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Sarco(endo)plasmic Reticulum Calcium ATPase (SERCA) Inhibition by Sarcolipin Is Encoded in Its Luminal Tail*

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Background: Sarcolipin is a regulator of SERCA in skeletal and atrial muscle with inhibitory properties thought to be similar to phospholamban.

Results: Residues critical for SERCA inhibition reside in the luminal extension of sarcolipin.

Conclusion: The luminal extension of sarcolipin is a distinct and transferrable domain that encodes most of its inhibitory properties.

Significance: Sarcolipin and phospholamban use different inhibitory mechanisms to regulate SERCA.

The sarco(endo)plasmic reticulum calcium ATPase (SERCA) is regulated in a tissue-dependent manner via interaction with the short integral membrane proteins phospholamban (PLN) and sarcolipin (SLN). Although defects in SERCA activity are known to cause heart failure, the regulatory mechanisms imposed by PLN and SLN could have clinical implications for both heart and skeletal muscle diseases. PLN and SLN have significant sequence homology in their transmembrane regions, suggesting a similar mode of binding to SERCA. However, unlike PLN, SLN has a conserved C-terminal luminal tail composed of five amino acids (RSYQY), which may contribute to a distinct SERCA regulatory mechanism. We have functionally characterized alanine mutants of the C-terminal tail of SLN using co-reconstituted proteoliposomes of SERCA and SLN. We found that Arg27 and Tyr31 are essential for SLN function. We also tested the effect of a truncated variant of SLN (Arg27stop) and extended chimeras of PLN with the five luminal residues of SLN added to its C terminus. The Arg27stop form of SLN resulted in loss of function, whereas the PLN chimeras resulted in superinhibition with characteristics of both PLN and SLN. Based on our results, we propose that the C-terminal tail of SLN is a distinct, essential domain in the regulation of SERCA and that the functional properties of the SLN tail can be transferred to PLN.

Sarcolipin (SLN)3 was first described as a low molecular weight protein that co-purified with preparations of SERCA, and it was later named to reflect its origin as a proteolipid of the sarcomplasmic reticulum (SR) (1). SLN is the predominant regulator of SERCA and calcium homeostasis in fast twitch skeletal muscle where it may play an additional role in thermogenesis (2). However, SLN is also expressed with phospholamban (PLN) in the atria of the heart (3–6), which raises the possibility of an atrium-specific ternary complex that could lead to superinhibition of SERCA (7). SLN is a 31-residue type I integral membrane protein with a transmembrane domain and short cytoplasmic and luminal domains (1). PLN is a 52-residue type I integral membrane protein with a transmembrane domain and a longer cytoplasmic domain but no luminal domain (8). Given the homology between the transmembrane domains of these proteins, it was hypothesized that SLN binds to SERCA and alters the apparent calcium affinity of the enzyme in a manner similar to PLN (9). Inhibition would result from SLN and/or PLN binding to SERCA and stabilizing an E2 calcium-free state (10). Mixed evidence exists on whether these regulatory sub-units dissociate (11) or remain bound to SERCA (12–14) during calcium transport.

Historically, SLN inhibition of SERCA has been less well characterized than PLN in part because of the assumption that SLN uses the same mechanism as PLN to inhibit SERCA. For PLN, SERCA inhibition is encoded by the transmembrane domain (15, 16), whereas reversal of inhibition via phosphorylation is enabled by the cytoplasmic domain (8). For SLN, the transmembrane domain contains residues involved in inhibitory function (9), the cytoplasmic domain contains a phosphorylation site (17), and the luminal domain is important for SR retention (18) and SERCA inhibition (19). However, there are important differences in the way that SLN inhibits SERCA. For example, some studies have found that SLN decreases the maximal activity (Vmax) of SERCA at saturating calcium concentrations, indicating that SLN inhibition is not reversed by calcium (19–21). In addition, two kinases have been reported to target SLN (17, 22), although it is not firmly established whether phosphorylation of SLN is an important physiological mechanism. Finally, it is well documented that the inhibitory PLN monomer can self-associate to form pentamers. In contrast, SLN is thought to exist primarily as a monomer, although evidence

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‡ A senior scholar of Alberta Innovates Health Solutions. To whom correspondence should be addressed: Dept. of Biochemistry, Medical Sciences Bldg., Rm. 327, University of Alberta, Edmonton, Alberta T6G 2H7, Canada. Tel.: 780-492-3931; Fax: 780-492-0886; E-mail: hyoung@ualberta.ca.
§1 Supported by doctoral awards from the Canadian Institutes of Health Research and Alberta Innovates Technology Futures.
¶ The abbreviations used are: SLN, sarcolipin; SERCA, sarco(endo)plasmic reticulum calcium ATPase; PLN, phospholamban; SR, sarcomplasmic reticulum; Km, calcium concentration at half-maximal activity; nH, Hill coefficient; Vmax, maximal activity.
suggests that SLN can also oligomerize in detergent and membrane environments (23, 24).

The modeled site of interaction between SLN and the calcium-free state of SERCA was the same binding groove identified for PLN (M2, M4, M6, and M9). This was based on mutagenesis of both SERCA and SLN combined with functional measurements (9) and co-immunoprecipitation studies (7). Alanine-scanning mutagenesis of SLN revealed similarities and differences when compared with PLN. In general, mutagenesis of SLN had lesser effects on function and did not recapitulate the gain of function behavior associated with residues that destabilize the PLN pentamer. Nonetheless, key residues in both proteins were found to be important for physical association and function. Notably, mutation of Leu8 and Asn11 in SLN resulted in the expected loss of function seen for the comparable Leu31 and Asn34 of PLN, and mutation of the predicted phosphorylation site to glutamate (Thr5 to Glu) appeared to mimic phosphorylation and result in loss of function (17). Although the remaining sampled residues were neutral or loss of function, there are mixed observations on the functional importance of the unique luminal tail of SLN (Fig. 1) (9, 18, 19). The C-terminal sequences of PLN and SLN represent a marked difference between these two proteins where the hydrophobic Met50-Leu-Leu52 in PLN is replaced by the more polar Arg27-Ser-Tyr-Gln-Tyr31 in SLN. Importantly, this latter sequence is perfectly conserved among mammals (18).

Given the highly conserved nature of the SLN luminal tail and our incomplete understanding of its role in SERCA inhibition, we chose to investigate this domain by the co-reconstitution of SLN mutants with SERCA into proteoliposomes. Another motivating factor for this study was the observation that PLN and SLN can simultaneously bind to and regulate SERCA (7). Although superinhibition is thought to result from the tight fit of both PLN and SLN in the SERCA binding groove (M2, M4, M6, and M9), we hypothesized that the luminal domain of SLN may contribute to the strong inhibitory properties of the ternary complex. This prompted us to investigate chimeric PLN-SLN constructs. Herein, we provide new insights into the regulation of SERCA by the C-terminal domain of SLN. Alanine-scanning mutagenesis of this domain revealed at least partial loss of function associated with all residues (Arg27-Ser-Tyr-Gln-Tyr31), and the removal of the luminal tail in an Arg27-stop construct also resulted in loss of function. Chimeric PLN variants possessing the luminal tail of SLN caused superinhibition of SERCA reminiscent of studies of the PLN-SLN-SERCA ternary complex (7). Finally, transferring the SLN luminal tail onto a generic transmembrane helix resulted in a chimera that completely mimicked SERCA inhibition by wild-type SLN. We conclude that the highly conserved C-terminal tail of SLN is a primary determinant for SERCA inhibition and that it is a distinct and transferrable functional domain.

**EXPERIMENTAL PROCEDURES**

**Expression and Purification of Recombinant SLN**—Recombinant SLN and PLN chimeras were expressed and purified as described previously (25) with the exception of an additional organic extraction step for SLN purification. Briefly, following protease digestion of the maltose-binding protein and SLN fusion protein, trichloroacetic acid was added to a final concentration of 6%. This mixture was incubated on ice for 20 min. The precipitate was collected by centrifugation at 4 °C and subsequently homogenized in a mixture of chloroform:isopropanol-water (4:4:1) and incubated at room temperature for 3 h. The precipitate was collected by centrifugation at 4 °C and subsequently homogenized in a mixture of chloroform:isopropanol-water (4:4:1) and incubated at room temperature for 3 h. The precipitate was collected by centrifugation at 4 °C and subsequently homogenized in a mixture of chloroform:isopropanol-water (4:4:1) and incubated at room temperature for 3 h.

**FIGURE 1.** Sequence alignments for primary structures of SLN and PLN from representative species. The cytoplasmic, transmembrane, and luminal domains are indicated. Sequence variations in the luminal domains, as compared to human sequences, are indicated in bold. Consensus sequences for SLN and PLN were generated based on all known sequences (ClustalW).
Luminal Domain of Sarcolipin and SERCA Regulation

Synthetic Peptide Handling—Synthetic peptides (Arg27 stop, Leu9, Leu9 tail, and 27RSYQY) were purchased from Biomatik (Wilmington, DE; 95% purity grade, HPLC- and MS-verified). Unless otherwise specified, all synthetic peptides were acetylated at the N terminus and amidated at the C terminus. Except for 27RSYQY, which was solubilized in distilled H2O, all peptides were solubilized in 3:1 chloroform:trifluoroethanol at a concentration of ~1 mg/ml. The peptide concentrations were verified by quantitative amino acid analysis.

Co-reconstitution of SERCA and Recombinant SLN—Routine procedures were used to purify SERCA1a from rabbit skeletal muscle SR vesicles and functionally reconstitute it into proteoliposomes with SLN. SERCA, SLN, egg yolk phosphatidylcholine, and egg yolk phosphatidic acid were solubilized with octaethylene glycol monododecyl ether (C12E10) to achieve final molar stoichiometries of 1 SERCA, 6 SLN, and 195 lipids. The co-reconstituted proteoliposomes containing SERCA and SLN were formed by the slow removal of detergent (with SM-2 Biobeads, Bio-Rad) followed by purification on a sucrose step gradient. The purified co-reconstituted proteoliposomes typically yield final molar stoichiometries of 1 SERCA, 4.5 SLN, and 120 lipids. This same procedure was used for the co-reconstitution of SERCA with PLN chimeras and synthetic transmembrane peptides. For the co-reconstitution of SERCA in the presence of 27RSYQY peptide, the peptide in aqueous solution was added to the reconstitution mixture at a molar ratio of 1 SERCA to 100 27RSYQY followed by detergent removal with SM-2 Biobeads to ensure incorporation of 27RSYQY inside the proteoliposomes.

Activity Assays—Calcium-dependent ATPase activities of the co-reconstituted proteoliposomes were measured by a coupled enzyme assay (26). The coupled enzyme assay reagents were of the highest purity available (Sigma-Aldrich). All co-reconstituted proteoliposome constructs were compared with a negative control (SERCA reconstituted in the absence of SLN) and a matched positive control (SERCA co-reconstituted in the presence of either wild-type SLN, wild-type PLN, or Leu9 peptide). A minimum of three independent reconstitutions and activity assays were performed for each peptide, and the calcium-dependent ATPase activity was measured over a range of calcium concentrations (0.1–10 μM) for each assay. This method has been described in detail (27). The calcium concentration at half-maximal activity (KCa), Vmax, and Hill coefficient (nH) were calculated based on nonlinear least square fitting of the activity data to the Hill equation using Sigma Plot software (SPSS Inc., Chicago, IL). Errors were calculated as the S.E. for a minimum of three independent measurements. Comparison of KCa, Vmax, and nH parameters was carried out using between-subjects one-way analysis of variance followed by the Holm-Sidak test for pairwise comparisons (Sigma Plot).

Throughout “Results” and “Discussion,” we refer to SLN and PLN inhibition of SERCA. Inhibition is intended to reflect the effects that SLN and PLN have on the apparent calcium affinity of SERCA. The effects that SLN and PLN have on the maximal activity of SERCA are considered separately.

Kinetic Simulations—Reaction rate simulations have been described (28, 29) for the transport cycle of SERCA in the absence and presence of PLN inhibition, and we have adopted this approach to understand SERCA inhibition by wild-type SLN. As before, we performed a global nonlinear regression fit of the model of Cantilina et al. (28) to each plot of SERCA ATPase activity versus calcium concentration using DynaFit (Biokin Inc., Pullman, WA). Such fits were performed for co-reconstituted wild-type SLN, which was compared with positive (SERCA co-reconstituted with wild-type PLN) and negative (SERCA alone) control samples. All reaction rate constants were allowed to vary in the kinetic simulations, although the SERCA activity in the presence of SLN was best fit with modifications to only the three calcium binding steps in the reaction cycle (29). Agreement between the simulated and experimental data is indicated by the lowest residual sum of squares.

RESULTS

Wild-type PLN Versus Wild-type SLN—We first compared the reconstitution of SERCA in the absence and presence of recombinant human SLN (Fig. 2). The co-reconstitution method has been used extensively to study the functional regulation of SERCA by PLN (25, 27, 29–33), and the same approach was used herein for detailed characterization of SLN. The reconstituted proteoliposomes contain low lipid-to-protein ratios that mimic the native SR membranes, allowing the direct correlation of functional data (27, 29, 32, 33) with structural observations (34–36). As before, the proteoliposomes contained a lipid-to-protein molar ratio of ~120:1 and a SERCA-to-SLN molar ratio of ~4:5:1. For co-reconstitution of PLN, this molar ratio is similar to that found in cardiac SR (33, 37, 38); however, the SLN molar ratio used is higher than that found in skeletal SR (9). Although there is growing evidence that SLN can form higher order oligomers (23, 24, 39), the primary reason for using a higher ratio of SLN was to facilitate comparison with PLN variants studied previously (27, 29, 33) and herein. We measured the calcium-dependent ATPase activity of SERCA in the absence and presence of SLN. Proteoliposomes containing SERCA alone yielded a KCa of 0.46 μM and a Vmax of 4.1 μmol mg−1 min−1. Incorporation of wild-type SLN into proteoliposomes with SERCA resulted in a KCa of 0.80 μM calcium and a Vmax of 2.9 μmol mg−1 min−1 (Fig. 2 and Table 1). Thus, in the presence of SLN, SERCA had a lower apparent affinity for calcium (ΔKCa of 0.34) and a lower turnover rate (ΔVmax of −1.2). Comparative data for PLN indicated that it lowers the apparent calcium affinity of SERCA to a degree similar to that of SLN, and it has the opposite effect on Vmax. Nonetheless, the observed inhibitory activity of wild-type SLN in our system was consistent with previous observations (24, 30, 40) and served as a positive control for further studies.

Kinetic Simulations—In our previous studies, we have used kinetic reaction rate simulations to describe calcium transport by SERCA in the absence and presence of PLN (29, 33). The reaction scheme assumes that the binding of calcium to SERCA occurs as two steps linked by a slow structural transition that establishes cooperativity (E + Ca ↔ ECa ↔ E’Ca + Ca ↔ E’2Ca) (28, 41). The conformational change, represented by reaction rate constants Bfor and Brev, is the primary step affected by PLN that manifests as a decrease in the apparent calcium affinity of SERCA and increased cooperativity for calcium binding. To provide a mechanistic framework for the function of
### TABLE 1

Kinetic parameters for SERCA in the absence and presence of various sarcolipin mutants, chimeras, and peptides

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{max}}$ (μmol mg $^{-1}$ min $^{-1}$)</th>
<th>$K_{Ca}$ (μM)</th>
<th>$n_H$</th>
<th>$n$</th>
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<tr>
<td>SERCA</td>
<td>4.1 ± 0.1</td>
<td>0.46 ± 0.02</td>
<td>1.7 ± 0.1</td>
<td>32</td>
</tr>
<tr>
<td>WT SLN</td>
<td>2.9 ± 0.1</td>
<td>0.80 ± 0.02$^a$</td>
<td>1.4 ± 0.1</td>
<td>10</td>
</tr>
<tr>
<td>V26A</td>
<td>2.9 ± 0.1</td>
<td>0.69 ± 0.03$^a$</td>
<td>1.4 ± 0.1</td>
<td>7</td>
</tr>
<tr>
<td>R27A</td>
<td>3.4 ± 0.1$^a$</td>
<td>0.51 ± 0.01$^b$</td>
<td>1.4 ± 0.1</td>
<td>6</td>
</tr>
<tr>
<td>S28A</td>
<td>3.5 ± 0.1$^a$</td>
<td>0.59 ± 0.03$^b$</td>
<td>1.5 ± 0.1</td>
<td>6</td>
</tr>
<tr>
<td>Y29A</td>
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<td>0.63 ± 0.03$^b$</td>
<td>1.3 ± 0.1</td>
<td>13</td>
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<tr>
<td>Q30A</td>
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<td>0.60 ± 0.04$^b$</td>
<td>1.4 ± 0.1</td>
<td>4</td>
</tr>
<tr>
<td>Y31A</td>
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<td>0.52 ± 0.02$^b$</td>
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<td>5</td>
</tr>
<tr>
<td>Arg27stop</td>
<td>3.4 ± 0.1</td>
<td>0.55 ± 0.02$^b$</td>
<td>1.6 ± 0.1</td>
<td>9</td>
</tr>
<tr>
<td>WT PLN</td>
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<td>0.88 ± 0.03$^b$</td>
<td>2.0 ± 0.1</td>
<td>9</td>
</tr>
<tr>
<td>WT PLN + WT SLN</td>
<td>3.4 ± 0.1</td>
<td>1.36 ± 0.07$^b$</td>
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<td>3</td>
</tr>
<tr>
<td>cPLNlong</td>
<td>2.9 ± 0.1</td>
<td>2.3 ± 0.09$^a$</td>
<td>1.6 ± 0.1</td>
<td>6</td>
</tr>
<tr>
<td>cPLNshort</td>
<td>2.2 ± 0.1</td>
<td>3.4 ± 0.20$^a$</td>
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</tr>
<tr>
<td>Y26A/Y29A</td>
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<td>0.41 ± 0.02$^b$</td>
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<tr>
<td>Leu9</td>
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<td>Leu9tail</td>
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$^a$ $p < 0.05$ in the absence of wild-type SLN.

$^b$ $p < 0.05$ in the presence of wild-type SLN.

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**FIGURE 2. Functional data for wild-type SLN.** A, topology models for wild-type SLN and wild-type PLN (white, cytosolic residues; gray, transmembrane residues; black, luminal residues). Shown are ATPase activity (B) and normalized ATPase activity (C) as a function of calcium concentration for SERCA alone (solid black line), SERCA in the presence of wild-type SLN (solid gray line), and SERCA in the presence of wild-type PLN (dashed line). The curves fitted to the experimental data are from a global nonlinear regression fit of SERCA reaction rate constants (28) to each plot of ATPase activity versus calcium concentration. The $V_{\text{max}}$, $K_{Ca}$, and $n_H$ are given in Table 1. Each data point is the mean ± S.E. (error bars) ($n = 4$). D, kinetic simulations highlighting the differences between PLN and SLN. Starting from values determined for wild-type PLN (Table 2 and Ref. 29), simulations were performed allowing all reaction rate constants to vary (solid black line), allowing only $B_{\text{rev}}$ to vary (Fit 1; solid gray line), or allowing only $B_{\text{for}}$ and $B_{\text{rev}}$ to vary (Fit 2; dashed line). The reaction rate constants are given in Table 2.

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**TABLE 2**

Kinetic parameters for SERCA in the absence and presence of various sarcolipin mutants, chimeras, and peptides

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$^a$ $p < 0.05$ in the absence of wild-type SLN.

$^b$ $p < 0.05$ in the presence of wild-type SLN.
SLN, we used the same approach to gain further insight into the subtle differences between SLN and PLN regulation of SERCA (Fig. 2 and Table 2). Our kinetic analyses revealed that wild-type SLN targets the first two reaction steps, binding of the first calcium ion \( (A_{\text{for}} \text{ and } A_{\text{rev}}) \) and the subsequent conformational transition \( (B_{\text{for}} \text{ and } B_{\text{rev}}) \).

A dramatic increase in \( A_{\text{rev}} \) was observed, indicating that SLN decreases the apparent calcium affinity of SERCA by driving the enzyme toward a calcium-free conformation. SLN also decreased the forward rate constant for the SERCA conformational change \( (B_{\text{for}}) \), indicating that SLN lowers the maximal activity of SERCA by making this reaction step less favorable. To test whether our kinetic simulations for wild-type SLN were reliable, we ran additional simulations starting from the reaction rate constants determined for SERCA in the presence of wild-type PLN (28, 29). Holding all reaction rates constant and allowing only \( B_{\text{for}} \) and \( B_{\text{rev}} \) to vary, we attempted to force the simulation to fit the wild-type SLN experimental data with reaction rate constants determined for SERCA in the presence of Arg27-to-Ala SLN (3.4 μM calcium for wild type; \( K_{Ca} \) of 0.51 and 0.52 μM calcium; \( \Delta K_{Ca} \) of 0.11). This compared well with findings for PLN where alanine substitution of the homologous residue in PLN (Val19; Fig. 1). The Val26-to-Ala mutant also served as an internal comparison for the luminal tail mutants described below. As expected, alanine substitution of Val26 had only a minor effect on the inhibitory properties of SLN, resulting in mild loss of function (\( K_{Ca} \) of 0.69 μM compared with 0.80 μM calcium for wild type; \( \Delta K_{Ca} \) of 0.11). This compared well with findings for PLN where alanine substitution of the homologous position, Val19, had also been shown to have a mild effect on PLN function (29, 44). Thus, we concluded that Val26 is part of the transmembrane domain and not the tail region of SLN. For mutations within the luminal tail domain, the two most severe alanine substitutions were Arg27 to Ala and Tyr31 to Ala, which resulted in nearly complete loss of SERCA inhibition (\( K_{Ca} \) of 0.51 and 0.52 μM calcium; \( \Delta K_{Ca} \) of 0.05 and 0.06, respectively). These mutants were determined to be the strongest loss of function mutations in the luminal domain of SLN, indicating the importance of a positively charged residue at the membrane surface and a more distal aromatic residue. Interestingly, these mutants had distinct effects on the maximal activity of SERCA. Given the ability of wild-type SLN to reduce the maximal activity of SERCA (Fig. 3 and Table 1), the Arg27-to-Ala mutant resulted in a slight loss of this behavior, and the Tyr31-to-Ala mutant resulted in a complete loss of this behavior. In fact, the Tyr31-to-Ala mutant had the opposite effect in that it caused a slight increase in the maximal activity of SERCA. Compare the \( V_{\text{max}} \) values for SERCA alone (4.1 μmol mg\(^{-1}\) min\(^{-1}\), SERCA in the presence of wild-type SLN (2.9 μmol mg\(^{-1}\) min\(^{-1}\)), SERCA in the presence of Arg27-to-Ala SLN (3.4 μmol mg\(^{-1}\) min\(^{-1}\)), and SERCA in the presence of Tyr31-to-Ala SLN (2.2 μmol mg\(^{-1}\) min\(^{-1}\)).

### Table 2

<table>
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<tr>
<th>Reaction constants from kinetic simulations (s(^{-1}))</th>
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<th>( A_{\text{rev}} )</th>
<th>( B_{\text{for}} )</th>
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*Only the values in bold were allowed to vary in the kinetic simulations.*

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Luminal Domain of Sarcolipin and SERCA Regulation

**Table 2**

Rate constants from kinetic simulations (s\(^{-1}\))

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at any position in the SLN luminal tail results in loss of function, indicating a crucial role of each of the five luminal residues in proper regulation of SERCA. Clearly, Tyr$^{31}$ was the most essential residue for altering the apparent calcium affinity and depressing the maximal activity of SERCA. This suggests that, in addition to contributing to SERCA inhibition, the residues Ser$^{28}$, Tyr$^{29}$, and Gln$^{30}$ may play a role in the proper positing of Tyr$^{31}$.

It should be noted that the SLN luminal tail was examined in a previous study using HEK-293 cells and co-expression with SERCA (9). Alanine substitution of the luminal tail residues was found to have a minimal impact on SERCA activity, which contrasts with our findings described above. However, it was later shown that mutations in the SLN tail affect the retention of SLN in the endoplasmic reticulum of HEK-293 cells (18) such that improper trafficking of SLN may have been an unappreciated factor in the previous study. In addition, the previous study measured calcium transport activity of SERCA, whereas we have measured ATPase activity. Recent evidence suggests that SLN may play a role in thermogenesis by uncoupling SERCA ATPase activity from calcium transport (2).

**Removal of the SLN Luminal Tail (Arg$^{27}_{\text{stop}}$)—**Because all of the alanine substitutions in the SLN luminal domain created defects in SERCA regulation, we next chose to remove the luminal tail and test the inhibitory capacity of the transmembrane domain of SLN alone. For comparative purposes, recall that ~80% of the inhibitory activity of PLN is encoded by its transmembrane domain (29). To this end, a truncated variant of SLN, Arg$^{27}_{\text{stop}}$, missing the last five C-terminal amino acids (27RSYQY) was generated by chemical synthesis. During synthesis, the C terminus was amidated to avoid a free carboxyl at the end of the transmembrane domain. Incorporation of Arg$^{27}_{\text{stop}}$ into proteoliposomes with SERCA proceeded normally, and the final SERCA-to-peptide ratio was comparable with that for wild-type SLN (data not shown). The effect of this peptide on SERCA activity was measured in the same fashion as the alanine mutants described above. As one might expect given the results from alanine mutagenesis, the complete removal of the luminal tail resulted in major loss of SLN function (Fig. 4 and Table 1). The $K_{\text{Ca}}$ of SERCA was 0.59 $\mu$M calcium in the presence of Arg$^{27}_{\text{stop}}$ compared with 0.80 $\mu$M calcium in the presence of wild-type SLN (~26% of wild-type inhibitory capacity). Note that the $K_{\text{Ca}}$ value for Arg$^{27}_{\text{stop}}$ is not significantly different from the alanine substitutions discussed above. Arg$^{27}_{\text{stop}}$ also resulted in a partial recovery of the maximal activity with a $V_{\text{max}}$ value halfway between that of SERCA alone and SERCA in the presence of wild-type SLN. The large change in the inhibitory potency of Arg$^{27}_{\text{stop}}$ agrees with the alanine substitution data and further demonstrates the necessity of the luminal domain of SLN in SERCA regulation. Interestingly, the luminal tail of SLN rather than the transmembrane domain appeared to encode most of the inhibitory properties of SLN. This contrasts with PLN where the inhibitory properties are encoded by the transmembrane domain. This was a surprising finding given that SLN and PLN have homologous transmembrane domains, which are thought to interact with the same site on SERCA and use a similar mechanism of inhibition.
Adding the SLN Luminal Tail to PLN—If the luminal domain encodes the inhibitory properties of SLN, we wondered what would happen if the luminal tail were transferred to the homologous PLN. To test this idea, two chimeric peptides were constructed from wild-type PLN, one with the five luminal residues of SLN (27RSYQY) added to the C terminus (cPLNlong) and one with the luminal residues added after Val49 of PLN (cPLNshort). This latter construct placed the luminal tail of SLN at the homologous position in PLN (Fig. 1 and Fig. 5). The calcium-dependent ATPase activity was measured for SERCA in the presence of the chimeras where SERCA alone served as a negative control and SERCA in the presence of wild-type PLN served as a positive control (Fig. 5 and Table 1). Including wild-type PLN in proteoliposomes with SERCA resulted in the expected decrease in the apparent calcium affinity of SERCA ($\Delta K_{Ca}$ of 0.42 $\mu$M calcium) and increase in the maximal activity of SERCA (from 4.1 to 6.1 mol mg$^{-1}$ min$^{-1}$). Compared with wild-type PLN, including the chimeras in proteoliposomes resulted in superinhibition of SERCA ($\Delta K_{Ca}$ values of 1.84 $\mu$M calcium for cPLNlong and 2.94 $\mu$M calcium for cPLNshort). Importantly, both chimeras also resulted in a decrease in the maximal activity of SERCA that was comparable with wild-type SLN. This was in marked contrast to the increase in SERCA maximal activity observed with wild-type PLN in the co-reconstituted proteoliposomes (27, 29, 33). Thus, adding the SLN luminal tail to PLN had a synergistic effect on the apparent calcium affinity of SERCA and an SLN-like effect on the maximal activity of SERCA. Although both PLN chimeras were superinhibitory, the cPLNshort construct resulted in a much larger shift in the apparent calcium affinity of SERCA. The potent inhibition by cPLNshort may be due to better positioning of the SLN luminal tail and the fact that this chimera appears to be monomeric by SDS-PAGE (Fig. 5D).
The SLN Luminal Tail Is a Distinct Functional Domain—The experiments thus far seemed to indicate that the luminal domain of SLN encodes most of its inhibitory activity. To test the inhibitory properties of this domain in isolation, we synthesized a peptide corresponding to 27RSYQY with an acetylated N terminus. Previous work by others has demonstrated that such a peptide can decrease the maximal activity of SERCA albeit under excess peptide conditions (~100-fold (19)). Herein, the soluble peptide was co-reconstituted with SERCA such that the peptide was on the interior of the proteoliposomes with access to the luminal region of SERCA, and excess peptide on the exterior of the proteoliposomes was removed by sucrose gradient purification. Although SERCA was treated with up to a 100-fold molar excess of peptide prior to reconstitution, this had no effect on SERCA activity (Table 1). These data indicate that the 27RSYQY peptide by itself did not result in the robust inhibitory properties of this domain in isolation, we synthesized a peptide that contained the Leu9 sequence with the five luminal residues of SLN at its C terminus (Fig. 6; designated Leu9tail). Because the Leu9 peptide has been characterized (31), it served as a positive control for our studies of the Leu9tail peptide. In the co-reconstituted proteoliposomes, Leu9 had a slight effect on the apparent calcium affinity of SERCA ($\Delta K_{Ca}$ of 0.15 mM calcium; ~36% of wild-type PLN inhibitory activity) and a small effect on the maximal activity of SERCA. Inclusion of the SLN luminal tail significantly increased the inhibitory capacity of the Leu9 peptide ($\Delta K_{Ca}$ of 0.35 mM calcium compared with $\Delta K_{Ca}$ of 0.34 mM for wild-type SLN) and reduced the maximal activity of SERCA to the same degree as wild-type SLN. Compare the $V_{max}$ values for SERCA alone (4.1 $\mu$mol mg$^{-1}$ min$^{-1}$), SERCA in the presence of Leu9 (4.4 $\mu$mol mg$^{-1}$ min$^{-1}$), SERCA in the presence of wild-type SLN (2.9 $\mu$mol mg$^{-1}$ min$^{-1}$), and SERCA in the presence of Leu9tail (3.0 $\mu$mol mg$^{-1}$ min$^{-1}$). These observations support the notion that the luminal tail encodes much of the inhibitory properties of SLN and that it is a distinct and transferrable regulatory domain.

DISCUSSION

Wild-type PLN Versus Wild-type SLN—Based on the available evidence, it was reasonable to assume that SLN and PLN would use similar inhibitory mechanisms to regulate SERCA. As such, SLN and PLN could represent redundant regulatory subunits separated by distinct tissue distributions with SLN primarily in skeletal muscle and PLN in cardiac and smooth muscle. As an endogenous inhibitor of SERCA, SLN plays a central role in regulating calcium transport in skeletal muscle. However, SLN is co-expressed in atrial muscle along with PLN (3–6), which raises questions about why redundant regulatory mechanisms would be required in this tissue. As has been shown for PLN, SLN alters the apparent calcium affinity of SERCA albeit to a lesser degree (Fig. 2 and Ref. 9). PLN is highly conserved among mammalian species with a transmembrane domain that encodes SERCA inhibition and a cytoplasmic
domain that is a target for regulation. SLN is also highly conserved with a transmembrane domain analogous to that in PLN, a short cytoplasmic domain that is a target for regulation, and a unique, highly conserved luminal domain. Given these similarities and differences between SLN and PLN, it is important to understand the regulatory mechanism of SLN with potential relevance for heart and skeletal muscle diseases.

Because this is our first detailed characterization of SLN, it is important to consider aspects of the experimental system, namely co-reconstituted proteoliposomes containing SERCA1a and recombinant SLN. Such proteoliposomes have been extensively used by us (27, 29, 32–36, 46) and others (16, 47–52) for the detailed characterization of PLN structure and function. They contain SERCA-to-lipid molar ratios that approximate SR membranes, and the inclusion of PLN in these proteoliposomes has the expected effect on the apparent calcium affinity of SERCA (28). At these low lipid-to-protein ratios, PLN has an additional effect on the maximal activity of SERCA (27, 29, 51). As shown herein, SLN is readily incorporated into the proteoliposomes, and we observed the expected effect on the apparent calcium affinity of SERCA (Fig. 3) (9). In contrast to PLN, SLN has an opposite effect on the maximal activity of SERCA.

Using the proteoliposomes described above, we found that wild-type SLN altered the apparent calcium affinity of SERCA at a level equivalent to ∼80% of the inhibitory capacity of wild-type PLN. Interestingly, the SERCA inhibition by wild-type SLN is comparable with what is observed for peptides encoding only the transmembrane domain of PLN (31, 53, 54). Nonetheless, in contrast to what is observed for PLN, SLN decreased the maximal activity of SERCA (Fig. 2 and Table 1). Given these differential effects on SERCA activity, we used kinetic simulations to identify SERCA reaction steps that may be altered by SLN. In this regard, PLN is known to alter a SERCA conformational change that follows binding of the first calcium ion, thereby establishing cooperativity for binding of a second calcium ion (28, 29). Surprisingly, we found that SLN does not fit this kinetic model. Instead, SLN stabilizes a calcium-free conformation of SERCA by altering the binding of the first calcium ion. Combined with the observed decrease in the maximal activity of SERCA, we concluded that SLN uses an inhibitory mechanism that is distinct from that used by PLN.

**SLN Structural Elements Involved in SERCA Inhibition**—Because SLN appeared to use a unique mechanism to regulate SERCA, it was important to identify the structural features that encode this behavior. There are nine invariant residues in SLN that mainly occur in the transmembrane domain (Fig. 1), and only four of these residues are invariant in the homologue PLN. The short cytoplasmic domain of SLN is variable across a wide range of species, whereas the luminal domain exhibits a high degree of conservation particularly among mammals. Alanine-scanning mutagenesis of the luminal domain revealed that Arg27 and Tyr31 are the two most essential residues for SERCA regulation; both residues are required for the effect on the apparent calcium affinity of SERCA, and Tyr31 is required for the effect on the maximal activity of SERCA (Fig. 3). The interaction of Tyr31 with SERCA has been recognized (19), although another study did not identify luminal residues as important for SLN inhibitory function (9). Nonetheless, we found that mutation of either Arg27 or Tyr31 strongly suppressed SERCA inhibition by SLN. One might predict that Arg27 could reside at the membrane interface and therefore aid in positioning of SLN relative to SERCA and the lipid bilayer. Alanine substitution would remove the positively charged side chain and extend the hydrophobic surface of the transmembrane domain of SLN, thereby causing misalignment of SLN within the binding groove of SERCA (M2, M4, M6, and M9).

It is interesting to notice that the nature of the critical residues, Arg27 and Tyr31, suggest that cation–π or π–π interactions might be involved in the SERCA–SLN inhibitory complex. By analogy with PLN, the C terminus of SLN is thought to interact with the luminal end of the M2 transmembrane segment of SERCA (55). Toward the luminal end of the M1–M2 region, there are five aromatic residues, Phe73, Trp77, and Phe78 on M1 and Phe88 and Phe92 on M2. Phe88 and Phe92 on M2 flank an interaction site identified for PLN where Val99 of SERCA was cross-linked to Val199 of PLN (55, 56). Val99 of PLN is equivalent to Val26 of SLN; thus, Arg27, Tyr29, and Tyr31 of SLN may be proximal to Phe88 and Phe92 of SERCA (Fig. 7). Arg27 may form a cation–π interaction with Phe92, whereas Tyr29 and/or Tyr31 may form a cation–π or π–π-stacking interactions with Phe88. Given that the M1–M2 region of SERCA undergoes large structural rearrangements as the enzyme transitions from the calcium-free E2 state to the calcium-bound E1 state, these molecular interactions could explain the important inhibitory role of the luminal residues of SLN.
Luminal Domain of Sarcolipin and SERCA Regulation

The Luminal Extension of SLN Is a Distinct and Transferrable Regulatory Domain—There are several roles that have been suggested for the luminal domain of SLN, including SR retention and functional interaction with SERCA. For PLN, SR retention occurs via the diarginine motif in its cytoplasmic domain as well as through the direct interaction with SERCA (57). The luminal 27RSYQY sequence of SLN has been shown to be involved in SR retention, although the interaction with SERCA may also be a retention mechanism (18). There have been mixed reports on the inhibitory contributions of the SLN luminal domain (9, 19). Co-expression of SERCA and SLN mutants in HEK-293 cells revealed minor contributions of the C-terminal residues where loss of function occurred only when both Tyr29 and Tyr31 were mutated (9). Endoplasmic reticulum retention may have been affected in this study (18). Another study highlighted the importance of the two luminal aromatic residues in regulating SERCA. Using solid-state NMR combined with functional measurements, a soluble 27RSYQY peptide was shown to interact with SERCA and lower its maximal activity (19). There was no effect of this peptide on the apparent calcium affinity of SERCA. In contrast, our results indicate that the luminal domain of SLN alters both the maximal activity and apparent calcium affinity of SERCA. Given these disparate observations, we sought another experimental approach to elucidate the regulatory capacity of the SLN luminal domain.

To test the functional contributions of this domain, two PLN-SLN chimeras were constructed. The first construct possessed the 27RSYQY sequence added to the C terminus of wild-type PLN. In the context of the chimera, the full-length PLN sequence was expected to retain wild-type functional properties, and the functional effects of the SLN luminal domain were expected to be additive. The second construct possessed the 27RSYQY sequence added after Val49 of PLN, effectively replacing the C-terminal 50MLL sequence. In the context of this chimera, the shortened PLN sequence might alter its functional properties; however, the SLN luminal domain would be optimally positioned for interaction with SERCA. To our surprise, both chimeras turned out to be potent superinhibitors of SERCA where the luminal domain of SLN had a synergistic effect on PLN inhibitory function. In fact, the chimeras were reminiscent of the superinhibition observed for the ternary SERCA-PLN-SLN complex (7) thought to exist in the atria. These observations are consistent with the mutagenesis data described above and support the notion that the luminal domain of SLN possesses inhibitory activity. Although the chimeras were reminiscent of the ternary complex, they were much more potent inhibitors of SERCA. Comparing the values in Table 1, the ΔK values were 0.9 μM calcium for the ternary complex, 1.84 μM calcium for the long chimera (cPLNlong), and 2.94 μM calcium for the short chimera (cPLNshort). In the ternary complex, PLN and SLN are thought to interact with SERCA as well as each other (7), and this may create steric restrictions that impact the proper positioning of critical regulatory domains, the transmembrane domain of PLN and the luminal domain of SLN. However, in the context of the chimeras, both the transmembrane domain of PLN and the luminal domain of SLN may be properly positioned in the SERCA binding groove (M2, M4, M6, and M9 (7)). Because these two domains use distinct mechanisms to regulate SERCA, the combined effect could result in the observed superinhibition. It is also noteworthy that by SDS-PAGE the short chimera is largely monomeric, which could contribute to the superinhibition seen for this construct.

Although the PLN-SLN chimeras were consistent with a functional role for the luminal domain of SLN, this was one of several potential explanations for the observed superinhibition. There are a variety of ways to convert PLN into a superinhibitor of SERCA that might not reflect a functional contribution from the luminal 27RSYQY sequence. PLN superinhibition can result from mutation (27, 58), depolymerization of the PLN pentamer (44, 59), and reverse engineering of PLN peptides (25, 31). If the luminal region of SLN is an independent functional and structural domain, it should be able to regulate SERCA in the absence of either the SLN or PLN transmembrane domain. However, a soluble 27RSYQY peptide by itself did not alter SERCA activity over a range of excess concentrations. This may not be surprising because the luminal 27RSYQY sequence is normally tethered to the SR membrane. To further test the luminal domain as an independent functional entity, we tethered the 27RSYQY sequence to a model transmembrane peptide designated Leuα (31). Using a reverse engineering approach, Leuα was derived from the PLN transmembrane sequence where the nine leucine residues were retained and all other residues were mutated to alanine. This peptide is a weak inhibitor of SERCA with ~36% of wild-type PLN inhibitory activity. Adding the luminal tail of SLN to Leuα generated a construct that was indistinguishable from wild-type SLN (Table 1 and Fig. 6). Compare the K and V values for SERCA in the presence of Leuα (0.81 μM calcium and 3.0 μmol mg⁻¹ min⁻¹) and SERCA in the presence of wild-type SLN (0.80 μM calcium and 2.9 μmol mg⁻¹ min⁻¹). These data clearly demonstrate that the luminal region of SLN is a distinct structural and functional domain.

In summary, critical determinants for SLN inhibitory function are found in its unique and conserved luminal tail. The structural elements that may contribute to the formation of a SERCA-SLN inhibitory complex include Arg27, Tyr30, and Tyr31 of SLN and a series of aromatic residues at the base of M1-M2 of SERCA (particularly Phe88 and Phe92). These molecular interactions account for much of the inhibitory function of SLN, and this contrasts sharply with what is known for PLN. The transmembrane domain of PLN encodes ~80% of its inhibitory activity, whereas ~75% of the inhibitory activity of SLN is encoded by the luminal tail. These distinct structural elements that are used by PLN and SLN to regulate SERCA translate into different inhibitory mechanisms (28, 29). PLN slows a SERCA conformational transition that follows binding of the first calcium ion and establishes cooperativity for binding of a second calcium ion. SLN alters binding of the first calcium ion, thereby stabilizing a calcium-free conformation of SERCA. Given that these functional properties can be transferred to PLN or a generic transmembrane helix, we conclude that the luminal tail of SLN is a distinct, essential, and transferrable regulatory domain.
Luminal Domain of Sarcolipin and SERCA Regulation

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