

Sarcospan, the 25-kDa Transmembrane Component of the Dystrophin-Glycoprotein Complex*

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The dystrophin-glycoprotein complex is a multisubunit protein complex that spans the sarcolemma and forms a link between the subsarcolemmal cytoskeleton and the extracellular matrix. Primary mutations in the genes encoding the proteins of this complex are associated with several forms of muscular dystrophy. Here we report the cloning and characterization of sarcospan, a unique 25-kDa member of this complex. Topology algorithms predict that sarcospan contains four transmembrane spanning helices with both N- and C-terminal domains located intracellularly. Phylogenetic analysis reveals that sarcospan's arrangement in the membrane as well as its primary sequence are similar to that of the tetraspan superfamily of proteins. Sarcospan co-localizes and co-purifies with the dystrophin-glycoprotein complex, demonstrating that it is an integral component of the complex. We also show that sarcospan expression is dramatically reduced in muscle from patients with Duchenne muscular dystrophy. This suggests that localization of sarcospan to the membrane is dependent on proper dystrophin expression. The gene encoding sarcospan maps to human chromosome 12p11.2, which falls within the genetic locus for congenital fibrosis of the extraocular muscle, an autosomal dominant muscular dystrophy.

In skeletal muscle fibers, the dystrophin-glycoprotein com-

plex (DGC)¹ (1–5) is located at the sarcolemma and is composed of both peripheral and integral membrane proteins. Collectively, these proteins provide a physical connection between the extracellular matrix and the intracellular cytoskeleton of muscle cells. Disruption of this linkage eventually progresses to muscle cell necrosis, as evidenced by the dystrophic muscle phenotypes that result from defects in several of the DGC components (for review, see Refs. 6 and 7). Although the DGC is known to be essential for normal muscle function, the precise role of this multi-protein complex remains to be determined.

Purification of the DGC has led to the identification of many of its constituent polypeptides, which range in size from 25 kDa to over 400 kDa and include glycosylated as well as non-glycosylated proteins (1–4). Characterization of these proteins has increased our understanding of how the DGC is oriented in the sarcolemma and has provided clues to its function. In addition to dystrophin, the DGC consists of α/β -dystroglycan, the sarco-glycans (α , β , γ , and δ subunits), and the syntrophins. While most of the “dystrophin-associated proteins” (DAPs) have been identified, one of them, a 25-kDa protein (also called A5) (1, 3–5), has remained an enigma.

In the present work, we have determined the amino acid sequence of two peptides derived from 25DAP and have isolated the corresponding human cDNA. Previous analysis of the 25DAP indicated that it is an integral membrane protein, since it reacts strongly with a probe for protein hydrophobicity (4). We now report that 25DAP is a novel component of the DGC and is predicted to span the sarcolemma four times. This is unusual for integral membrane proteins of the DGC, which possess only a single transmembrane span. We have renamed 25DAP “sarcospan” in reference to its multiple sarcolemma-spanning domains. The predicted topology of sarcospan is similar to that of the tetraspan superfamily of proteins (8, 9), in which all members have four transmembrane domains and a large extracellular loop.

EXPERIMENTAL PROCEDURES

DGC Purification and Protein Sequencing—The DGC was extracted from rabbit skeletal muscle membranes (10) and then purified by sWGA affinity chromatography followed by ion exchange on a DEAE-column, as described previously (1, 2, 5). Purified DGC was electrophoresed on 3–15% gradient gels (0.7 mm thick) and stained with Coomassie Brilliant Blue as described by Ervasti *et al.* (5). The 25-kDa band was cut from the gel and sent to the Biopolymers Laboratory at the Massachusetts Institute of Technology for in-gel Lys-C digestion (11) and peptide microsequence analysis (12).

cDNA Isolation and Sequencing—Sarcospan cDNA clones were isolated by hybridization screening of a CLONTECH human adult skeletal muscle cDNA library (HL5002a) with a PCR-derived sarcospan cDNA probe encoding exons 1 to 3. The exon structure of the cDNA clones was confirmed by PCR, and the 5' sequence was determined by direct analysis of biotinylated PCR products, as described previously (13). Sequencing analysis of the clones was performed using dye terminator cycling and analyzed on a 373A Stretch Fluorescent Automated sequencer (Applied Biosystems). The 5' end of rabbit sarcospan was sequenced from a CLONTECH rabbit skeletal muscle cDNA library, as described for the human clone.

Computational Analysis—Multiple sequence alignment of sarcospan

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The nucleotide sequence(s) reported in this paper has been submitted to the GenBank™/EBI Data Bank with accession number(s) AF016028.

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¹ The abbreviations used are: DGC, dystrophin-glycoprotein complex; CFEOM, congenital fibrosis of the extraocular muscle; DAP, dystrophin-associated protein; DMD, Duchenne muscular dystrophy; KRAG, Kirsten ras associated gene; Spn1, sarcospan-1; Spn2, sarcospan-2; PCR, polymerase chain reaction; PAGE, polyacrylamide gel electrophoresis; kb, kilobase(s).

and the tetraspanins was accomplished as before (9) with the GCG Wisconsin Sequence Analysis software programs. Predictions of transmembrane regions and orientations were made with the TMpred program.² This algorithm is based on the statistical analysis of Tmbase, a data base of naturally occurring transmembrane proteins (14).

Northern Blotting—Adult human multiple tissue Northern blots (CLONTECH) containing 2 µg of poly(A⁺) RNA per lane were probed with PCR-amplified probes representing the full-length cDNA (exons 1 to 3) of sarcospan (13).

Sarcospan Antibody—The strategy for generating polyclonal antibodies has been described previously (15). For generating sarcospan antibodies, we injected two New Zealand White rabbits (rabbits 216 and 217; Knapp Creek Farms) at intramuscular and subcutaneous sites with 500 µg of an N-terminal sarcospan-2 synthetic peptide, CAADRQPRGQQRQGDAAAGPD (Research Genetics), coupled to key-hole limpet hemocyanin in an emulsion of Freund's complete adjuvant (Sigma). The amino acids Cys-Ala-Ala were added to the peptide for coupling purposes. Affinity purification of sarcospan antibodies was accomplished using Immobilon-P (Millipore) strips containing the N-terminal peptide coupled to bovine serum albumin (15). This antibody did not react with mouse tissue.

Immunofluorescence—Immunofluorescence on muscle biopsies from control and several DMD patients was accomplished as described (15) except that muscle sections were incubated with affinity-purified rabbit 216 sarcospan antibody (1:10) at room temperature for 12 h. The sections were observed under a Bio-Rad MRC-600 laser scanning confocal microscope, and the digitized images were captured under identical conditions.

Sucrose Gradient Centrifugation—DGC fractions from the DEAE-column were pooled and concentrated to 800 µl. The samples were separated by centrifugation through a 5–30% sucrose gradient (2, 5). The gradients were fractionated into 1-ml fractions, and 80 µl of each fraction was resolved by 3–15% SDS-PAGE and either stained with silver or transferred to nitrocellulose. Immunoblot staining with antibodies to DGC (goat 20, 1:500) and sarcospan (rabbit 216 and 217, 1:20) was performed as described previously (15).

RESULTS AND DISCUSSION

To determine the identity of the 25DAP (1–3) (also called A5 (3)), proteins of the DGC were purified from rabbit skeletal muscle and separated using preparative SDS-PAGE. Peptide fragments of the 25DAP were obtained by Lys-C digestion. Microsequencing of the resultant peptides gave the following sequences: peptide I, KHRYQVFYVGV; peptide II, KDRQPRGQQRQGDAAAGPDDPG.

The amino acid sequences of these two peptides were used to search the GenBankTM data base with the tBLASTn program (16). This analysis revealed a homology between peptide I and Kirsten ras-associated gene (KRAG) from human and mouse (accession numbers X89105 and U02487, respectively). Murine KRAG was first identified based on coamplification of its transcript with Kirsten ras in Y1 adrenal carcinoma cells (17). Similarly, the human KRAG gene was also identified through analysis of transcripts co-amplified with KRAS2 in lung and ovarian carcinoma cells (13). Although peptide II was not found in GenBankTM, TIGR, or dbEST data bases, sequencing of additional KRAG clones from a human skeletal muscle cDNA library identified at least four cDNAs that do encode peptide II. Translation of these cDNAs predicts a protein identical to the KRAG sequence deposited in GenBankTM including an additional 26 residues at the N terminus (Fig. 1, A and B). This 26-amino acid extension includes a perfect match with 17 out of 21 amino acids found in peptide II isolated from rabbit (see above). We suspect that the amino acid differences between the rabbit peptide and the human cDNA are due to species variation. As verification of this, partial sequencing of the 5' sarcospan cDNA from rabbit skeletal muscle was performed. Translation of this region demonstrates an exact match between the amino acids deduced by the rabbit cDNA (KDRQPRGQQRQ-

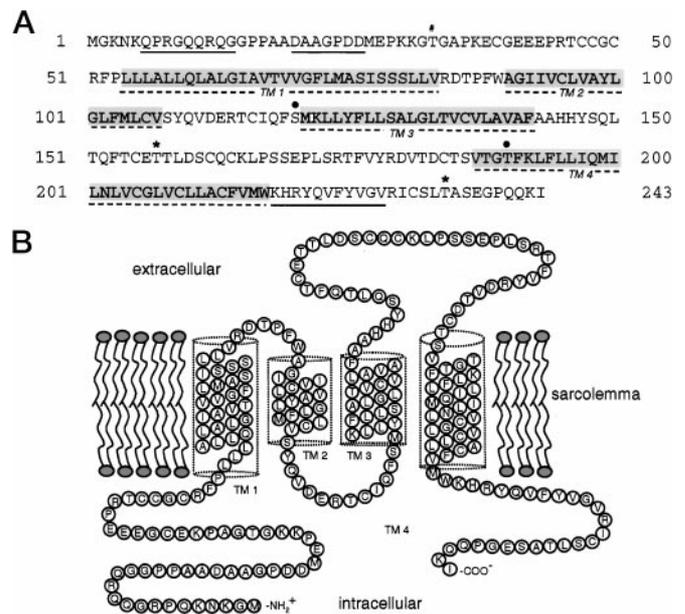


FIG. 1. Primary structure and predicted membrane topology of sarcospan. A, the deduced amino acid sequence of human sarcospan is shown in single-letter code. Homology between the human sarcospan sequence and the Lys-C-digested fragments of rabbit sarcospan are shown (underlined). Predicted transmembrane domains are shaded with gray boxes. Consensus phosphorylation sites for cAMP-dependent protein kinase (#), protein kinase C (●), and casein kinase II (*) are indicated. B, schematic representation of membrane topology of sarcospan. Predictions of the topology and transmembrane helix orientation were made with the program TMpred (14).

DAAGPDDPG) and the amino acid sequence of peptide II (shown above). Furthermore, we confirmed sarcospan expression in rabbit skeletal and cardiac muscle by Northern analysis with a full-length cDNA probe (data not shown).

The primary amino acid sequence deduced from the human cDNA predicts a protein with four transmembrane spanning domains and a topology similar to that of the tetraspan proteins (Fig. 1B). Based on the predicted membrane topology of the human protein and its residence in the sarcolemma, we have named this protein sarcospan. The tetraspans, also referred to as the transmembrane 4 superfamily (TM4SF) and the tetraspanins, have four transmembrane spanning helices that are conserved among family members (8, 9). Although there is no clear function for the TM4SF members, many of them are associated with integrins and have been implicated in the regulation of cell proliferation (9). Using phylogenetic analysis, we find that sarcospan is more closely related to the divergent family members Rom-1, peripherin, and uroplakin (data not shown). We refer to the two cloned cDNAs as sarcospan-1 (*spn1*; GenBankTM accession number X89105) and sarcospan-2 (*spn2*; GenBankTM accession number AF016028), where *Spn2* includes 26 amino acids at its N terminus. In light of the identification of sarcospan, we have redesignated KRAG (13) as the *spn1* gene.

To examine the tissue distribution of sarcospan, we performed RNA hybridization analysis. We probed human multiple tissue Northern blots with a full-length *spn1* cDNA probe. As shown in Fig. 2, a 6.5-kb transcript is present exclusively in skeletal and cardiac muscles. However, a 4.5-kb transcript is also found in skeletal and cardiac muscle, as well as in thymus, prostate, testis, ovary, small intestine, colon, and spleen. Our data suggest the presence of tissue-specific sarcospan transcripts. The expression of sarcospan in a broad array of tissues is most similar to that of dystroglycan (18, 19), suggesting that these proteins play important roles in muscle as well as non-muscle tissues.

² This program is available on the Internet (http://ulrec3.unil.ch/software/TMPRED_form.html).

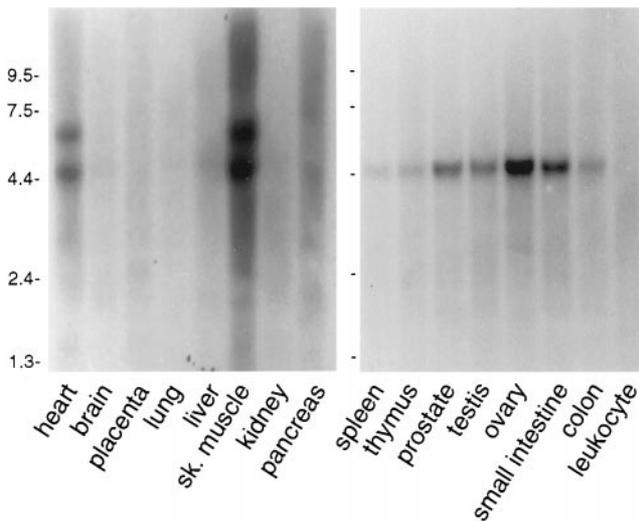


FIG. 2. **Expression of sarcospan in human tissues.** Northern blots containing 2 μ g of poly(A⁺) RNA from the indicated human tissues were hybridized with a sarcospan-1 cDNA probe. Equal RNA loading was confirmed by hybridizing blots with an actin probe (not shown). Molecular size markers are indicated on the left (kb).

We confirmed that the 25-kDa Coomassie-stained band in the DGC was sarcospan by staining immunoblots containing purified DGC with sarcospan antibodies. Although a 25-kDa band is present in purified DGC from rabbit skeletal muscle, it does not elicit an antibody response when DGC preparations were used to immunize either sheep or goat (Fig. 3A). Thus, we generated a polyclonal antibody to sarcospan by immunizing rabbits with peptide II. This affinity-purified antibody specifically stains a 25-kDa band on immunoblots of purified DGC from rabbit skeletal muscle membranes (Fig. 3A).

As a first demonstration that sarcospan is an integral component of the DGC, we show that sarcospan enriches in purification of the complex. Immunoblots of purified DGC stained with DGC antibodies show a clear enrichment of these purified proteins relative to the levels in rabbit skeletal muscle membranes (Fig. 3A). Identical immunoblots illustrate that sarcospan also enriches in DGC prepared from rabbit membranes (Fig. 3A).

As another test for association between sarcospan and the DGC, we examined sarcospan expression in muscle from DMD patients. We examined several DMD patients with primary mutations in dystrophin, resulting in loss of the entire dystrophin protein. Indirect immunofluorescence assays with antibodies against dystrophin's N and C termini and the central rod domain verify that dystrophin is completely absent from the DMD sarcolemma (data not shown). Without dystrophin, the other members of the complex are reduced, perhaps the result of premature protein degradation, improper assembly of the complex, or aberrant transportation to the sarcolemma. We show that sarcospan is present at the sarcolemma in normal muscle and is dramatically reduced in DMD muscle (Fig. 3B). The reduced staining of sarcospan in DMD muscle provides further evidence that this protein is complexed with the DGC.

The tight association of sarcospan with the DGC is illustrated by centrifugation of the DGC through sucrose gradients. Sucrose gradient sedimentation separates the DGC from any proteins which might bind with low affinity to the complex. Proteins from the sucrose gradient fractions were separated by SDS-PAGE. The resultant polyacrylamide gels were stained with silver to better visualize sarcospan (Fig. 4), which stains weakly with Coomassie Brilliant Blue (Fig. 3A). Immunoblotting with sarcospan antibodies confirms that the intensely silver-stained band at 25 kDa is sarcospan. The peak of DGC

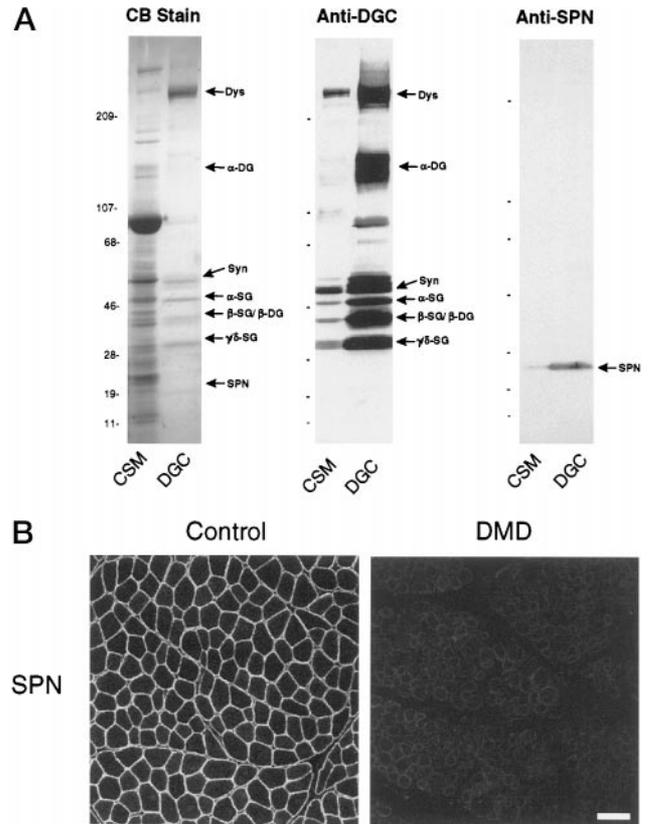


FIG. 3. **Association of sarcospan with the dystrophin-glycoprotein complex.** A, enrichment of sarcospan with the DGC. 50 μ g of crude surface membranes (lane 1) and 80 μ l of purified DGC (lane 2) were electrophoretically separated on 3–15% SDS-polyacrylamide gels and transferred to nitrocellulose. An SDS-polyacrylamide gel stained with Coomassie Brilliant Blue is shown in the left panel. Nitrocellulose transfers were separately stained with antibodies against DGC (middle panel) or affinity-purified rabbit polyclonal antibodies against sarcospan (right panel). *Dys*, dystrophin; α -, β -DG, α/β -dystroglycan, respectively; α -, β -, γ -, and δ -SG, α -, β -, γ -, and δ -sarcoglycans, respectively; *Syn*, syntrophins; and *SPN*, sarcospan. Molecular size standards are indicated on the left of each blot ($\times 10^3$ Da). B, immunohistochemical analysis of sarcospan in normal human control (Control) and DMD (DMD) skeletal muscle. Transverse cryosections were labeled by indirect immunofluorescence with antibodies against dystrophin, sarcospan, and laminin-2. Absence of dystrophin in the DMD patient was confirmed with three separate dystrophin antibodies (not shown). Laminin-2 staining was positive on both control and DMD muscle (not shown). Bar, 100 μ m.

proteins migrates in fractions 9 and 10 as seen by the silver-stained gels and Western blotting of these same fractions with anti-DGC antibodies (Fig. 4). Sarcospan migrates in the same fractions as the DGC during sedimentation through sucrose gradients, confirming that sarcospan is an integral member of this complex (Fig. 4).

The structural connection between the extracellular matrix and the intracellular actin network is dependent on the integrity of the DGC. Disruption of this linkage eventually progresses to muscle cell necrosis, as evidenced by the dystrophic phenotype that results from defects in several of the DGC components, including the dystrophin and the sarcoglycans (for review, see Refs. 6 and 7). Mutations in sarcospan would feasibly also give rise to a dystrophic phenotype. The gene encoding sarcospan maps to human chromosome 12p11.2 (13). Congenital fibrosis of the extraocular muscle (CFEOM) is an autosomal dominant disorder which primarily affects the ocular muscles, rendering patients with little or no eye movement. Linkage analysis of two large unrelated families with CFEOM indicate that this disease locus lies within 12p11.2-q12 (20, 21).

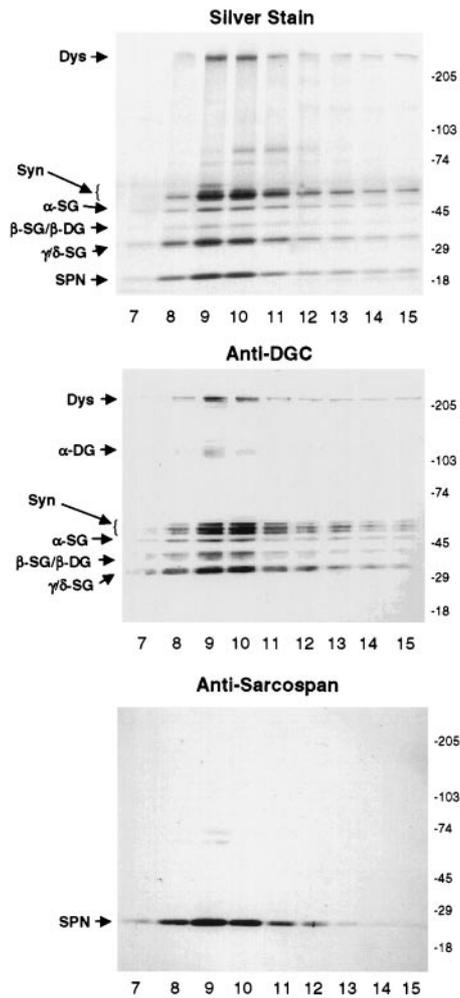


FIG. 4. Isolation of the DGC by sedimentation through linear sucrose gradients. DGC purified from rabbit skeletal muscle membranes was centrifuged through sucrose gradients. DGC proteins in fractions 7 to 15 from the sucrose gradient were electrophoresed on 3–15% SDS-polyacrylamide gels and stained with silver. Nitrocellulose transfers of identical samples were stained with DGC and sarcospan antibodies. Molecular size standards are indicated on the right of each panel ($\times 10^3$ Da).

We propose that sarcospan is a prime candidate gene for this disease.

Sarcospan is the first identified member of the DGC that spans the membrane more than once. In fact, over 60% of sarcospan's amino acids are predicted to be within the membrane and this unique characteristic may be providing clues to sarcospan's function. For instance, sarcospan's transmembrane

domains are expected to hold this protein firmly within the lipid bilayer, in which case it could provide a solid anchorage for the rest of the DGC. Additionally, the multiple transmembrane regions of sarcospan might form a pore in the sarcolemma and thereby serve as a membrane channel. The latter scenario is particularly attractive in light of the emerging concept that the DGC performs functional as well as structural roles in muscle. The charged residues in sarcospan's transmembrane domains may be important for protein-protein interactions, perhaps with integrins or other DGC components. Finally, the observation that sarcospan expression is amplified in some human tumors, in combination with the proposal that tetraspan proteins play a role in cell growth, supports the idea that sarcospan itself has essential functions that extend beyond its role in muscle.

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