figs. 2 and 4).

Among different *T-box* gene–family members, the size range of the T-box domain is ~180–190 amino acids, and the amino acid identity is highly conserved. The T-box may be located at various positions within each protein, and sequence similarities outside the T-box are observed only among closely related members of the *T-box* gene family (Papaioannou and Silver 1998). Thus, it appears that the DNA-binding activity between *T-box*–gene–family members has been retained while the domains that may be involved in protein-protein interactions have diversified. A comparison of TBX2 and TBX3 proteins indicates that, in addition to their T-boxes, which are ~95% identical, the amino-terminal domains of the two proteins are also similar, sharing ~70% identity over two regions composed of ~70 and ~100 amino acids, respectively. The significance of these regions of shared homology is not known, but the similarity suggests that TBX2 and TBX3 may share functional domains in addition to their DNA-binding domain.

Analysis of the crystal structure of the DNA-binding domain of *Xenopus* T protein reveals that T is bound as a homodimer, interacting with the major and minor grooves of DNA (Müller and Herrmann 1997). At least two mutations in *TBX3* disrupt the DNA-binding domain and produce a protein fragment that presumably has reduced, if any, DNA-binding activity. Two missense mutations in exon 2 produce nonconservative amino acid substitutions near a critical dimerization site in the DNA-binding domain of *Xenopus* T protein. These two sites are highly conserved across *T-box* genes. However, five mutations in *TBX3* are located 3′ of the region encoding the T-box. This suggests that, although these mutant TXB3 proteins may bind DNA, their function is substantially impaired. The observation that many of the mutations in *TBX3* do not disrupt the T-box underscores the existence of an additional functional domain(s) in TBX3 protein. However, it remains to be demonstrated that mutant *TBX3* transcripts encode a truncated protein product.

TBX3 is widely expressed in a variety of tissues and organs that are not affected in individuals with UMS; in other words, development of most tissues in which *TBX3* is expressed is normal in individuals with UMS. This suggests that different tissues may require quantitatively different levels of normal TBX3 protein. Alternatively, other genes, including *T-box* genes, with expression domains overlapping *TBX3* (e.g., *TBX2*), may be able to compensate for reduced levels of normal TBX3 protein in certain tissues and organs. Such functional redundancy is also observed for other families of transcription factors that play prominent roles in limb development and that cause human birth-defect syndromes (e.g., *HOX* genes).

TBX3 is widely expressed in adult tissues, although *TBX3*'s role beyond organogenesis is largely unexplored. Because delayed puberty is a consistent feature of individuals with UMS, it has been suggested that

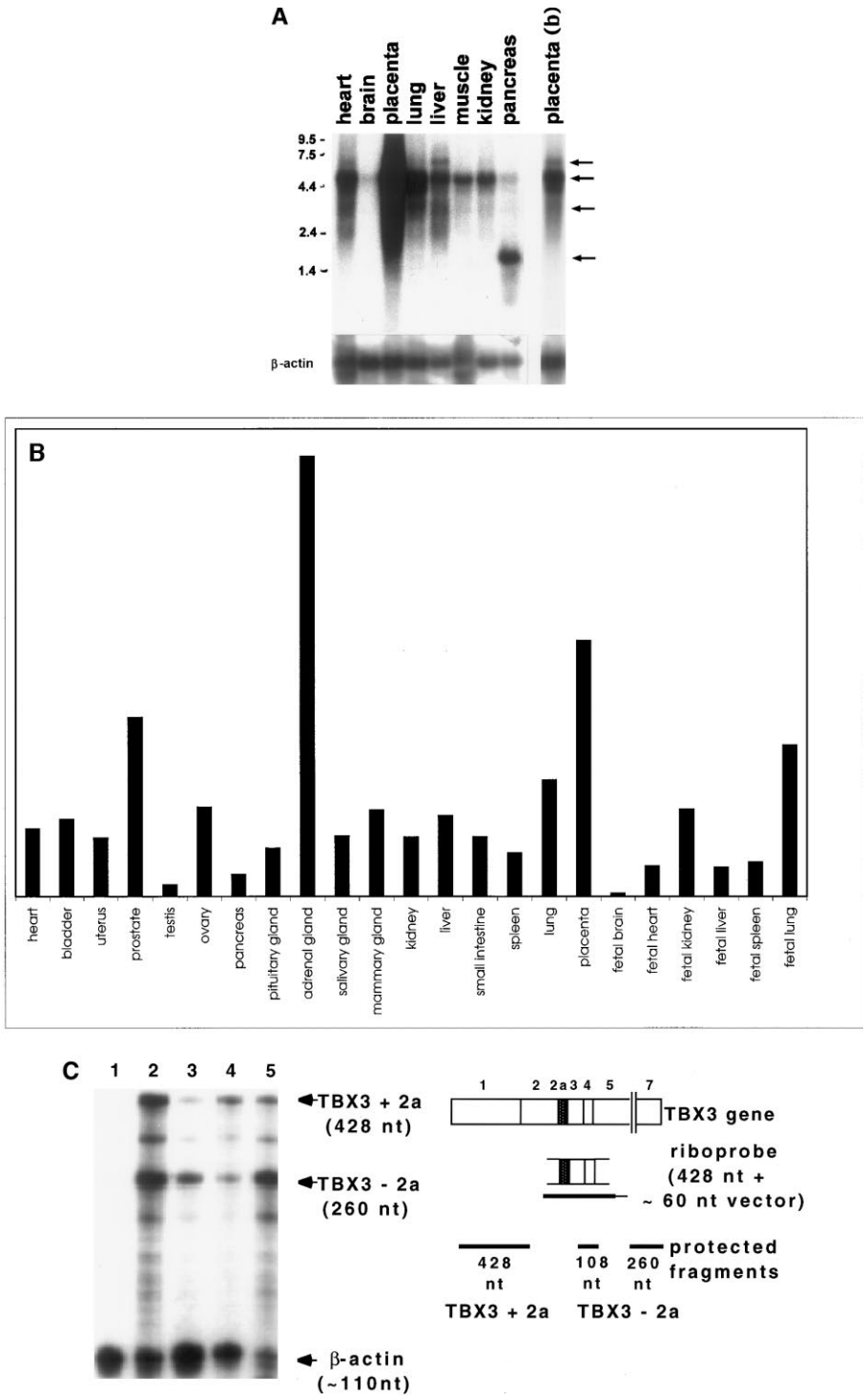

Figure 5 *A,* Northern blot of *TBX3* mRNAs (*arrows* [←]) isolated from heart, brain, placenta, lung, liver, skeletal muscle, kidney, and pancreas. The predominant *TBX3* transcript is 5.2 kb in length. Alternatively spliced/transcribed forms of *TBX3* are found in the placenta, liver, and pancreas. *B,* Histogram of relative mRNA expression patterns of *TBX3* in various adult and fetal tissues. *C,* RNAse protection assay illustrating the alternative transcript of *TBX3,* which has a 60-bp insertion within the region encoding its DNA-binding domain. Lane 1, Breast-carcinoma cell line not expressing *TBX3*. Lanes 2 and 3, Breast-carcinoma cell lines expressing different amounts of *TBX3*. Lane 4, Mammary epithelial cells. Lane 5, Human fetal kidney. The diagram indicates the derivation of the riboprobe, which encompasses part of exon 2 through part of exon 5 and includes all but the first ~250 nt of the DNA-binding domain. The alternative *TBX3* transcript containing exon 2a is indicated by a stippled box. The predicted sizes of the protected fragments are 428 nt, for transcripts containing exon 2a (i.e., *TBX3* + 2a), and 260 nt plus 108 nt, for transcripts without exon 2a. Note that the signal for the 108-nt protected fragment is obscured by the signal produced by *β*-actin.

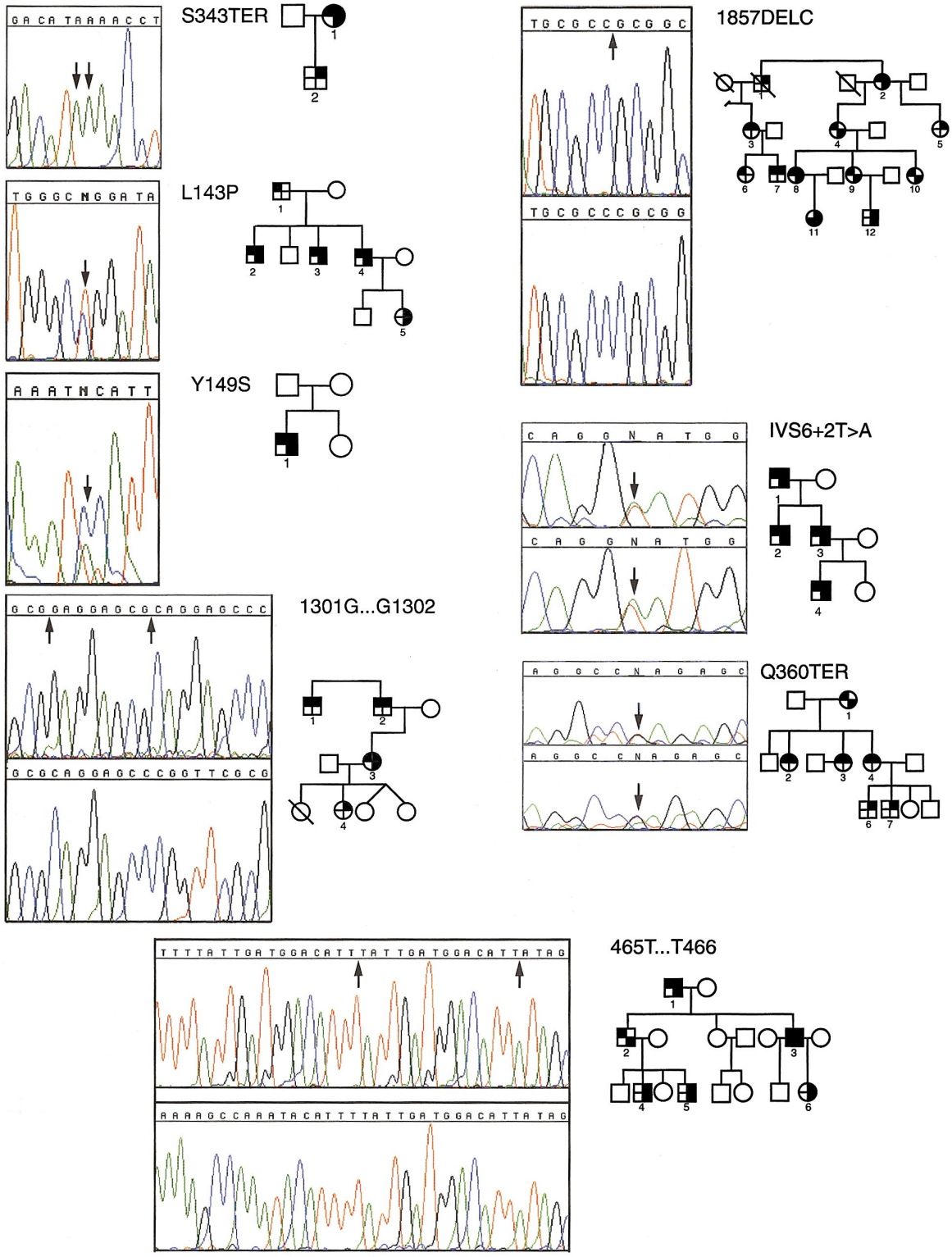

Figure 6 Pedigrees of eight newly identified families with UMS, with electropherograms of the mutations identified in each kindred. Blackened quadrants within each symbol represent the different organ systems affected in each individual: Upper-right quadrant = limb deficiencies and/or duplications; upper-left quadrant = apocrine-gland dysfunction and/or abnormal axillary hair; lower-right quadrant = abnormalities of the breast ; lower-left quadrant = dental defects. Numbers below each symbol in the pedigree correspond to the identification numbers listed in table 1.Table 1 provides a more detailed summary of clinical findings. Panels for S343TER, L143P, and Y149S represent the forward strand of each mutant sequence. For 1301G…G1302, 465T…T466, and 1857delC, the upper panel represents the forward strand of the mutant sequence, and the lower panel represents the forward strand of the wild-type sequence. For IVS+2T→A and Q360TER, the upper panel represents the forward strand of the mutant sequence, and the lower panel represents the reverse strand of the mutant sequence.

TBX3 might participate in the transcriptional control system of the hypothalamic-pituitary-adrenal axis (Bamshad et al. 1996). This is consistent with the observation that *TBX3* is expressed in the adult pituitary and adrenal glands (fig. *5B*).

Mechanism of Disease

The mouse mutant, *Brachyury,* is caused by a 200-kb deletion that removes the entire *T* gene and effectively produces a null mutation. Additionally, correlation between *T* gene dosage and severity of the phenotype has been suggested (McMurray and Shin 1988). Consequently, the observed defects in *Brachyury* are thought to result from haploinsufficiency of T protein. In contrast, other *T* alleles (e.g., T^{wis}, T^{c}, and $T^{c\text{-}2H}$) are due to insertions and deletions that cause frameshifts and truncated T proteins (Herrmann 1991). These alleles retain their DNA-binding activity in vitro and produce developmental defects more severe than those observed in *T* null mutants. Thus, it has been suggested that they act as dominant-negative mutations (Herrmann 1991).

Mutations in *TBX3* could alter normal development by means of at least three different mechanisms—that is, by (1) disturbing the normal proportions of different *TBX3* transcripts produced by a mutant allele; (2) generating templates for the synthesis of abnormal proteins; or (3) reducing the production of normal TBX3 protein, leading to functional haploinsufficiency. There are at least four different transcripts produced by *TBX3,* including one in which exon 1 is directly spliced to exon 7. This transcript could still be produced by ⩾80% of mutant *TBX3* alleles that are not able to make a full-length *TBX3* transcript. This could alter the proportion of alternative transcript (i.e., exon 1/7) to full-length *TBX3* transcript. However, each mutation in *TBX3,* including those in exons 1 and 7, results in a similar UMS phenotype. Thus, it is unlikely that UMS results from alteration of the ratios among different transcripts of *TBX3*. Half the observed *TBX3* mutations could produce a mutant TBX3 protein that retains its DNA-binding domain. These truncated proteins could exert a functional effect through their remaining amino-terminal domains, resulting in dominant-negative interactions with normal TBX3 protein. However, analysis of the clinical features of 75 individuals with UMS shows no obvious phenotypic differences between those who have missense mutations and those who have deletions or frameshifts. Thus, it is unlikely that mutant *TBX3* alleles behave as dominant-negative mutations.

Most of the mutations in *TBX3* encode a truncated protein with a long carboxy-terminal tract of nonsense sequence, and five of six transcripts end with a premature termination codon. In general, transcription from such mutant alleles may be reduced as a result of nonsense-mediated mRNA decay (Maquat 1995), producing a functional null allele (Willing et al. 1996). Even if mutant *TBX3* alleles that encode a truncated protein were accurately translated, functional haploinsufficiency of TBX3 protein could be produced if mutations *5′* and *3′* disrupt important functional domains. Loss of function is easier to reconcile with the observation that the various *TBX3* mutations appear to produce the same functional effects. This is consistent with the wide range of types and of severity of birth defects among individuals in the same kindred. These data support the conclusions that UMS is caused by haploinsufficiency of TBX3 protein and that the wide variety of defects observed within each kindred with UMS is caused by epistatic modifiers.

There are substantial data to suggest that different mutations in the same *T-box* gene may disrupt development of different subpopulations of mesodermal cells. For example, a deletion in the promoter region of *optomotor blind* (*omb*), a *Drosophila T* homologue, causes both a dramatic reduction in *omb* expression and abnormal development of the optic neural pathways. Yet other *omb* alleles, such as *bifid* and *Quadroon,* have normal optic lobes but exhibit defects of wings and tergites, respectively (Kopp and Duncan 1997). However, no *TBX3* mutations are associated with defects of only a specific organ.

The Role of Tbx3 *in Development*

At least five *T-box* genes are expressed in the developing vertebrate limb. These include *Tbx2, Tbx3, Tbx4, Tbx5,* and *Tbx15* (Agulnik et al. 1998; Gibson-Brown et al. 1998). In chick and mouse, *Tbx5* and *Tbx3* are expressed in the lateral-plate mesoderm prior to limb-bud initiation. In the forelimb, *Tbx3* is expressed along the entire length of the posterior margin of the limb-bud mesoderm. *Tbx3* expression does not extend as far distally along the anterior margin of forelimb mesoderm (Gibson-Brown et al. 1998). This is consistent with the finding that the defects observed in individuals with UMS are typically deficiencies and/or duplications of the posterior skeletal elements of the upper limb.

Defects of the apocrine glands, teeth, and external genitalia are common findings in individuals with UMS (Bamshad et al. 1996). This is consistent with the observation that *Tbx3* is expressed in mammary buds, jaw mesenchyme, and the genital tubercle (Chapman et al. 1996). Mammary buds are epithelial structures derived from the surface ectoderm. The mammary buds interact with a thickened ridge of underlying mesenchyme (i.e., the milk ridge) to form the branching-duct system of the breast (Hennighausen and Robinson 1998). Similarly, tooth development is initiated by the inductive effect of the oral epithelium on the underlying mesenchyme

(Thesleff and Sharpe 1997), and the epithelium of the genital tubercle has an inductive effect on the underlying mesenchyme that will eventually form the external genitalia (Dolle et al. 1991). Although the apical ectodermal ridge of the limb bud is organized differently, the mammary buds, the oral epithelium, and the epithelium of the genital tubercle each exhibit a similar inductive effect of epithelium on mesenchyme, or vice versa.

It has been suggested that the regulatory system of limb development was coapted for more evolutionarily derived features, such as scales, feathers, hair, and teeth (Thesleff et al. 1995). This is based on anatomical and molecular studies indicating that the early developmental anatomy of limbs, teeth, hair, and apocrine glands, including the breasts, is similar (Schwabe et al. 1998). As might be predicted, it appears that the transcriptional control systems involved in the development of the limb are also used to build other appendages of the body wall. Thus, understanding the mechanisms by which *TBX3* mutations result in malformations in developing nonlimb tissues should reveal general insights about the developmental programs controlling and coordinating organogenesis.

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Electronic-Database Information

Accession numbers and URLs for the data in this article are as follows:

GenBank, http://www.ncbi.nlm.nih.gov (for partial*TBX3* cDNA [AF002228], *TBX3* cDNA containing alternatively-spliced T-box [U69556], alternatively spliced transcript of *TBX3* composed of exons 1 and 7 [N94306], exon 7 and the 3′ UTR of *TBX3* [AF140240], murine *Tbx3* [U57328]), and chick *Tbx3* [AF033669])

Online Mendelian Inheritance in Man (OMIM), http://www.ncbi.nlm.nih.gov/Omim (for HOS [MIM 142900] and UMS [MIM 181450])

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