

Research article

Genomic organization of *Tropomodulins 2* and *4* and unusual intergenic and intraexonic splicing of *YL-1* and *Tropomodulin 4*

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Abstract

Background: The tropomodulins (TMODs) are a family of proteins that cap the pointed ends of actin filaments. Four TMODs have been identified in humans, with orthologs in mice. Mutations in actin or actin-binding proteins have been found to cause several human diseases, ranging from hypertrophic cardiomyopathy to immunodeficiencies such as Wiskott-Aldrich syndrome. We had previously mapped *Tropomodulin 2* (*TMOD2*) to the genomic region containing the gene for amyotrophic lateral sclerosis 5 (*ALS5*). We determined the genomic structure of *Tmod2* in order to better analyze patient DNA for mutations; we also determined the genomic structure of *Tropomodulin 4* (*TMOD4*).

Results: In this study, we determined the genomic structure of *TMOD2* and *TMOD4* and found the organization of both genes to be similar. Sequence analysis of *TMOD2* revealed no mutations or polymorphisms in *ALS5* patients or controls. Interestingly, we discovered that another gene, *YL-1*, intergenically splices into *TMOD4*. *YL-1* encodes six exons, the last of which is 291 bp from a 5' untranslated exon of *TMOD4*. We used 5' RACE and RT-PCR from *TMOD4* to identify several intergenic RACE products. *YL-1* was also found to undergo unconventional splicing using non-canonical splice sites within exons (intraexonic splicing) to produce several alternative transcripts.

Conclusions: The genomic structure of *TMOD2* and *TMOD4* have been delineated. This should facilitate future mutational analysis of these genes. In addition, intergenic splicing at *TMOD4/YL-1* was discovered, demonstrating yet another level of complexity of gene organization and regulation.

Background

Tropomodulins are the vertebrate proteins that cap the pointed ends of filamentous actin [1]. The first *tropomodulin* (*TMOD*) gene was cloned by Sung and colleagues (1992) from a fetal liver library. Three additional family members have been identified in humans, and TMOD homologs have been identified in mouse, rat, chick, *Drosophila*, and *C. elegans* [2–8]. Expression patterns vary extensively: *Tropomodulin 3* (*TMOD3*) is

ubiquitous; *Tropomodulin 1* (*TMOD1*) is widespread in heart, muscle, brain, lens, erythrocytes, and arterioles; *Tropomodulin 2* (*TMOD2*) is restricted to neuronal tissue; *Tropomodulin 4* (*TMOD4*) is expressed in skeletal muscle, with a less abundant ~7 kb transcript expressed in both skeletal and cardiac muscle [8]. Whereas tropomodulins or the Arp 2/3 complex cap the pointed end of actin filaments, the barbed end can be capped by CapZ, α , β , and γ adducins as well as gelsolin [9–11]. Control of

thin filament length is critical for maintaining proper sarcomere function and length [12]. Inhibition of Tmod1's capping activity – either by using an antibody to its C-terminal end or by decreasing expression using an antisense *Tmod1* transcript – results in elongated thin filaments and decreased cardiac contractility [13,14]. *Tmod1* overexpression in rat cardiomyocytes causes shortening of the thin filaments and sarcomere disorganization, resulting in myofibril degeneration [14]. Likewise, mice overexpressing *TMOD1* in the heart show disrupted sarcomere organization with shortened thin filaments, leading to myofibril degeneration and dilated cardiomyopathy [15]. Recently, Littlefield and colleagues showed that overexpression of GFP-Tmod1 in chick cardiac myocytes results in shortening of thin filaments; the authors proposed that excess Tmod1 decreases the affinity between actin monomers and pointed ends, leading to monomer dissociation and filament shortening [42]. Mutations in many proteins making up the cardiac sarcomere have been shown to cause cardiac hypertrophy [16–19]: mutations in the *TPM1* gene, for example, cause type 3 familial hypertrophic cardiomyopathy (CMH3), and a transgenic mouse expressing a CMH3 mutation develops ventricular myocyte disarray and hypertrophy [20]. Mutations in myosin heavy chain 7 are estimated to account for 40–50% of the cases of hypertrophic cardiomyopathy [21].

Given the importance of actin-binding proteins in human disease, we mapped *TMOD2* and *TMOD4* and found them to localize to 15q21.1 and 1q12, respectively [8]. These loci overlap with the genomic regions containing the genes for amyotrophic lateral sclerosis 5 (ALS5) and limb girdle muscular dystrophy 1B (LGMD1B), respectively [22,23]. We characterized these tropomodulin genomic loci for use in mutational analysis. During the course of this study, the gene mutated in LGMD1B was identified as Lamin A/C [24]. Our investigation, however, revealed that an unrelated gene, *YL-1*, intergenically spliced into *TMOD4*. *YL-1* is a putative transformation suppressor gene that localizes to the nucleus and binds to DNA [25,26]. *YL-1* is organized into six exons and produces several alternatively spliced transcripts using both intergenic and cryptic splicing. This relationship between *YL-1* and *TMOD4* serves as yet another example of the complexity of genomic organization and gene regulation.

Results

Genomic organization of *TMOD2*, *TMOD4*, and *YL-1*

We determined the exon/intron boundaries of *TMOD2* and *TMOD4* by sequencing PCR products amplified from primers within adjacent exons, and sequencing short exon containing genomic fragments. We identified nine coding exons in *TMOD2* and in *TMOD4* which are

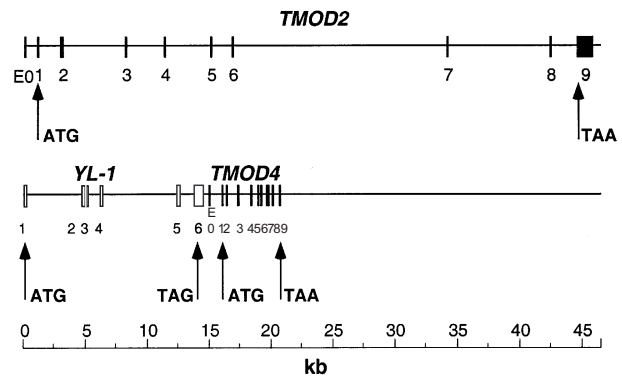


Figure 1

Genomic structure of *TMOD2*, *TMOD4*, and *YL-1*. Numbered rectangles represent coding exons, E0 represents 5' UTR exons. ATG represents the start codon of each gene and TAA or TAG represent the termination codon of each gene. Scale below is in kilobases (kb).

spread over a 45 kb and 4.7 kb genomic region, respectively (Fig. 1). The exon/intron boundaries of the two genes are conserved, except that *TMOD2* has more 5' untranslated region (UTR) in coding exon 1 and more 3' UTR in exon 9 than *TMOD4*. *TMOD2* and *TMOD4* also contain additional 5' UTR exons. Our reported cDNAs have 69 and 19 bp additional sequence 5' to what is contained in exon 1 for each gene, respectively [8]. A search of the EST database using the *TMOD4* 5' end extended this sequence by 8 bp (ESTs AA194560, AA192772, and AA178988). We were able to align this sequence and found that it lies 1006 bp from *TMOD4* exon 1 and contained a consensus donor splice site. Using 5' rapid amplification of cDNA ends (RACE) from *TMOD4* exon 2, we discovered that this exon was 93 bp in length and contained no consensus AG acceptor. 3' RACE from *TMOD4* exon 2 extended our reported cDNA by an additional 9 bp, bringing the entire length of the *TMOD4* transcript to 1.267 kb (Genbank Accession# AF393374).

Using the 5' end of the *TMOD2* cDNA, we searched the high throughput genomic sequences (HTGS) database and identified a sequence, NT 010204, that contained 100% identity to the 69 basepairs of *TMOD2* 5' UTR and contained a consensus GT donor splice site. The distance from this UTR exon to coding exon 1 is 14.6 kb, but the sequence is not completely ordered. Using nomenclature from previous tropomodulin genes we designated these 5' UTR exons as E0 [27].

We sought to determine the genomic structure of *YL-1* when we discovered that it lies next to and intergenically splices into *TMOD4* (see below). Using the same methods described above, we identified six coding exons of

Table 1:

TMOD2				
Exon	5' intron (5'-3')	Exon (bp)	3' intron (5'-3')	Intron (kb)
E0	5' UTR	69	GTGAGCGCCCCGGGGGGCGGGTGG	14.6
1	TATTGTGTTTCTTTTTTATTAACAG	195	GTTAGTGACATGGAACCTGAAGCAGA	1.7
2	CCTGCTCACACCTCTTCTTGTCAG	157	GTAAGGACCACAGGCAGAGCATCTT	5
3	TTTTTGTTTTCTTCTGATTTAAAG	123	GTTAGTCCTGAACTCTGGGAACTTT	3
4	ATGCTCATTTGTTGACTGTTTTAG	87	GTAAGTTGATGTGCAATCTGTGGTT	3.6
5	TTTAAAATGAAAACCTGTGTTTTAG	131	GTATTCATTGTGATTATCATCAGT	1.6
6	ACTAGCCATGTCCTCTGTCTTAG	108	GTGAGTAAAATTCTTAGAAATATAA	17
7	GTTTTTTTTCTTTTTGCATCATAAG	144	GTAAGGAAGGCCAGAGAATAGGCAA	8
8	TGCATGTGTCTGCACCTGCAACCAG	145	GTAATTCAGCCATAATTTTGCTGT	2
9	TTTTGTTCTTTCTTTTACCTAG	1314	3' UTR	
TMOD4				
Exon	5' intron (5'-3')	Exon (bp)	3' intron (5'-3')	Intron (bp)
E0	5' UTR	93	GTAGGTGGGAAGACAGGGGGCTTA	1006
1	CATCCTTTTGTCCCATGTTGCCAG	165	GTAGGGGCTCCAGCACAGGGAACCA	205
2	TTGCTCCCCAAAACCTCATCCCTAAG	157	GTATGGGGACCCTGACATCCATGCC	775
3	GAGCCATCCTTCATCTCCCCATCAG	117	GTGGGTAGCTGTGGGAAGTTGAGGG	952
4	TGACTCCTCTTTACCCTCTCCAG	90	GTGAGTGTGTTTGGGGAGCATGGTC	506
5	TTCCCTTCCTGCCCTCATTACCAG	131	GTATTTGACTTGACATCCTCCAAACC	92
6	ACCATCTCCTATTCCCCTCCGATAG	108	GTAAGGCTAGTTGACATCCCCAGCC	368
7	CCTAACCCAAGTCCCTACTACCCAG	144	GTCAGCATTCCCTTCCCCTGATGTT	256
8	CAGCTTTTGCCTCTCCCTCCCCAG	145	GTGAGTAACTGCAGACATGATGTGT	415
9	TATGTTTAATATTGCTCCTTTACAG	108	3' UTR	
YL-1				
Exon	5' intron (5'-3')	Exon (bp)	3' intron (5'-3')	Intron (kb)
1	5' UTR	122	GCAAGATCCGGGCCTGGGAAAAGGG	4.5
2	AACCCTTATCTCCCTGTGCCTTAG	153	GTACAGGGGGAGTCCTAGTTGTCTT	0.178
3	GTATCTGATTCCAATCTGTCCCTCAG	115	GTGAGTAGGGATGTTAGGGTCAATT	1
4	TTCTTCTTATCTCACTCTCTCCAG	177	GTAAGTCTGTGGTTTCAGAAAAAGT	6
5	CTCATTTCTTCTTTGACCCTAAAG	145	GTGAGTGAATCTCAAGAGGAAAAGA	1.2
6	GTTTTTCCTGTCTTTTGCCTCAG	724	3' UTR	

Table 2:

TMOD2				
Exon	Anneal (° C)	Forward Primer (5'-3')	Reverse Primer (5'-3')	Product size (bp)
1	54	TTCAATACAGTAGGCTCCA	CGAGCTAAGGGATTCTAC	393
2	55	GGTATCCTTCCTGCTTCC	GGCTTATTTCCCATGTCT	413
3	54	TCTGCTCAGTCTACTTACCC	CCATAATGCCTTGTGTCA	322
4	54	TTCAAGGGACAAATTAACA	AAAGCCCAAGTGATCCTA	289
5	54	AGTGTTATTGGAATCAGCAT	CTCCAACCTCAGTGACTACAAA	358
		*GTAAAACGACGGCCAGTTGCTGAAGGCTA	**GGAAACAGCTATGACCATGACTATAAT	
6	57	GGTAATGA	TTTGCTCACTAACTGT	390
7	54	TTAATTTGGGAGTGAGGG	ACAGGAAATCCAGTACATCA	356
8	54	CCTGTGCAAGTAACTGTTTC	AGTGACATCAGAGGCCAG	323
9	54	ATGTTGTTTATCTGGAATTTA	CCCATGAGCAAATAAAAC	307
		*indicates a M13 universal sequence attached at 5' end	**indicates a M13 reverse sequence attached at 5' end	

YL-1 spanning 14.2 kb (Fig. 1). The distance from the last exon of *YL-1* to Eo *TMOD4* is 291 bp. We sequenced the entire genomic region encompassing *TMOD4* from the end of *YL-1* exon 6 through *TMOD4* exon 9 and deposited it in Genbank (Accession No. AF393375). The sizes of the exons and introns as well as the boundary sequences for *TMOD2*, *TMOD4*, and *YL-1* are provided (See Table 1). Consensus splice sites were identified for all *Tropomodulin* exons, but *YL-1* exon 1 contained a GC 5' splice site instead of the more common GT 5' splice site. This splice site also conforms well to other nonconsensus GC 5' splice sites as described in Mount (2000) with a G at the -1 and +5 positions [28]. We used the very 3' end of the *YL-1* cDNA to look for additional 3' UTR. We identified three ESTs (ESTs AA128103, AW627363, and AI591193) that were identical at the 3' end and extended the reported UTR by an additional 150 bp.

Mutational Analysis of *TMOD2* in *ALS5*

Two patients and two controls from a family with an autosomal recessive form of familial ALS (*ALS5*) were analyzed for mutations in *TMOD2*. We amplified coding exons 1–9 using primers flanking each exon (See Table 2). These PCR products were sequenced to identify any potential point mutations or small deletions. We did not detect any mutations or polymorphisms in any of the patients or controls.

Inter genic splicing of *YL-1* into *TMOD4*

During our analysis of *TMOD4*'s genomic structure we identified EST AI763406, which contains *TMOD4* exon 9 and part of the coding region of another unrelated gene

known as *YL-1*. Using 5' RACE we were able to confirm the presence of this transcript and identify other unique intergenic RACE products. Figure 2 summarizes our findings. There are two main intergenic products, each of which was represented multiple times in our RACE clones. The first intergenic splice products (RACE #9–11, and 13–15) are similar to EST AI763406. These variants consist of *YL-1* exons 1–5, and *TMOD4* exon 9. The ORF of this splice variant keeps the reading frame of *YL-1* but changes the *TMOD4* endogenous reading frame to make the reading frame of exon 9 completely open. Translation of this ORF would theoretically produce a protein of at least 271 amino acids containing the amino terminal half of *YL-1* but a unique carboxy terminus. If, however, we extend the sequence to include intronic sequence downstream of exon 9, we discover that the frame is kept open an additional 45 bp, making this theoretical protein 286 amino acids in length. Using primers to exon 1 of *YL-1* and exon 9 of *TMOD4*, we confirmed the presence of this intergenic product by RT-PCR on human heart RNA. RACE product #12 was similar to RACE products #9–11, 13–15 except that *YL-1* splices from exon 5 to *TMOD4* exon 8 which then splices to exon 9 (Fig. 2). This produces an ORF coding for a 252 amino acid protein that changes the frame of *TMOD4*, adding only 16 additional amino acids before encountering a stop codon. Another set of RACE products (RACE # 1–5) consists of *YL-1* exons 4 and 5 and *TMOD4* exons 1–9, except that exon 2 uses an internal consensus cryptic splice site. Using the *YL-1* endogenous frame we find that this ORF terminates in *TMOD4* exon 1. If we assume an ORF including *YL-1* exons 1–3 along with the isolated RACE product, then it

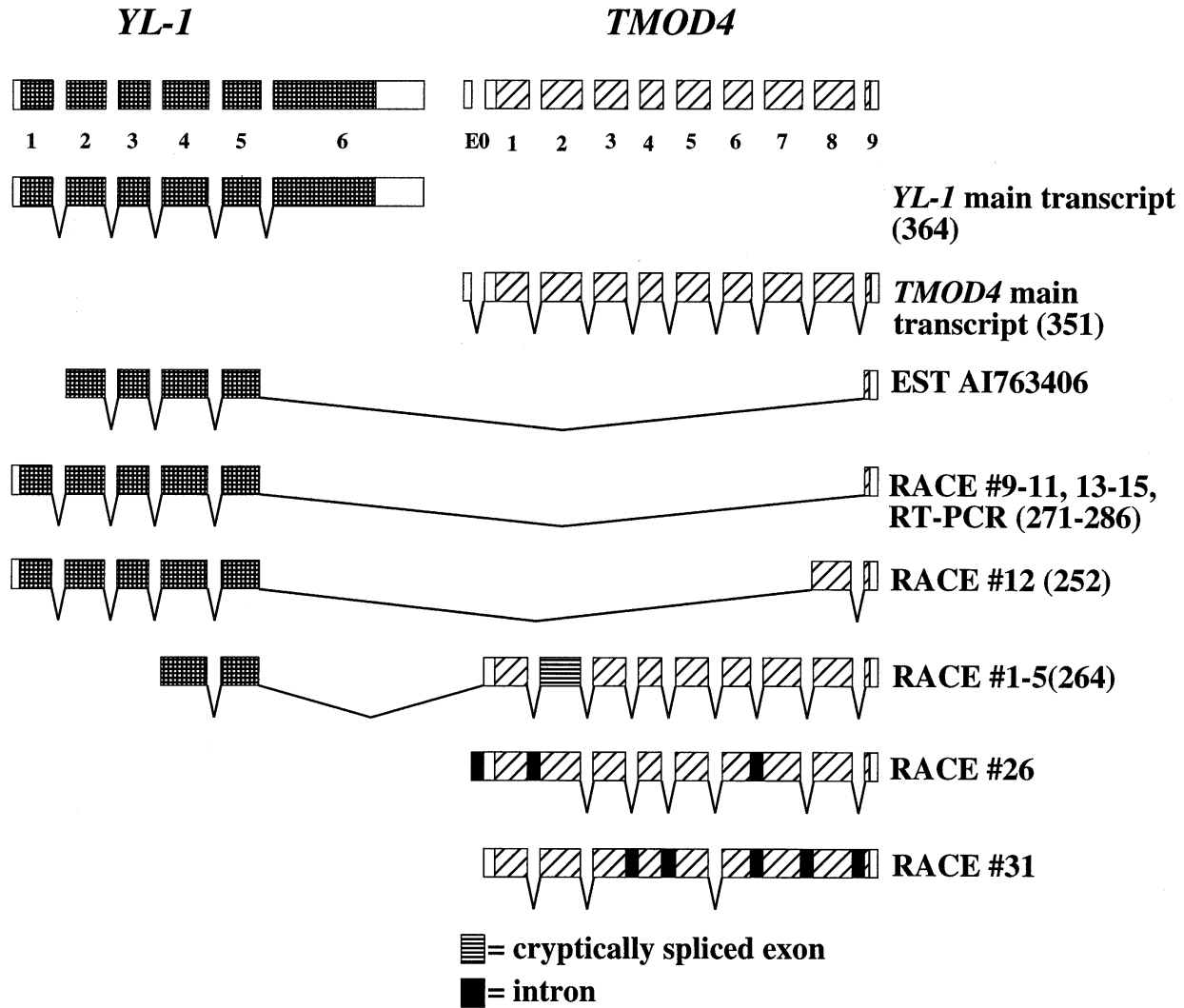


Figure 2
 Summary of RACE products: Hatched rectangles represent *YL-1* exons. Diagonal striped rectangles represent *TMOD4* exons. Numbers in parentheses represent the number of amino acids produced from each ORF. Black rectangles represent introns, and horizontally striped rectangles represent exons which used a cryptic splice site.

would theoretically produce a protein of 264 amino acids. We used the translated protein sequences from these intergenic ORFs and analyzed them using InterPro Scan via EXPASY. No additional sequence motifs or domains were identified. Another type of RACE product we identified (RACE# 26–31) is the incompletely spliced products of *TMOD4*. In no case did we observe the inclusion of *YL-1* exon 6 or the use of the normal splice acceptor of *TMOD4* exon 2 – the cryptic splice acceptor was always present in intergenic RACE products. Furthermore, the *YL-1* alpha helical domain, which is thought to contain

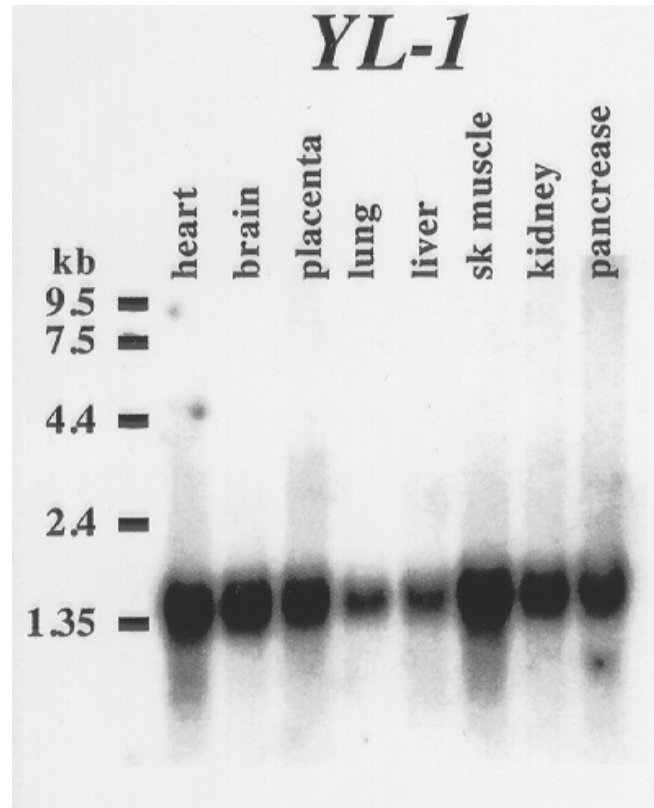
the DNA binding domain, is maintained in all intergenic splice products contained within *YL-1* exons 4 and 5.

***YL-1* intraexonic spliced transcripts and expression pattern**
 To better understand the nature of *YL-1*'s intergenic splicing, we searched the EST database for other alternative and intergenic *YL-1* transcripts. Using either the *YL-1* or *TMOD4* cDNAs in a BLAST search of the human EST database, we were unable to identify any additional intergenic transcripts, but we did uncover several *YL-1* ESTs that had apparently spliced within exons in such a way as to not use the canonical consensus splice accep-

**Figure 3**

Hatched rectangles represent YL-1 exons. Thick black lines represent the intraexonic splice events. The number of amino acids produced by each ORF is in parentheses. Asterisks represent the positions of intraexonic non-canonical splice sites used in multiple ESTs.

tors or donors, the rarer GC or AT donor sites or the AC acceptor site[29]. ESTs AI560960 and AI369608 were identical and contained YL-1 exons 1 and 2 but splice within exon 2 at position 276 (position is in bp relative to Genbank sequence D43642) to position 1107 (internal to exon 6) (Fig. 3). Translation of this ORF would produce a truncated protein of only 121 amino acids. EST AI560960 was obtained from the IMAGE consortium and sequenced. It is 476 bp in length and contains YL-1 exons 1 and up to position 276 in exon 2 at which it splices internal to exon 6 at position 1107. A second splice product was represented by ESTs AI366716 and AW005187, in which the sequence appears to splice from position 113 in exon 1 to exon 6 at position 936 (Fig. 3). This would produce another truncated protein that is 89 amino acids in length. Another unusual splice product was represented by ESTs AA443950 and AA653180. These ESTs demonstrate splicing within YL-1 exon six itself, from position 936 to 1062 (skipping over ~126 bp), changing the frame and making it open past the endogenous stop codon (Fig. 3). EST AA443950 was obtained from the image consortium and sequenced. It contained a 1199 bp insert which contained all of YL-1 exons 1–5 and exon six as described above and encodes an ORF for a 358 amino acid protein. However, EST AA653180 has an additional six base pairs at the splice junction site coding for leucine and proline, suggesting that either the site produces two different splice variants or there is some type of intermediate stage of splicing at this site. In either case, the protein produced from this ORF (if AA653180 contains the rest of the intact 5' YL-1 transcript) would be 360 amino acids. This truncates the reported YL-1 protein only by 6 or 4 amino acids. Using InterPro Scan via EXPASY, we determined that these few amino acids do not produce any potential phosphorylation sites or protein domains or motifs. Two of these three splice variants use the 936 position for splicing as a putative donor in one case and as an acceptor in the other. We cannot explain this finding, but it may suggest that YL-1 undergoes a great degree of intraexonic splic-

**Figure 4**

Human multiple tissue Northern blot probed with YL-1 RT-PCR product revealed a single highly expressed transcript between 1.4–1.6 kb in all tissues.

ing. This high degree of splicing together with the lack of a GT donor site in the last exon, and the close proximity of YL-1 and TMOD4, may account for the intergenic splicing between these genes.

We also wanted to determine whether the YL-1 expression pattern overlapped with TMOD4. A human multiple tissue Northern blot was probed with a YL-1 RT-PCR product revealing a single 1.4–1.6 kb band in all lanes (Fig. 4). This is consistent with the reported ubiquitous expression of YL-1 in the rat [25].

Discussion

Sequencing PCR fragments and genomic subclones from phage artificial chromosomes (PACs) and bacterial artificial chromosomes (BACs) that contain TMOD2 and TMOD4 allowed us to determine the genomic structure of these two Tropomodulin genes. Although mutational analysis of the coding region of TMOD2 in ALS5 and TMOD4 in LGMD1B patients failed to reveal any point mutations, small deletions, or polymorphisms, we did find that TMOD2 and TMOD4 consist of nine coding exons and at least one 5' untranslated exon (E0).

This is identical to the genomic structure reported for *TMOD1* and *Tmod1* by Chu and colleagues and Conley et al. [27,41]. In addition, they identified an 86 bp 5' UTR exon which was expressed in a tissue-specific manner. We performed 5' RACE for *TMOD4* and identified only a single 93 bp 5' UTR exon (EO) which lies 1006 bp from coding exon 1. We did not examine whether the EO exons of *TMOD2* and *TMOD4* were expressed in a tissue-specific manner. In addition, the *TMOD2* transcript is approximately 9.5–10 kb in length and our reported cDNA only accounts for 2.47 kb [8]. Therefore, there are additional UTR exons or sequence that we have not identified in this study. This may not be the case for *TMOD4*, because our reported cDNA in addition to the 93 base pairs from the EO sequence and the additional 9 bp from the 3' end produces a transcript of the same size as the major transcript seen by Northern. However, the larger transcripts (2.4 and 3.0 kb) seen on Northern may contain additional sequence that we were unable to identify in this study, or may represent incompletely spliced transcripts.

EST database searches in conjunction with the *YL-1* genomic structure allowed us to identify three unique intraexonic splicing events. Two of the three events theoretically would produce truncated proteins with little similarity to the normal protein. These splicing events do not use the canonical AG and GT splice sites, nor do they use the rarer GC, AT, or AC splice sites. This may represent yet another form of splicing for the creation of unique transcripts and, or gene regulation.

We also identified two intergenic transcripts between *YL-1* and *TMOD4*, both of which theoretically would code for truncated versions of *YL-1*. Intergenic splicing appears to be a rare event: apparently there have been only six other cases reported in mammals. Fears *et al.* (1996) reported that the *Myelodysplasia syndrome 1 (MDS1)* gene spliced into exon 2 of the adjacent *Ectropic viral integration site 1 (EVI1)* gene, producing a unique transcript containing an ORF that produces a GATA-binding transcriptional activator [30,31]. The human *Galactose-1-phosphate uridylyltransferase (GALT)* gene produces an intergenic transcript by skipping its last exon and splicing into exon 2 of *Interleukin-11 receptor α -chain (IL-11R α)* [32]. This produces an intergenic transcript that keeps the endogenous frame of both genes, thereby coding for a theoretical protein with domains from both proteins. A long terminal repeat from a human endogenous retrovirus (HERV) was shown to drive the expression of an intergenic transcript from an unknown gene named *HERV-HLTR associating 1 (HHLA1)* and human *otoconin-90 (OC90)* to produce a transcript that is highly expressed in teratocarcinoma cells but not in normal human tissues or cell lines [33].

In the mouse, a Prion-like downstream gene named *doppel (Dpl)* was found to have an intergenic transcript that is upregulated in Prion-deficient mice [34]. The deletion of the Prion gene in these mice removes the splice acceptor site of exon 3, causing the normal Prion transcript to skip the deleted exon and inadvertently upregulate the normally low-abundance intergenic transcript by forcing it to splice more often to the *doppel* gene. The human cytochrome P450 2C gene cluster maps to chromosome 10q24 and consists of four genes which are composed of nine exons with conserved exon/intron boundaries, and have been shown to produce intergenic transcripts [35–38]. These transcripts have been identified by RT-PCR for both neighboring genes such as *CYP2C18* and *CYP2C19*, as well as *CYP2C* members separated by another gene, such as *CYP2C18* and *CYP2C8* [37,38]. The latter was shown by RT-PCR to include exons from both genes consisting of nine exons and therefore could code for a chimeric *CYP2C* protein [38]. Recently, the *Translin-associated factor X gene (TRAX)* was demonstrated to intergenically splice into *Disrupted in schizophrenia gene 1 (DISCI)* [39]. Several intergenic transcripts were described, the majority of which contain intervening non-coding exons that contain multiple stop codons.

At least half of the reported cases of intergenic splicing result from skipping the last exon of the upstream gene and the first exon of the downstream gene [32,33,39]. This is thought to be due to the lack of donor and acceptor splice sites in these exons, respectively. For *YL-1* exon 6 there is no GT donor site at the end of the exon, and the EO exon of *TMOD4* contains no AG acceptor. Thus the same pattern seen in the other reported intergenic splicing events is born out in our studies. This idea is supported by the fact that we never identified any part of the EO exon in our RACE products screened using the *YL-1* cDNA. However, we did discover this product when we re-screened our RACE products using a 5' *TMOD4* probe. Of the previously reported cases, the closest distance between adjacent genes is 4 kb [32]. *YL-1* and *TMOD4* are separated by 291 bp. Since this genomic region is so small, it raises the question as to the location of the *TMOD4* promoter. One possibility is that it lies within the 1006 bp between the EO exon and coding exon 1, or even within the 291 bp between the EO exon and *YL-1* exon 6. A more intriguing possibility is that the *TMOD4* promoter lies further upstream, possibly within the intronic structure of *YL-1*, or as a shared promoter with *YL-1*.

Whether these intergenic splice products are biologically relevant is unclear. Due to the fact that the size of the transcripts for *TMOD4* and *YL-1* overlap (1.3 – 1.5 kb), we cannot demonstrate the co-existence of these intergenic variants by Northern blot analysis. The only re-

ported case in which an intergenic transcript has been shown to produce a functional protein *in vivo* is the case of MDS1/EVI1[31]. In all other cases, the intergenic transcript or the theoretical protein produced from such transcripts has been difficult to demonstrate by Northern blot analysis, and none have been shown by Western analysis in normal tissues. However, all of these transcripts have been identified by RT-PCR and some by RNase protection assays. Thus, further analysis will be needed to determine if any of the *YL-1/TMOD4* intergenic transcripts play an important biological role either at the RNA or protein levels.

Conclusion

Through our genomic analysis we were able to determine that *TMOD2* and *4*, like *TMOD1/Tmod1*, share conserved genomic structures consisting of nine coding exons and a single 5' UTR exon (Eo). Using primers flanking the coding exons of *TMOD2* we performed mutational analysis on ALS5 patients. No mutations or polymorphisms were detected, but our primer pairs and reaction conditions may prove useful for future mutational analyses. We determined that *YL-1* comprises six exons, and its last exon lies 291 bp from *TMOD4*. We also identified six ESTs that show nonconventional splicing. Intergenic splice products between *YL-1* and *TMOD4* were identified in the EST database, by 5' RACE, and by RT-PCR. Although we did not determine whether this relationship between *YL-1* and *TMOD4* is conserved in the mouse, it may be an important possibility to consider when devising strategies for targeted deletion not only of *YL-1* or *TMOD4* but any gene pair in which intergenic splicing occurs. This is clearly illustrated by the Prion deficient mice produced by Sakaguchi et. al (1996) and Moore (1997). In these animals exon 3 and its splice acceptor were deleted, causing a rare intergenic transcript between *Prion* and *Doppel* to be highly upregulated and abnormally expressed in the brain, leading to late-onset ataxia and Purkinje cell degeneration[34].

The recent completion of the human genome by Ventner et. al (2001) has led to the new prediction that the human genome contains only ~30,000 genes, significantly lower than previous estimates of ~100,000 genes [40]. This estimate does not, however, include the possibility of additional proteins encoded by alternative or intergenic transcripts. The genomic organization between *YL-1* and *TMOD4* clearly raises the possibility of additional proteins being produced from intergenic transcripts. In addition, it highlights the difficulties that may arise when trying to understand gene regulation for genes that lie extremely close to one another or that form intergenic transcripts. *YL-1*'s intraexonic splicing illustrates yet another level of genomic complexity in that alternative transcripts could be produced from the use of non-ca-

nonical splice sites that lie even within an individual exon. This, in conjunction with intergenic splicing, may significantly increase the number of predicted proteins encoded by the human genome and will certainly pose a challenge for anyone trying to decipher genomic organization and regulation.

Materials and Methods

Genomic organization and sequence analysis of *TMOD2*, *TMOD4*, and *YL-1*

The genomic organization of each gene was determined using two methods. The first involved PCR amplification from either PAC 61J10 (for *TMOD2*) or BAC HB342I3 (for *TMOD4* and *YL-1*) using primers within each exon to amplify the exon and the intervening intron and use it as a substrate for sequencing the exon-intron boundaries. We also digested PAC 61J10 (from the RPCI-1 human PAC library, Roswell Park Cancer Institute) and BAC HB342I3 (from the human CITB BAC library, Research Genetics, Inc.) with RSAI and then subcloned the DNA fragments into pZero 2.0 according to the manufacturer's instructions. We screened colonies by hybridization using the cDNA for each gene as a probe. All labeling reactions for all procedures were performed using the Megaprime DNA labeling system (Amersham Pharmacia Biotech, Piscataway, NJ). Positive colonies were isolated and sequenced using a PRISM BigDye Terminator Cycle sequencing kit and an ABI 3700 automated DNA sequencer (Perkin-Elmer Applied Biosystems, Foster City, CA).

Mutational Analysis of *TMOD2* for ALS5 and *TMOD4* for LGMD1B

The coding exons of *TMOD2* and *TMOD4* were amplified from patient lymphoblast genomic DNA using primers flanking the exon (Table 2). Reaction conditions were as follows for a 50 µl PCR reaction : Perkin-Elmer Cetus PCR buffer; 1.5 mM MgCl₂, 0.25 mM dNTPs, 1.5 µl of each primer (10 µM), 1% DMSO, 5 U of Taq polymerase (Life Technologies). Thermocycler conditions were as follows for a Perkin Elmer 9600 thermocycler: 94°C for 4 min, followed by 35 cycles of 94°C for 30 s, annealing temperature (see Table 2) for 30 s, 72°C for 1 min, and a final extension of 72°C for 10 min. The resulting PCR products were subjected to agarose gel electrophoresis and the DNA was recovered from excised bands using the Qiagen Quick Gel Extraction Kit (CAT# 28706). Each PCR product was then sequenced.

5' and 3' Rapid Amplification of cDNA ends for *TMOD4*

We used Clontech's Human Heart Marathon-Ready cDNA (Cat # 7404-1) to perform 5' and 3' RACE to the *TMOD4* gene. Nested primers were designed within exon 9 and exon 2 of *TMOD4*, TMOD4EX9RACE5'.1 5'TACAGGAAAGGAGGACAGATGAGG3', and TMOD4E

X9RACE5'.2 5'GATTTAAGTGTCCAGTGTCCAG3', and TMOD4EX2RACE5'.1 5'GGGCACCAAGTCATCAC GCTCT3', TMOD4EX2RACE5'.2 5'CCAAGTACTGCAA AAGGGCCTC3', TMOD4EX2RACE3'.1 5'GGACTAAGA CAACGTGACCAGACA3', and TMOD4EX2RACE3'.2 5'GAGGCCCTTTTGCAGTACTTGG3'. The initial RACE reaction to identify intergenic RACE products was performed using the gene specific primer, TMOD4RACE5'.1, and Clontech's AP1 primer in a 50 µl reaction using the Roche High Fidelity Kit (CAT# 1-732-641). Thermocycler conditions for a PE9600 were as follows: 94°C for 5 min, followed by 10 cycles of 94°C for 30 s, 71°C for 30 s, 72°C for 4 min; followed by one cycle of 94°C for 30 s, 68°C for 4 min 20 s, followed by 17 additional cycles each adding 20 s to each extension; final extension at 72°C for 10 min. 5 µl of a 1:50 dilution of the product from the first RACE reaction served as template for the second nested RACE reaction. Reaction and thermocycler conditions were the same as before except gene specific primer 2, TMOD4RACE5'.2, and Clontech's AP2 primer were used. RACE products were then subcloned into pbluescript KS II⁺ using TA vector cloning. Positive products were then identified by colony hybridization using the *YL-1* cDNA as a probe. A secondary screening was then performed using exon 2 primers TMOD4EX2RACE5'.1, followed by a second round of race using TMOD4EX2RACE5'.2. Likewise the 3' RACE was performed using TMOD4EX2RACE3'.1, followed by TMOD4EX2RACE3'.2. RACE products were then subcloned and identified by using either a 5' or 3' probes made from the *TMOD4* cDNA. Positive RACE products were sequenced.

RT-PCR of *YL-1* and Expression Analysis of *YL-1*

For RT-PCR of *YL-1*, we performed the same procedure as described in Cox and Zoghbi (2000). Exceptions were the RNA source, human heart poly (A)⁺ RNA, (Clontech, 6533-1), primers were YL1-35, GTAGGCGGTAT-GAGTTTG, and YL1-1277, AAAACACAACGAAACCTG, respectively, and the annealing temperature was 53°C. The resulting RT-PCR product was subcloned using TA cloning into pbluescript KSII⁺. This product was then sequenced to confirm that it matched the reported cDNA. We examined the expression pattern of *YL-1* using this RT-PCR product as a probe on a Clontech Human multiple tissue Northern blot (CAT# #7760-1).

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References

- Weber A, Pennise CR, Babcock GG, Fowler VM: **Tropomodulin caps the pointed ends of actin filaments.** *J Cell Biol* 1994, **127**:1627-1635
- Sung LA, Fowler VM, Lambert K, Sussman MA, Karr D, Chien S: **Molecular cloning and characterization of human fetal liver tropomodulin. A tropomyosin-binding protein.** *J Biol Chem* 1992, **267**:2616-2621
- Sussman MA, Sakhi S, Barrientos P, Ito M, Kedes L: **Tropomodulin in rat cardiac muscle. Localization of protein is independent of messenger RNA distribution during myofibrillar development.** *Circ Res* 1994, **75**:221-232
- Ito M, Swanson B, Sussman MA, Kedes L, Lyons G: **Cloning of tropomodulin cDNA and localization of gene transcripts during mouse embryogenesis.** *Dev Biol* 1995, **167**:317-328
- Watakabe A, Kobayashi R, Helfman DM: **N-tropomodulin: a novel isoform of tropomodulin identified as the major binding protein to brain tropomyosin.** *J Cell Sci* 1996, **109**:2299-2310
- Sussman MA, Ito M, Daniels MP, Flucher B, Buranen S, Kedes L: **Chicken skeletal muscle tropomodulin: novel localization and characterization.** *Cell Tissue Res* 1996, **285**:287-296
- Almenar-Queralt A, Lee A, Conley CA, Ribas de Pouplana L, Fowler VM: **Identification of a novel tropomodulin isoform, skeletal tropomodulin, that caps actin filament pointed ends in fast skeletal muscle.** *J Biol Chem* 1999, **274**:28466-28475
- Cox PR, Zoghbi HY: **Sequencing, expression analysis, and mapping of three unique human tropomodulin genes and their mouse orthologs.** *Genomics* 2000, **63**:97-107
- Sun HQ, Yamamoto M, Mejillano M, Yin HL: **Gelsolin, a multifunctional actin regulatory protein.** *J Biol Chem* 1999, **274**:33179-33182
- Caldwell JE, Heiss SG, Mermall V, Cooper JA: **Effects of CapZ, an actin capping protein of muscle, on the polymerization of actin.** *Biochemistry* 1989, **28**:8506-8514
- Kuhlman PA, Hughes CA, Bennett V, Fowler VM: **A new function for adducin. Calcium/calmodulin-regulated capping of the barbed ends of actin filaments.** *J Biol Chem* 1996, **271**:7986-7991
- Littlefield R, Fowler VM: **Defining actin filament length in striated muscle: rulers and caps or dynamic stability?** *Annu Rev Cell Dev Biol* 1998, **14**:487-525
- Gregorio CC, Weber A, Bondad M, Pennise CR, Fowler VM: **Requirement of pointed-end capping by tropomodulin to maintain actin filament length in embryonic chick cardiac myocytes.** *Nature* 1995, **377**:83-86
- Sussman MA, Baque S, Uhm CS, Daniels MP, Price RL, Simpson D, Terracio L, Kedes L: **Altered expression of tropomodulin in cardiomyocytes disrupts the sarcomeric structure of myofibrils.** *Circ Res* 1998, **82**:94-105
- Sussman MA, Welch S, Cambon N, Kleivitsky R, Hewett TE, Price R, Witt SA, Kimball TR: **Myofibril degeneration caused by tropomodulin overexpression leads to dilated cardiomyopathy in juvenile mice.** *J Clin Invest* 1998, **101**:51-61
- Thierfelder L, Watkins H, MacRae C, Lamas R, McKenna W, Vosberg HP, Seidman JG, Seidman CE: **Alpha-tropomyosin and cardiac troponin T mutations cause familial hypertrophic cardiomyopathy: a disease of the sarcomere.** *Cell* 1994, **77**:701-712
- Tanigawa G, Jarcho JA, Kass S, Solomon SD, Vosberg HP, Seidman JG, Seidman CE: **A molecular basis for familial hypertrophic cardiomyopathy: an alpha/beta cardiac myosin heavy chain hybrid gene.** *Cell* 1990, **62**:991-998
- Geisterfer-Lowrance AA, Kass S, Tanigawa G, Vosberg HP, McKenna W, Seidman CE, Seidman JG: **A molecular basis for familial hypertrophic cardiomyopathy: a beta cardiac myosin heavy chain gene missense mutation.** *Cell* 1990, **62**:999-1006
- Poetter K, Jiang H, Hassanzadeh S, Master SR, Chang A, Dalakas MC, Rayment I, Sellers JR, Fananapazir L, Epstein ND: **Mutations in either the essential or regulatory light chains of myosin are associated with a rare myopathy in human heart and skeletal muscle.** *Nat Genet* 1996, **13**:63-69
- Muthuchamy M, Pieples K, Rethinasamy P, Hoit B, Grupp IL, Boivin GP, Wolska B, Evans C, Solaro RJ, Wieczorek DF: **Mouse model of a familial hypertrophic cardiomyopathy mutation in alpha-tropomyosin manifests cardiac dysfunction.** *Circ Res* 1999, **85**:47-56
- McKenna WJ: **Hypertrophic cardiomyopathy: an update.** *Cardiology* 1993, **38**:277-281
- Hentati A, Ouahchi K, Pericak-Vance MA, Nijhawan D, Ahmad A, Yang Y, Rimmler J, Hung W, Schlotter B, Ahmed A, Ben Hamida M, Hentati F, Siddique T: **Linkage of a commoner form of recessive amyotrophic lateral sclerosis to chromosome 15q15-q22 markers.** *Neurogenetics* 1998, **2**:55-60

23. van der Kooij AJ, van Meegen M, Ledderhof TM, McNally EM, de Visser M, Bolhuis PA: **Genetic localization of a newly recognized autosomal dominant limb-girdle muscular dystrophy with cardiac involvement (LGMD1B) to chromosome 1q11-21.** *Am J Hum Genet* 1997, **60**:891-895
24. Muchir A, Bonne G, van der Kooij AJ, van Meegen M, Baas F, Bolhuis PA, de Visser M, Schwartz K: **Identification of mutations in the gene encoding lamins A/C in autosomal dominant limb girdle muscular dystrophy with atrioventricular conduction disturbances (LGMD1B).** *Hum Mol Genet* 2000, **9**:1453-1459
25. Horikawa I, Tanaka H, Yuasa Y, Suzuki M, Oshimura M: **Molecular cloning of a novel human cDNA on chromosome 1q21 and its mouse homolog encoding a nuclear protein with DNA-binding ability.** *Biochem Biophys Res Commun* 1995, **208**:999-1007
26. Horikawa I, Tanaka H, Yuasa Y, Suzuki M, Shimizu M, Oshimura M: **Forced expression of YL-1 protein suppresses the anchorage-independent growth of Kirsten sarcoma virus-transformed NIH3T3 cells.** *Exp Cell Res* 1995, **220**:111-117
27. Chu X, Thompson D, Yee LJ, Sung LA: **Genomic organization of mouse and human erythrocyte tropomodulin genes encoding the pointed end capping protein for the actin filaments.** *Gene* 2000, **256**:271-281
28. Mount SM: **Genomic sequence, splicing, and gene annotation.** *Am J Hum Genet* 2000, **67**:788-792
29. Burset M, Seledtsov LA, Solovvey VV: **Analysis of canonical and non-canonical splice sites in mammalian genomes.** *Nucleic Acids Res* 2000, **28**:4364-4375
30. Fears S, Mathieu C, Zeleznik-Le N, Huang S, Rowley JD, Nucifora G: **Intergenic splicing of MDS1 and EVII occurs in normal tissues as well as in myeloid leukemia and produces a new member of the PR domain family.** *Proc Natl Acad Sci USA* 1996, **93**:1642-1647
31. Soderholm J, Kobayashi H, Mathieu C, Rowley JD, Nucifora G: **The leukemia-associated gene MDS1/EVII is a new type of GATA-binding transactivator.** *Leukemia* 1997, **11**:352-358
32. Magrangeas F, Pitiot G, Dubois S, Bragado-Nilsson E, Chereh M, Jobert S, Lebeau B, Boisteau O, Lethe B, Mallet J, Jacques Y, Minvielle S: **Cotranscription and intergenic splicing of human galactose-1-phosphate uridylyltransferase and interleukin-11 receptor alpha-chain genes generate a fusion mRNA in normal cells. Implication for the production of multidomain proteins during evolution.** *J Biol Chem* 1998, **273**:16005-16010
33. Kowalski PE, Freeman JD, Mager DL: **Intergenic splicing between a HERV-H endogenous retrovirus and two adjacent human genes.** *Genomics* 1999, **57**:371-379
34. Moore RC, Lee IY, Silverman GL, Harrison PM, Strome R, Heinrich C, Karunaratne A, Pasternak SH, Chishti MA, Liang Y, Mastrangelo P, Wang K, Smit AF, Katamine S, Carlson GA, Cohen FE, Prusiner SB, Melton DW, Tremblay P, Hood LE, Westaway D: **Ataxia in prion protein (PrP)-deficient mice is associated with upregulation of the novel PrP-like protein doppel.** *J Mol Biol* 1999, **292**:797-817
35. Gray IC, Nobile C, Muresu R, Ford S, Spurr NK: **A 2.4-megabase physical map spanning the CYP2C gene cluster on chromosome 10q24.** *Genomics* 1995, **28**:328-332
36. Romkes M, Faletto MB, Blaisdell JA, Raucy JL, Goldstein JA: **Cloning and expression of complementary DNAs for multiple members of the human cytochrome P45011C subfamily [published erratum appears in Biochemistry 1993 Feb 9;32(5):1390].** *Biochemistry* 1991, **30**:3247-3255
37. Zaphiropoulos PG: **RNA molecules containing exons originating from different members of the cytochrome P450 2C gene subfamily (CYP2C) in human epidermis and liver.** *Nucleic Acids Res* 1999, **27**:2585-2590
38. Finta C, Zaphiropoulos PG: **The human CYP2C locus: a prototype for intergenic and exon repetition splicing events.** *Genomics* 2000, **63**:433-438
39. Millar JK, Christie S, Semple CA, Porteous DJ: **Chromosomal location and genomic structure of the human translin-associated factor X gene (TRAX; TSNAX) revealed by intergenic splicing to DISC1, a gene disrupted by a translocation segregating with schizophrenia [In Process Citation].** *Genomics* 2000, **67**:69-77
40. Venter JC, Adams MD, Myers EW, Li PW, Mural RJ, Sutton GG, Smith HO, Yandell M, Evans CA, Holt RA, Gocayne JD, Amanatides P, Ballew RM, Huson DH, Wortman JR, Zhang Q, Kodira CD, Zheng XH, Chen L, Skupski M, Subramanian G, Thomas PD, Zhang J, Gabor Miklos GL, Nelson C, Broder S, dark AG, Nadeau J, McKusick VA, Zinder N, Levine AJ, Roberts RJ, Simon M, Slayman C, Hunkapiller M, Bolanos R, Delcher A, Dew I, Fasulo D, Flanigan M, Florea L, Halpern A, Hannenhall S, Kravitz S, Levy S, Mobarry C, Reinert K, Remington K, Abu-Threideh J, Beasley E, Biddick K, Bonazzi V, Brandon R, Cargill M, Chandramouliswaran I, Charlab R, Chaturvedi K, Deng Z, Francesco VD, Dunn P, Eilbeck K, Evangelista C, Gabrielian AE, Gan W, Ge W, Gong F, Gu Z, Guan P, Heiman TJ, Higgins ME, Ji RR, Ke Z, Ketchum KA, Lai Z, Lei Y, Li Z, Li J, Liang Y, Lin X, Lu F, Merkulov GV, Milshina N, Moore HM, Naik AK, Narayan VA, Neelam B, Nusskern D, Rusch DB, Salzberg S, Shao W, Shue B, Sun J, Wang ZY, Wang A, Wang X, Wang J, Wei MH, Wides R, Xiao C, Yan C, et al: **The Sequence of the Human Genome.** *Science* 2001, **291**:1304-1351
41. Conley CA, Fritz-Six KL, Almenar-Queralt A, Fowler VM: **Leiomodins: larger members of the tropomodulin (Tmod) gene family.** *Genomics* 2001, **73**:127-39
42. Littlefield R, Almenar-Queralt A, Fowler VM: **Actin dynamics at pointed ends regulates thin filament length in striated muscle.** *Nat Cell Biol* 2001, **6**:544-51

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